Thrust Area 2: Manufacturing Information and Control

Active Projects

1. Reducing unscheduled downtime (GEMA)
2. Performance metrics for wireless networks (Ford, USCAR)
3. Factory-wide time synchronization (NIST)
4. Hardware in-the-loop simulation (GM)
5. Development, application and transfer of a network ROI cost calculator (Pilz, Chrysler)
6. Consolidation of control (RFT)

Completed Projects

1. Industrial Ethernet testing (GM)
2. Automatic logic generation (Ford)
3. Control logic verification
4. Improving quality while reducing cost through virtual inspection and process control
5. Enterprise-wide control
6. Implementation of reconfigurable logic control (NI)

Dawn Tilbury and James Moyne

Engineering Research Center for Reconfigurable Manufacturing Systems ERC/RMS

University of Michigan

September 2007

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University of Michigan – GEMA[1]

Reducing Unscheduled Downtime through Automated Event-based Control

Jing Zhang, Vinod Anandarajah

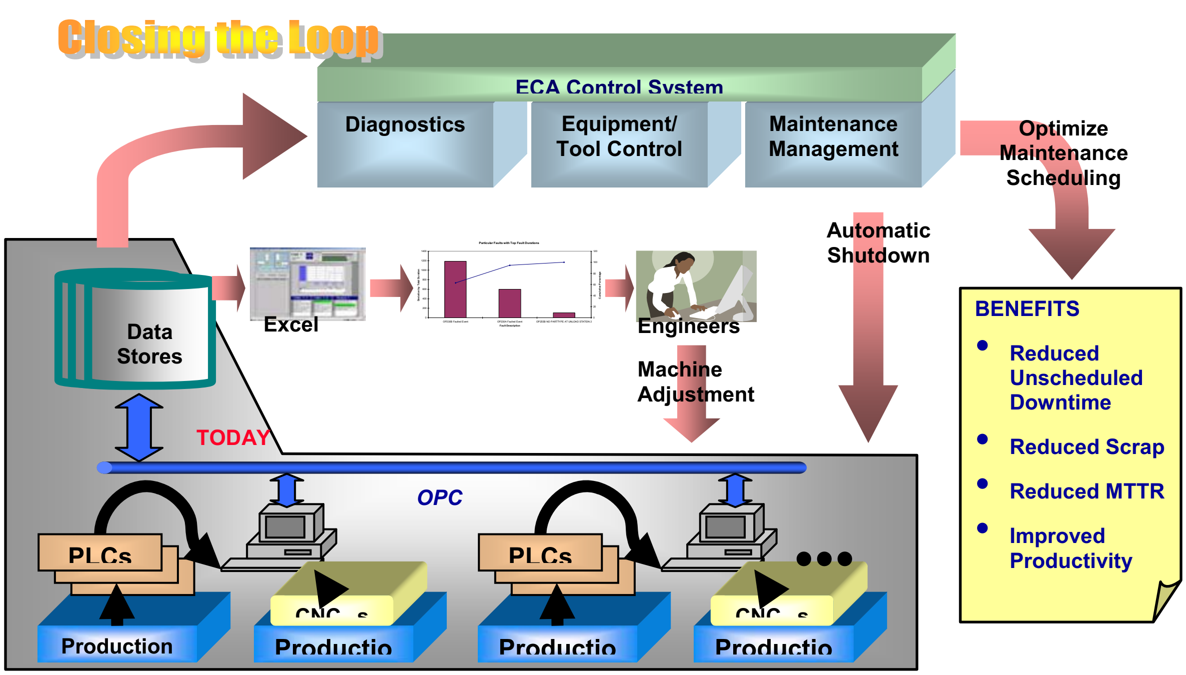
Sept 28, 2007

Goal:

Develop and demonstrate an open-architecture event-driven software control system that (1) links equipment data collection, equipment control and equipment & tool maintenance capabilities and (2) provides for reduction in unscheduled downtime and reduction of Mean-Time-To-Repair (MTTR)

Overview:

- Leverage GEMA's data collection infrastructure for OPC data, maintenance data and tool change data
- Analyze the relationship between OPC data and maintenance/tool change data
- Optimize maintenance scheduling/tool change scheduling
- Deliver the control solution in an open-architecture, event driven system so as to allow scalability to accommodate other control workflow scenarios



[1] GEMA: Global Engine Manufacturing Alliance

Scope:

- Use the GEMA facility to verify <u>concepts</u>
- Focus on <u>manufacturing operations</u> at GEMA facility
- <u>Multi-year project</u> with concise intermediate and final deliverables
- Project is structured to produce results that are <u>scalable to other candidate processes and other facilities</u>

Benefits:

- Reduction of unscheduled downtime
- Reduction of MTTR
- Improved understanding and practice of data collection
- Improved maintenance/tool change scheduling
- Improved data visibility
- Definition of data consolidation approach
- Scalable solution that can be applied to other control scenarios

Deliverables/Milestones:

- Historical Data Study indicating potential improvement (Q1/06) √
- Report on potential ROI improvement and success metrics (Q1/06) √
- Best Practices document for Maintenance Management (Q2/06) √
- Develop automated mechanism for finding trends in process data (Q2/06) √
- Develop mechanism to get feedback from process engineers (Q3/06) √
- Develop an analysis scripts to pick anomalies on the plant floor (Q1/07) √
- Develop a user interface for reporting (Q9/07) √
- Study on OPC data collection for data quality analysis (Q9/07) √
- Study on relationship of OPC data and maintenance/tool change data (Q9/07) √
- Demonstration of conservative practice of preventive maintenance (Q9/07) √
- Manual for Pareto user interface (Q11/07)
- Normalization of overlay plots (Q12/07)
- Including scrap data into analysis (Q02/08)
- Improved scheduling of maintenance and tool change (Q03/08)

Project Progress:

- Developed automated solution for finding trends
- Developed module for generating plant floor feedback
- Best practices for data entry
- Developed script to analyze data on a daily basis
- Developed mechanism to identify plant floor anomalies
- Generating a Pareto chart view for the plant floor anomalies
- Documenting the OPC data collection mechanism for data quality analysis
- Plotting relationship between OPC data and maintenance/tool change data
- Demonstration of conservative practice of maintenance through plots

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Wireless Network Analysis and Testing

Joachim Klima
September 2007

Goal:

Evaluate the performance of various wireless network technologies and standards (e.g. Wifi, Bluetooth, Zigbee) by analyzing and testing expected network delays under different environments and loading conditions in order to be able to determine best practices for the use of wireless in adequate areas of operation.

Background:

Wireless technology has boomed over the past years in the private sector – today there is hardly any notebook that does not come with built-in wireless connectivity possibilities. Private demand has driven product development, yet industrial applications are becoming more and more widespread. This has its reasons in the great opportunities for industry that are generally associated with wireless:

- Reduced cost for network equipment purchase, installation and maintenance
- Increased flexibility when changing plant layouts as well as machine configurations (e.g. with respect to location of sensors)
- New operational areas are being created (e.g. devices on robot end effectors)

Industry has been somewhat hesitant in their move to wireless as there are serious risks or at least unanswered questions to consider such as network performance variations, network failures and breakdowns due to special environment conditions and interference. Also, network security is an important point: Data transmitted over the air should not be readable for everyone but should also be stable so that network breakdowns cannot be forced by outsiders.

In order to address these questions, the University of Michigan conducts wireless network performance and interference tests:

Figure 1: Test setup for cordless phone interference test

Conducted tests and results:

- Preliminary 802.11g network performance test conducted at Ford Livonia (April 2007): The influence of distance, obstacles like walls and metal plates, and Bluetooth interference on the delays occurring in 802.11g communication.
  Result: Network performance was affected, yet only slightly so that this may be negligible in certain applications.

- Cordless phone interference in Wifi communication (June / September 2007)
  Result: Strong interference of 802.11g and a 2.4 GHz cordless phone that led to a breakdown of the Wifi network

Future work:

- Comparison of most important wireless technologies (Bluetooth, Zigbee, Wifi) in performance and interference tests
- Determining the breakpoint where wireless applications stop working properly / defining ways to avoid this
- Best practices for the replacement of wired networks as well as the creation of new operational areas

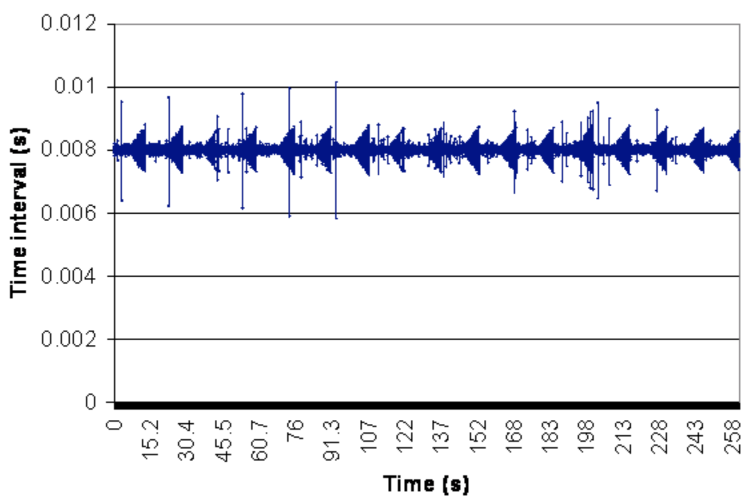

Figure 2: Interval time variation in 802.11g performance test

References:

[1] J. Klima, N. Kalappa, D. Tilbury, and J. Moyne, "Wireless Performance Testing / Ford Livonia Transmission Plant " ERC Test Report, April 2007

[2] J. Klima, K. Schroeder, D. Tilbury, and J. Moyne, "Cordless phone interference in Wifi communication" ERC Test Report, September 2007

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Manufacturing Network Time Synchronization Best Practices

J. Moyne, S. Hussaini, V.Anandarah, R Sangole, N.Kalappa, J. Baboud, and Y.Shian Li

Project Goal

Investigate methods for utilizing timing and networked time synchronization protocols such as IEEE 1588 in manufacturing control systems with focus on semiconductor manufacturing.

Motivation

- With Ethernet becoming the network of choice for the manufacturing floor, time-synchronization has gained importance.
- Consolidation of capabilities across the factory floor, such as diagnostics, requires synchronization.
- Synchronization mechanism is needed for defacto factory-wide data collection standards such as OPC.

Parameterization of the problem

As shown in Figure 1, the entire manufacturing floor is adopting Ethernet as the sole networking technology. Time synchronization allows us to take advantage of the information consolidation provided by the network to provide improved systems for diagnostics, control and safety. The extent and precision of time synchronization required at various levels of the factory floor needs to be investigated.

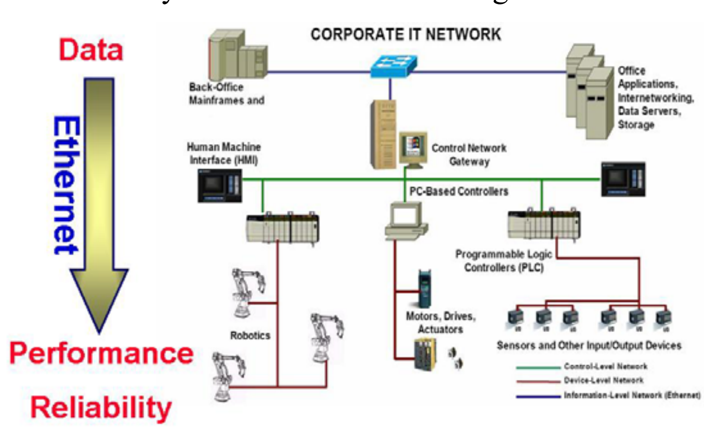


Figure.1

Approach and Deliverables

- Assess the *end to end delay* problem to evaluate the benefit of network time synchronization
- Investigate *best methods for utilizing time synchronization mechanisms, such as IEEE 1588*, in manufacturing networked control systems, in order to mitigate factory and equipment time synchronization issues in industry.
- Simulate semiconductor manufacturing environment and evaluate the performance improvement gained through the application of IEEE 1588.

Initial Results

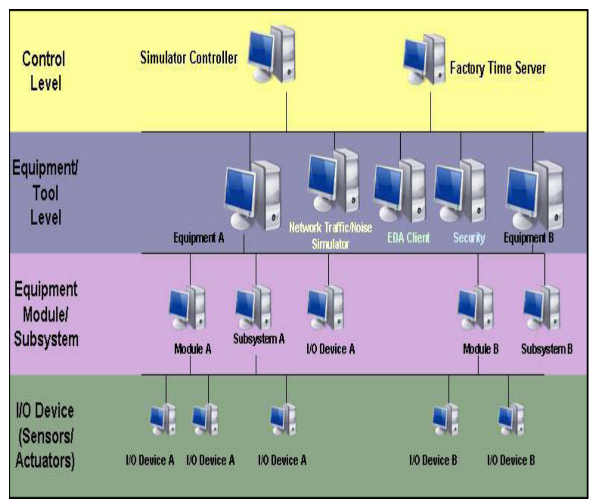
- Device speed and its variability dominate delays in network communication

Table 1: Network delay contributions

	UDP	VPN	OPC	DeviceNet
Delay Average (ms)	0.33	1.21	1.48	0.3-1.2
Delay Variation (3σ) (ms)	0.09	0.49	2.43	0.005-0.2
Network Contribution (ms)	0.035	0.035	0.035	0.188
% of Delay Due to Network	**11%**	**3%**	**2%**	**63%**

Semiconductor Factory Simulator

Goal:
To design a semiconductor factory simulator, which can accurately Model the factory network.



Accomplishments:
- The first phase of the simulator has been successfully completed.
- It has been able to create scenarios typical of the Equipment Data
  Acquisition messages seen on the factory floor.
- Practical perspective to study the accuracy achievable and potential network factors contributing to accuracy degradation of factory-wide time synchronization.

Future:
- Scaling the simulator to run multiple instances of equipment server objects simultaneously.
- Capability of extracting available parameters from all equipment.
- Implement SOAP Transport, for more realistic rendering of the EDA process.

References
N. Kalappa, J Moyne, J Parrott and Y.Shian Li. Practical Aspects Impacting Time Synchronization Data Quality in Semiconductor Manufacturing. In *Proceedings of the IEEE 1588 Conference*, October 2006

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Developing Hardware-in-the-Loop in a Hybrid Simulation for Verification and Validation of Logic Control

William Harrison III
Funded by General Motors and the National Science Foundation
September 28, 2007

Purpose for Hardware-in-the-Loop Simulation (HIL)

Develop a methodology for HILS in which hardware and software components of a manufacturing system can be swapped out for verification, testing, and analyzing logic controllers

- Creating a manufacturing system consisting of multiple regions of real and virtual (Hybrid Simulation)
- Monitoring manufacturing systems
- Playing back past manufacturing scenarios
- Predicting future system interaction and performance

Reason for HIL

- Standalone simulation is sometimes not reliably accurate
- Simulation models may not exist for parts of the system
- Controller and logic verification is best done with actual parts of the system

HIL System Components

- 3 Dimensional visualization software
- Fanuc Robot
- Modular Finite State Machine Cell controller

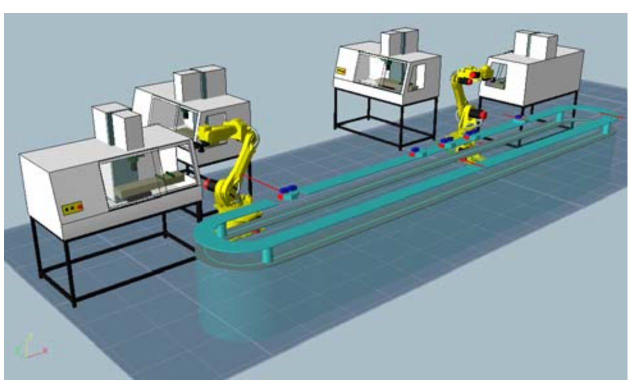

Figure 1: Technomatix visualization of the monitoring area

What Must Happen
To create a truly modular system with both real and virtual parts, regions of the process must be able to handle various different scenarios.

- Real part in real region of the system
- Virtual part in the virtual system
- Virtual part in the real system

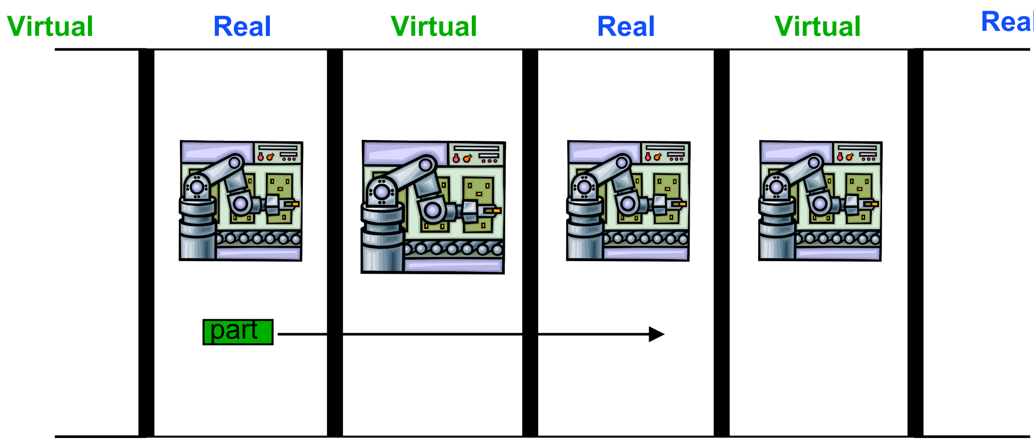

Figure 2: Parts can start in a real region traveling thru the system transitioning between real and virtual

What Happens
Parts transition from real to virtual and then back to real. The real system must act as if there is a part present despite its absence. This scenario is made possible by the part emulator. This enables testing to progress from complete simulation to complete physical implementation seamlessly.

Accomplishments
- **Understand state-of-the-art of simulation in auto manufacturing**
- **HILS implementation on ERC-RFT**
- **2007 Conference on Automation Science and Engineering: Hardware-in-the-Loop for Manufacturing Automation Control: Current Status and Identified Needs**

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Development, Application, and Transfer of a Network ROI Cost Calculator

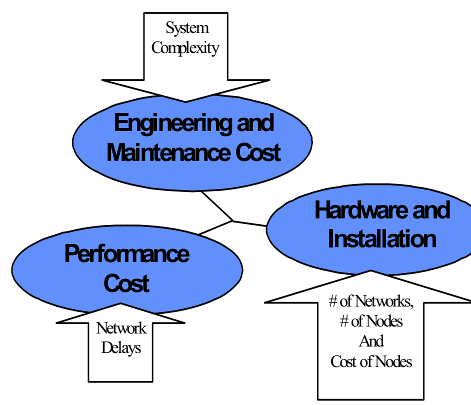
Kyle Schroeder
September 2007

Introduction

With a variety of different network configurations and protocols a fundamental question that must be explored is "how much does a network actually cost?", and "what is the relative cost of reconfiguring a network?" Any complete solution to this question must analyze the initial and recurring costs of a network and be flexible enough to be updated as technology changes. Resolving this issue is fundamental to plant floor network architectures and delivery of high Return-On-Investment. Results of applying a weighted cost calculator to the network design and reconfiguration process will aid in the development of a more cost effective network from the initial design through all stages of reconfiguration including adding or updating nodes, and adding in functionality such as safety.

Background

The purpose of a network is to reduce cost and improve performance and capabilities of the networked system. As networks proliferate throughout the factory, the associated up-front and on-going costs are significant. Traditionally, networks have been divided along the general lines of functionality: control, diagnostic, and safety. However, these lines are blurring and the ability to calculate the ROI of a network is becoming more complex.



Cost Calculator

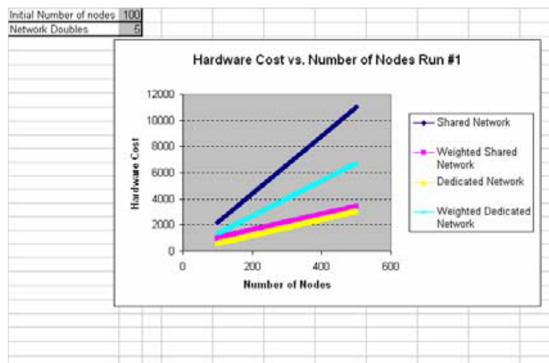
In a very general sense, each network configuration has advantages and disadvantages. For example a network configuration dedicated to a particular function such as control will be easier to set up, configure, and maintain than a network that shares multiple functions (such as control and safety) due to the interactions of two sets of performance requirements. System complexity impacts the performance, engineering, and maintenance costs of a system and hence is a significant issue. A benefit of shared networks is that they often have lower hardware (fixed) costs, while individual networks in some instances can have lower performance (recurring) costs.

In order to generalize this cost a two-tiered cost calculator was developed to include relevant costs that should be included when network cost is to be calculated. Each of the top tier terms can be further broken down to include second tier costs. In such an incremental cost calculator, terms can be added as the body of research on actual cost grows.

$$WCost_{total} = \frac{W_H}{(W_H + W_E + W_P)} Cost_H + \frac{W_E}{(W_H + W_E + W_P)} Cost_E + \frac{W_P}{(W_H + W_E + W_P)} Cost_P$$

Cost Calculator Application

An application was developed to aid in the research to further characterize the network costs and weights. The calculator has an easy to use Excel interface with a VBA code backbone. The output from the calculations is presented in Excel and therefore is easy to use and display. This type of functional macro allows for modularization and for the addition of proprietary performance and engineering cost calculators, such as the PILZ SafetyBUS p calculator. Currently the network cost calculator application is being used to characterize the total network cost of the RFT. The output from this scenario has been beneficial in providing insight into what has driven the cost of the RFT network. The calculator is available for application in the analysis of networking data . In other words the application of this process will provide networking ROI information, and also provide input into the improvement of the calculator. A second version of the software has been developed that further facilitates usability and customization of the software.



Future Work

With the calculator baseline in place the major work that remains in this project is to develop the terms in the cost calculator. While the hardware and engineering costs of a network have been defined in terms of monetary measurements that can be easily defined and measured, the methods required to find the cost of poor network performance are not straightforward and will require a significant effort to define. To move forward, tests will be needed to gather network performance data that can be used to develop the terms and weights of the cost calculator.

Acknowledgements

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References

[1] IEC 61508, Functional safety of electrical/electronic/programmable electronic safety-related systems, 2001.

[2] Moyne, James, Bradley Triden, Aditya Thomas, Kyle Shroeder, and Dawn Tilbury. "Cost function and tradeoff analysis of dedicated vs. shared networks for safety and control systems." Automated Technology in Practice 2(2006): 22-31.

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Factory Control Logic Consolidation

L. Allen, D. Sharma, J. Zhang
September 2007

Introduction and Objectives

Typical factory systems are characterized by fragmented data and control components that often operate as "silos" of control with often times conflicting objectives that do not tie well to overall factory objectives. This property of control systems, which usually results from the piecewise development and implementation of these systems by different teams, leads to control systems that are non-optimal, difficult to maintain, and very difficult to reconfigure. The Reconfigurable Factory Testbed (RFT) in the ERC-RFT is an example of such a system as it has been developed piecewise by different groups of students, often as part of industry and research projects. This distributed development has led to a broken control hierarchy, where the system level controller (SLC) performs both Factory and Cell level control, causing problems with debugging and degrading the system's reconfigurability. To address these problems a methodology is being developed to aid in the control consolidation of manufacturing systems, especially Event-Condition-Action (ECA) based systems. The project seek to preserve that property while fixing their control hierarchy. An RFT control consolidation project is being undertaken to guide the methodology development as well as to provide a case study of its use.

Background

The RFT control hierarchy has three levels of control – Factory, Cell, and Machine – with most controllers lying within one level and separated by well-defined interfaces. The SLC is an exception because it includes both Factory and Cell level control, as shown in Figure 1.

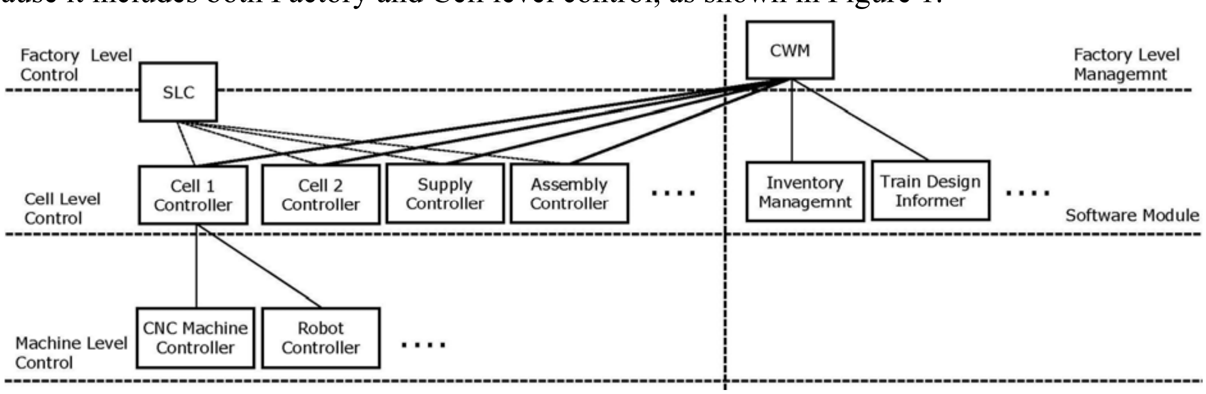

Figure 1: Control Hierarchy Prior to Consolidation

The ECA paradigm, originally used in active database systems, consists of the arrival of an event (E), the evaluation of conditions (C) associated with that event, and based on this evaluation, the performance of a pre-determined action (A). The CWM and SLC are both ECA-based, where the CWM is a rule engine for a set of ECA rules and the SLC is a set of communicating ECA MFSMs (Modular Finite State Machines) [3].

Methodology for (ECA) Control Consolidation

- Identify controllers that break the standard control level hierarchy.
- Eliminate those controllers by moving their logic to other parts of the system.
  - Identify each of its functions with a method, including inputs and outputs
  - For each method, assess whether its logic should be shifted up or down based on whether the function it performs is higher or lower level and with which side of the interface (above or below) its inputs/outputs are consistent.
- Re-route any communication that previously went through the eliminated controllers.

Application of Preliminary Methodology to RFT Control Consolidation

- The SLC, and its accompanying communication subsystems, is the only controller that violates the standard hierarchy.
- The procedure provided above is used to eliminate the SLC by moving its logic. An example of using the procedure is illustrated for in Table 1 (where C1C = Cell 1 Controller, SWI = Software Infrastructure) for the Cell 1 ECA MFSM in the SLC.
- The communication subsystems – trackers and RFID – associated with the SLC are shifted into the Software Infrastructure and CWM.

Table 1: Application of Procedure to Cell 1 ECA MFSM of SLC

Method	Function	Input (from)	Output (to)	Moved
M1	On pallet arrival, check if C1C available; if so pass on request, if not tell SWI rejected	PartDataReady (SWI), LoadPart1/2 (SWI) RobotAway (C1C)	LoadPartAck (SWI), PartNotTaken (SWI), Part1/2Taken (SWI), Start1/2 (C1C)	Down to C1C
M2	Tells C1C when an empty pallet is available and which part to unload	LoadPart0 (SWI), unload1/2 (C1C)	unload_part1/2 (C1C)	Down to C1C
M3	Passes messages between C1C and SWI & done1/2 (C1C) & Part1/2Finished (SWI)	done1/2 (C1C)	Part1/2Finished (SWI)	Down to C1C

Future Work

Finishing implementing the consolidation project on the RFT and formalizing the consolidation method are the two main focuses of future work. Thus far, the RFID subsystem has been moved and both the Cell 1 and Supply Cell ECA MFSMs are in the process of being shifted, but the rest of the ECA MFSMs and the trackers still need to be moved. The consolidation method developed during this consolidation needs to be better formalized, particularly noting what parts of the procedure are specific to ECA-based systems and which are applicable for more general manufacturing control systems.

Relevant Publications

1. H. Wijaya, K. Sukerkar, S. Gala, N. Arora, J. Moyne, D. Tilbury, J. Luntz, *"Reconfigurable Factory-wide Resource-based System Integration for Control",* IEEE Region 4 Electro-Information Technology Conference, Lansing, May 2006
2. N. Arora, S. Gala, B. Lee, J. Luntz, J. Moyne, D. Tilbury, "A 'Controls Workflow Management' HMI to Configure and Maintain an Event Based Control System" WODES 06, Ann Arbor, Michigan, July 2005
3. E. E. Almeida, J. E. Luntz, and D. M. Tilbury, "Event Condition Action Systems for Reconfigurable Logic Control," *IEEE Transactions on Automation Science and Engineering*, 4: 167-181, 2007.
4. L. Allen, J. Zhang, J. Moyne, and D. M. Tilbury, "Factory Level Control Consolidation for Event-Condition-Action: Case Study on the Reconfigurable Factory Testbed," to possibly appear in *Proceedings of the American Control Conference*, 2008.

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Industrial Ethernet Testing Project

Naveen Kalappa, Marco Antolovic, Kristen Acton,
Jonathan Parrott, Siddharth Mantri
October 10, 2006

Objective

Evaluate the network performance of EtherNet/IP and PROFINET, two widely used Industrial Ethernet specifications.

Background

Ethernet is being increasingly used as an industrial automation network. This is because of the low cost, interoperability, higher data rates and the rapid technological developments taking place due to its wide usage. EtherNet/IP and PROFINET are two such widely used industrial Ethernet solutions.

The two specifications represent different implementations of the Ethernet protocol stack. Identical tests were conducted on both, and their network performance in terms of the delay and jitter characteristics was analyzed. The tests focused on peer-to-peer (between two communicating PLCs), network management and HMI. In addition, an in-depth technology comparison of both specifications was conducted to identify the features offered.

Test Set Up

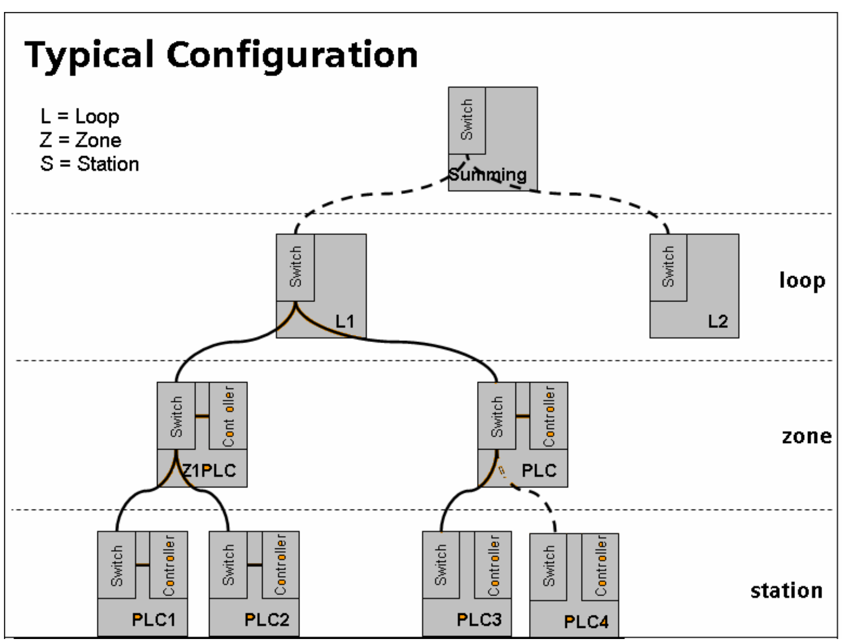

Figure1: Test configuration with multiple PLCs exchanging data over a switched network

Tests and Evaluation Conducted

Though the tests conducted were generic, emphasis was placed on the requirements of General Motors Powertrain.

- Peer-to-peer performance tests: Parameters such as network architecture, network traffic, data size, number of data items, number of connections and processor load were varied and their effect on network performance was noted. Ethereal was used as the tool to capture data from the network
- Network management and HMI tests: Through network management tests, the impact of changing network features and their effect on communication between the PLCs was analyzed. Also the response to PLCs supporting either protocol to standard network management tools (IntraVUE utilizing SNMP) was determined. In the HMI tests, parameters such as the number of tags, tag update rate and architectures were varied between HMI and communicating PLCs and their effects studied.
- Technology Analysis Report: A comprehensive technical report detailing the features supported from both specifications in areas such as their implementation, ease-of-use, communication (peer-to-peer, I/O), safety, security has also been compiled

Results

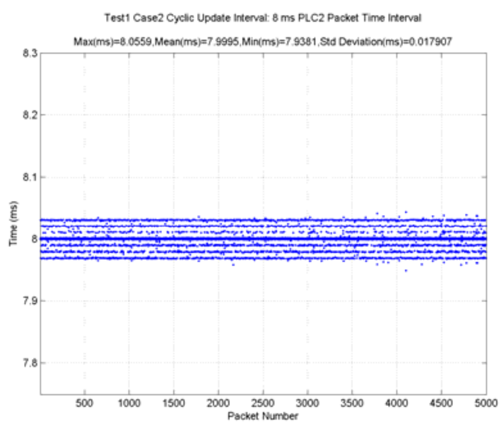

Figure 2: PLC Packet Interval

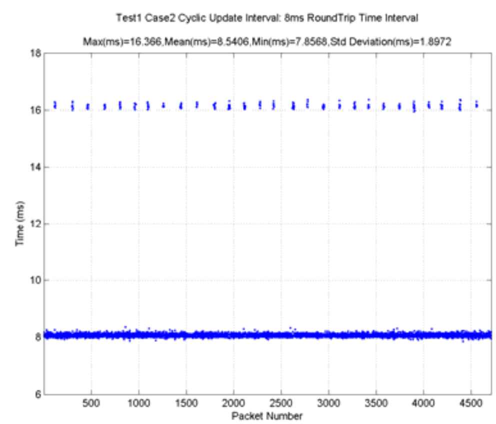

Figure 3: Round Trip Time Interval

Shown above are example test results for the peer-to-peer performance tests with two communicating PLCs. Packets were generated from one of the PLCs, and the second PLC echoed the packets generated by the first. In Figure 2, the max, min, avg and standard deviation of generated packets by a PLC for an update interval of 8ms is indicated. Figure 3 shows the round trip time interval for an update interval of 8ms. Round trip time is time taken for completion of a loop i.e. from first PLC to the second and back to the first.
Detailed reports are available at: ***http://erc.engin.umich.edu/publications/pub-TA2.htm***

Conclusions

Based on the results of the tests conducted, both protocols, PROFINET and EtherNet/IP are expected to meet the needs of peer-to-peer communication in a manufacturing plant.

Acknowledgements

ERC would like to thank General Motors Powertrain, Rockwell Automation, Siemens and Hirschmann for their support in the execution of this project.

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Automatic Logic Code Generation: Evaluation, Assessment, Recommendations

Seungjoo Lee/Dawn Tilbury

Summary of the Initiative: To ensure consistency of logic control codes across multiple machine vendors, and to enable improved diagnostics and reconfigurability, Ford Motor Company is investigating the use of automatic logic code generation tools. The University of Michigan ERC/RMS has developed several methodologies for automatic logic generation (including for transfer lines and flexible manufacturing cells) and has experience in applying Tecnomatix eM-PLC logic generation tools.

The purpose of this project is to (1) evaluate the state-of-the-art in commercially-available automatic logic generation tools through implementation on a test rig at Ford, (2) survey the state-of-the-art of academically-proposed methods, and (3) recommend a set of required capabilities that are needed to realize the vision of automatic logic code generation for all machines purchased by Ford Powertrain Operations.

Statement of Work: Ford has purchased a test rig for the evaluation. Ford engineers will be trained in Enterprise Controls by Rockwell. ERC/RMS researchers have already been trained in eM-PLC by Tecnomatix/Siemens. The two approaches for automatic logic code generation will be applied to the test rig, and the researchers and engineers will compare the two approaches for usability, functionality, etc. The survey of academic approaches will be done by the ERC/RMS. Recommendations, taking into account the best features of the commercially-available tools and the best ideas of the academic methods, will be agreed upon jointly by the ERC/RMS and Ford.

Deliverables:
- Logic control code for test rig automatically generated by multiple commercially-available tools
- Survey report of academic methods proposed for automatic logic code generation
- Report summarizing the capabilities of the available automatic logic code generation methods: Process definition, programming/editing methods, inclusion of diagnostics, reconfigurability
- Recommendations for “best practices” in automatic logic code generation

Benefits to Ford:
- Critical assessment of existing and proposed automatic logic code generation methods
- Reduced time (and cost) for launch, ramp-up, and reconfiguration of complex machining systems

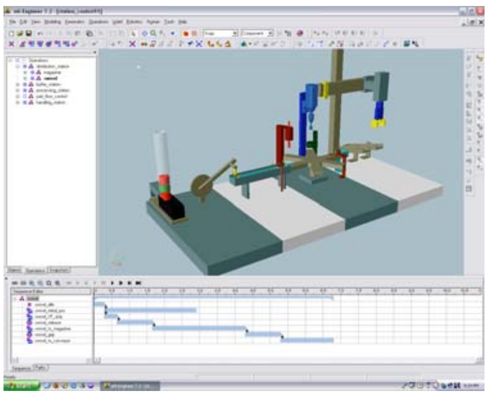
Expectations of UM:
- Implementation of eM-PLC automatic logic generation on Ford test rig
    - Build 3D model, program sequences, generate and validate code
- Survey report of methods proposed for automatic logic generation by academic researchers
- Collaborate with Ford engineers to write recommendations report

Support required from Ford:

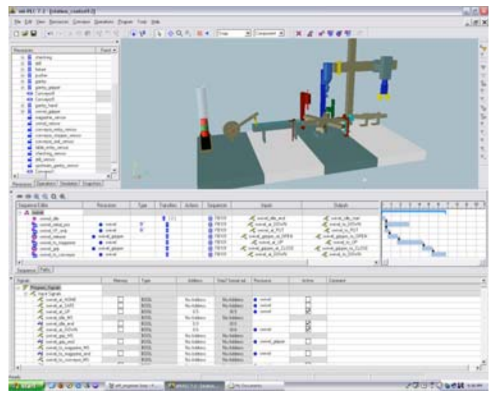
- Access to test rig
- Identification and acquisition of commercial tools for testing
- Engineering time for implementation of Enterprise Controls on test rig
- Collaborate with ERC/RMS researchers to write recommendations report

Results:

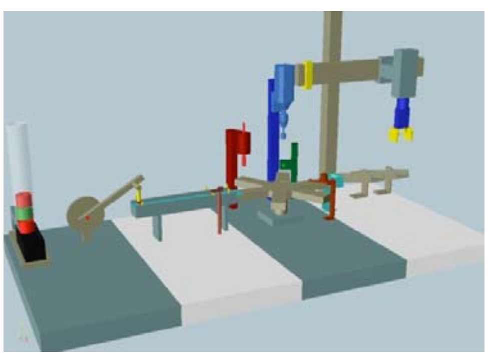
- Built 3D model of test rig in eM-Engineer
- Wrote process definition in eM-PLC, generated logic code, and tested with virtual factory
- Built logic model of test rig in RSTeststand
- Generated logic code with Enterprise Control, and tested with RSTeststand
- Time required to develop and debug code with two methods
- Measurements of control size, modularity and data accessibility using metrics from [1]
- Final report [2]



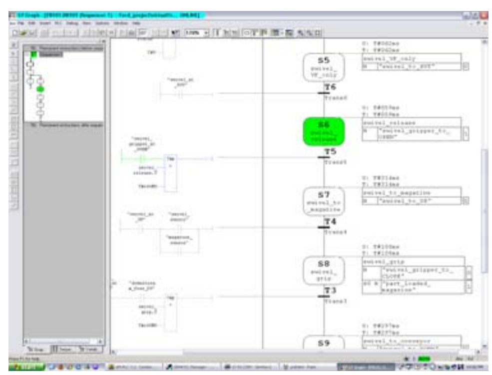
Test rig modeled in eM-Engineer



Control specifications prepared in eM-PLC



Verification of control with virtual models



Sequential function charts generated by eM-PLC for Siemens Step 7

References:

[1] M. R. Lucas and D. M. Tilbury, "Methods of Measuring the Size and Complexity of PLC Programs in Different Logic Control Design Methodologies," *International Journal of Advanced Manufacturing Technology,* 26(5–6):436–447, September 2005.

[2] Mark Ang, Jason Lee, Les Lee, Seungjoo Lee, and Dawn Tilbury, "Automatic Generation of Logic Control," ERC Technical Report, July 2006.

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Control Logic Reconfiguration & Verification

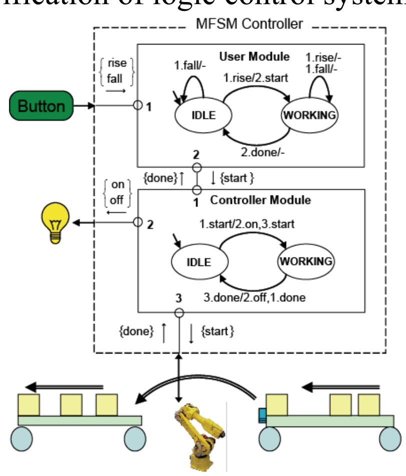
E. E. Almeida/D. M. Tilbury

Introduction and Objectives

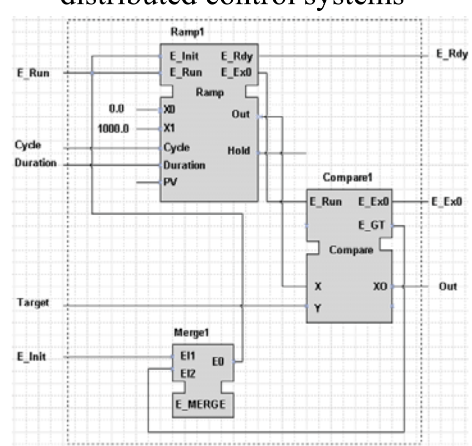
- Development of a logic control framework that optimizes **reconfigurability**
  - Using modular concepts, such as Modular Finite State Machines or the IEC 61499 Function Block standard
  - Introducing control rules as Event-Condition-Action (ECA) rules
  - Creating generic interfaces for the design of the control rules and software components
- Development of **modular verification** techniques for the created framework

Background – Modular Control Design Methods

<u>Modular Finite State Machines</u>
Developed at the ERC for modular verification of logic control systems



<u>IEC 61499 Function Blocks</u>
Standard developed for design of distributed control systems



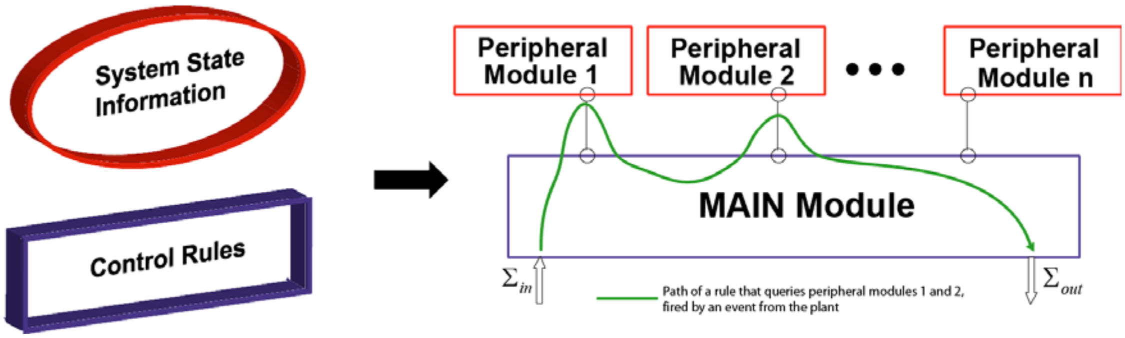
Method – Use ECA rules to specify dynamics of logic controller

<u>ECA Rules</u>

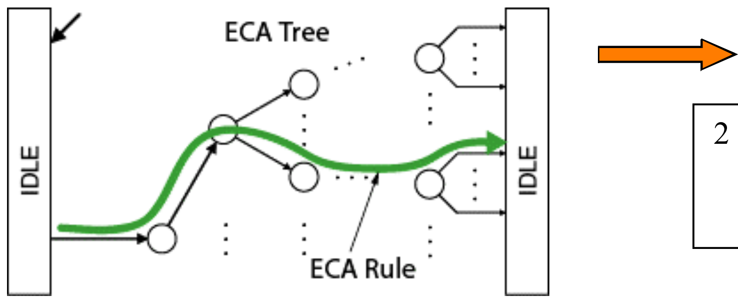
- A very 'natural' way to design system's dynamics
- Paradigm used in Active Databases and Expert Systems for specifying behavior

Results

Creation of ECA Logic Systems



Design of ECA Rules



Write the manufacturing ECA logic control rules as a table

2 Implementations:
- RFT System Level Controller
- RFT Cell 1 Controller

Reconfiguration

- Reconfiguration has been measured from resulting levels of:
  a. Modularity
  b. Integrability
  c. Diagnosability
- The ECA approach shows higher levels of all 3 measures compared to other modular logic control design approaches

Conclusions

- Using **ECA rules** to design logic controllers
  - **Improves reconfigurability**
  - **Facilitates integration** with other ECA system components, such as MES, etc…
  - Provides a generic design approach and an **easy** way to design control rules

Future Work

- Development of smart modular **verification** methods for ECA logic systems
  - Rules are responsible for the dynamics - their correctness must be verified!
  - Exploit special structure and relevant concepts such as rule confluence
- Development of a generic interface to design ECA rules and Peripheral Modules
- Consolidation of logic control with higher level system control

Relevant Publications:

E. W. Endsley, E. E. Almeida, and D. M. Tilbury, "Modular Finite State Machines: Development and Application to Reconfigurable Manufacturing Cell Controller Generation," *Control Engineering Practice,* 14(10):1127–1142, October 2006.

E. E. Almeida, J. E. Luntz, and D. M. Tilbury, "Event Condition Action Systems for Reconfigurable Logic Control," accepted for publication in *IEEE Transactions on Automation Science and Engineering,* May 2006.

E. E. Almeida, J. E. Luntz, and D. M. Tilbury, "Reconfigurable Logic Control Using IEC 61499 Function Blocks," *Proceedings of the IEEE Conference on Emerging Technologies and Factory Automation,* Prague, September 2006.

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Improving Quality While Reducing Cost Through Virtual Inspection/Metrology and Process Control

Aftab Khan (aftabak@umich.edu)

September 28, 2007

Introduction and Background

In most manufacturing processes, product quality control on a part-to-part or run-to-run (R2R) basis is highly desirable to compensate for process drifts and external disturbances. In this project we propose a predictive inspection (virtual metrology) based process control solution for a variety of manufacturing processes.

Problem: R2R control requires metrology data after each process run, which in some cases is not readily available (only a sampling of the parts are measured) or is only available at a cost of overall process throughput or cycle time (due to the time required for measurements).

Solution: Process diagnostic data is already collected in real time for purposes of fault detection and classification (FDC). This large amount of diagnostic data can be used to predict the product quality for every process run.

Benefits: The predicted product quality can be used as feedback to a control system that improves the product quality while reducing the need for post-process measurements. It also improves response to process disturbances and shifts. A factory-wide implementation of the approach can improve factory objectives such as improve throughput/yield and reduce cycle time/fabrication cost.

VM based R2R control

1. <u>*Virtual metrology Module:*</u> Multivariate analysis of FD data is performed to find a meaningful relationship between FD data and product quality. Partial least squares (PLS) regression technique is modified to build VM module for a multi-input multi-output (MIMO) process. PLS has been proven to provide superior results to Principle Components Analysis (PCA) and standard multivariate regression techniques in this domain.
2. <u>*Process controller:*</u> Standard model-based adaptive "R2R" controllers (e.g. exponentially weighted moving average (EWMA) controller, model predictive controller (MPC), etc.) are modified to deal with virtual as well as actual metrology data.
3. <u>*Update of VM module and process controller:*</u> Actual metrology (on sampled products) is used to update the VM and controller parameters (dashed line in Figure 1).

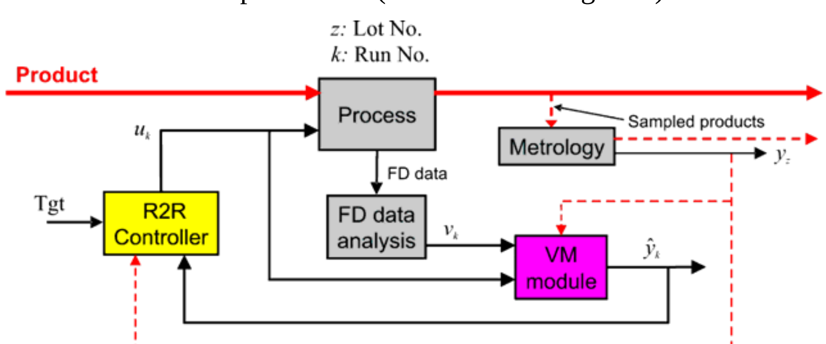

Figure 1: Schematic of VM based R2R process control

VM based R2R control for two consecutive processes: Results

VM modules and R2R controllers are developed for two consecutive MIMO process (simulated), in which the VM module of the second process also uses pre-process metrology (predicted + virtual). For both processes every 10th part is assumed to be measured at the metrology station.

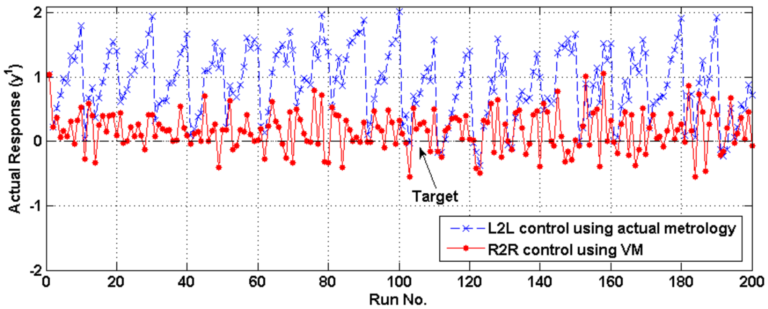

Figure 2: Advantage of using VM in R2R process control (process-1)

Figure 2 compares the y^1 response of the first process when an L2L process controller uses only the actual metrology and when a R2R process controller uses VM. It is clear from the figure that the L2L controlled output drifts away from the Target between metrology events while the R2R controlled output is close to the Target.

In **Error! Reference source not found.**, the y^2 response for process-2 is shown to be superior when the VM module uses pre-process

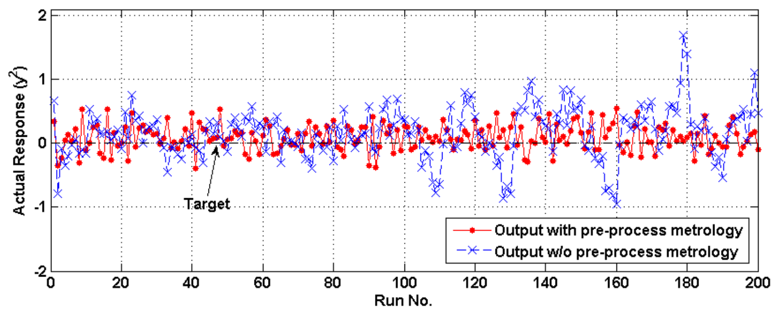

Figure 3: Using pre-process metrology in process control (process-2)

Conclusions

Market demands for high product quality and low cost necessitate R2R process control with VM. The results show that the VM based process control compensates for process drifts and disturbance on a R2R basis. Therefore product quality is improved without the need for measuring every product, thus saving the cost and time involved in employing extra metrology stations.

Future Work

Design new metrology strategies using VM data: measure products recommended by VM only thereby reduce metrology costs.

Integrate VM with factory CMMS: Schedule maintenance events on the machine using information from the VM modules, thus reduce maintenance costs.

Publications

1. Aftab Khan, James Moyne, and Dawn Tilbury, "Utilizing in-situ diagnostics to enable manufacturing process control through predictive inspection," in *Proc. of AEC/APC Symposium XVII*, Indian Wells, California, Sept. 2005.
2. Aftab Khan, Dawn Tilbury, and James Moyne, "Predictive-inspection based process control in end milling operations," in *Proc. of ASME International Mechanical Engineering Congress and Exposition (IMECE)*, Orlando, Florida, Nov. 2005
3. Aftab Khan, James Moyne, and Dawn Tilbury, "Predictive-inspection based control using diagnostic data for manufacturing processes," submitted to ASME Journal of Manufacturing Science & Technology.
4. Aftab Khan, James Moyne, and Dawn Tilbury, "Virtual metrology and feedback control for semiconductor manufacturing processes using recursive partial least squares," *submitted to* Journal of Process Control: special issue on advanced process control in semiconductor manufacturing.
5. Aftab Khan, James Moyne, and Dawn Tilbury, "Factory-wide control utilizing virtual metrology," *submitted to* IEEE Transactions on Semiconductor Manufacturing: special issue on APC.

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Enterprise - Wide Control

Namrata Arora, Shyam Gala

Introduction

Software systems in the factory have generally been integrated from the ground up (i.e., rarely with thought towards an enterprise-wide architecture in the initial stages). Over the past few years the industry has begun to address the issues of lower software reliability and higher software integration, reconfiguration, and maintenance costs by attempting to define elements of a software infrastructure for manufacturing. Our Enterprise-wide software architecture addresses the above with the following salient attributes:

- *Event driven system*
- *Data-centric architecture*
- *Web-Enabled HMIs*
- *Reconfigurability during run-time*
- *Support for both control and diagnostics activities*
- *Distributed Environment*
- *Enterprise-wide consolidated resource-based control environment*
- *Easy to visualize and re-configure visually.*

Solution Design

Software control systems have been utilizing the ECA paradigm to realize flexible event-based control systems. In event-based systems, actions are performed in response to events based on current conditions. In our system, this action is a sequence of resource utilizations and the ECA paradigm is realized using a database to house ECA rules.

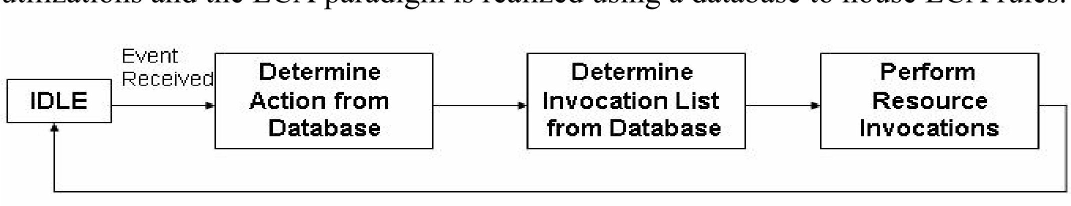

Figure 1: Event-Condition-Action Paradigm

The Resource-Based Management Solution architecture consists of modular components. One of the common approaches used is ***Web Services***, which allow the infrastructure to be distributed enterprise wide. This allows remote access to ***Software Resources***, where each software engine is a modular unit performing a unit task or a logical block of tasks. ***Middleware Server*** will create an individual thread for every event that requests a service. ***Control Workflow Manager*** maintains the integrity of control (workflow) rules used to coordinate the hardware and software resources. ***Web Services Communication*** among components is formalized utilizing industry standard protocols such as Simple

Object Access Protocol (SOAP), Extensible Markup Language (XML), Transmission Control Protocol/Internet Protocol (TCP/IP), and OLE for Process Control (OPC).

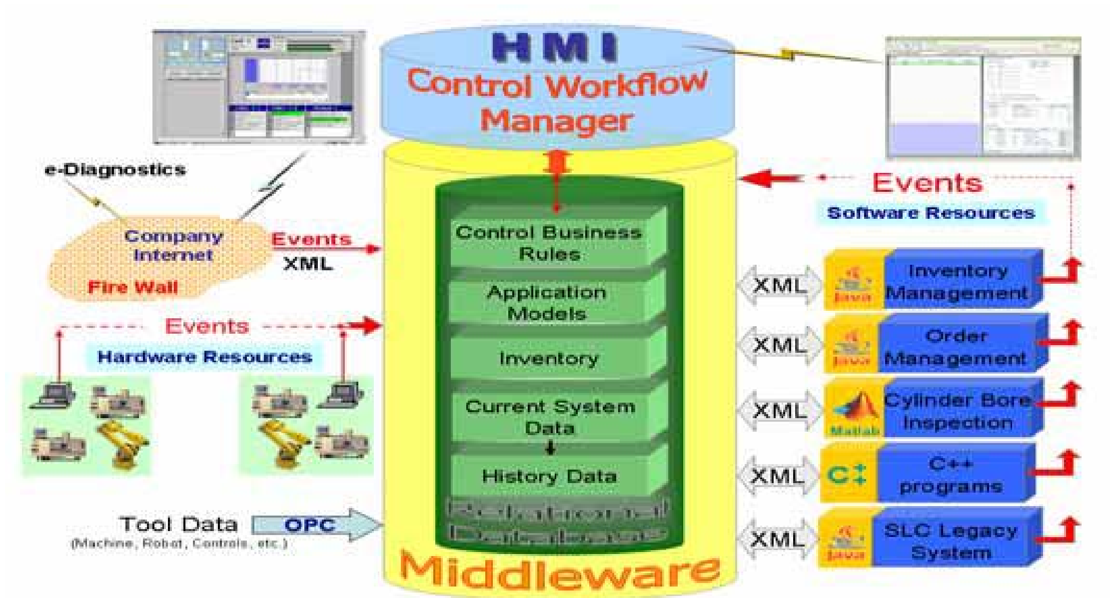

Figure 2: Solution Architecture Design

Results

- Solution implemented for cell and factory-level control of the Reconfigurable Factory Testbed--RFT (Oracle database, Web-services SOAP/XML module integration)
- Verification of capability and advantage over traditional control approaches utilizing RFT test case.
- Module Integration cradles for Matlab, C++ and Java.
- Modules integrated and utilized in ECA rules: Maintenance Management, Part Ordering, HMI, Diagnostics, Out-of-Control Action Plan (OCAP)
- "Control Rules Management" HMI for CWM

Looking Ahead

- Verification capabilities for the CWM
- Support for Visualizing Nested Events for more ergonomic electronic white board.

References

1. H. Wijaya, K. Sukerkar, S. Gala, N. Arora, J. Moyne, D. Tilbury, J. Luntz, *"Reconfigurable Factory-wide Resource-based System Integration for Control",* IEEE Region 4 Electro-Information Technology Conference, Lansing, May 2006
2. K. Sukerkar, H. Wijaya, J. Moyne, D. Tilbury, *"An Integrated Distributed Software System for Reconfigurable Manufacturing,"* Advanced Manufacturing Technologies 2004, London, Ontario, Canada, June 2004.
3. J. Moyne, D. Tilbury, H. Wijaya, *"An Event-Driven Resource-Based Approach to High-Level Reconfigurable Logic Control and Its Application to a Reconfigurable Factory Testbed,"* 3rd CIRP Reconfigurable Manufacturing Conference, Ann Arbor, Michigan, May 2005.
4. N. Arora, S. Gala, B. Lee, J. Luntz, J. Moyne, D. Tilbury, "A 'Controls Workflow Management' HMI to Configure and Maintain an Event Based Control System" WODES 06, Ann Arbor, Michigan, July 2005

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University of Michigan – National Instruments

National Instruments Programmable Automation Controller for Reconfigurable Logic Control: Implementation and Evaluation

Krishnakumar Ramamoorthy

February 22, 2007

Background:

National Instruments (NI) has been promoting a new class of industrial controller called Programmable Automation Controller (PAC). The PACs are as rugged and reliable as PLCs and the PACs can be programmed using open programming languages such as LabVIEW, JAVA and C.

In this project, the NI PACs are used for implementing the control of medium-size-manufacturing test beds. The implementation is used for evaluating PAC for reconfigurable manufacturing system control.

Goal:

The purpose of this project is to (1) Develop a suitable execution model for the NI PAC (2) Use LabVIEW for logic control of a high volume transfer line and address issues such as error handling and Human Machine Interface (HMI) (3) Develop logic control for a flexible manufacturing system to address issues such as resource allocation, multiple parts and part re-routing (4) Use commercial-off-the-shelf (COTS) components available in PACs to integrate with larger system such as the Reconfigurable Factory Testbed (RFT) (5) Evaluate NI PAC for reconfigurable logic control. The motivation behind the research is to demonstrate and evaluate the NI PAC for reconfigurable control of manufacturing system. The results of the research could help promote research and development of PACs.

Test set up:

- The NI FieldPoint controller as the Programmable Automation Controller
- The LabVIEW state diagram toolkit for developing the control logic
- The Fischertechnik linear test bed with three work stations as a high volume transfer line
- The Fischertechnik rotary test bed with three work stations as a flexible manufacturing system

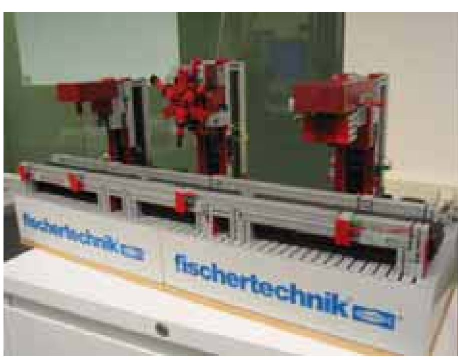

Fig 1. Linear test bed

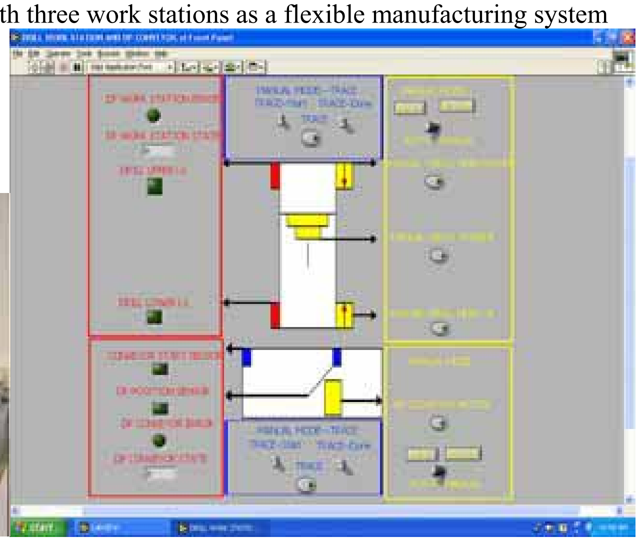

Fig 2. Human Machine Interface

Method:

(1) Used the LabVIEW execution trace tool kit to determine the execution model
(2) Developed the logic control of the linear test bed using the state diagram toolkit of LabVIEW
  - Translated the existing MFSM code of the linear test bed into the state diagram toolkit [4].
(3) Developed the logic control of the rotary test bed using the state diagram toolkit of LabVIEW
  - Adapted the methodologies developed for the flexible manufacturing systems [2] for LabVIEW.
(4) Assessed the re-configurability of LabVIEW control logic.
(5) Integrated the linear test bed as the wheel processing station of the RFT by using COTS such as XML and TCP/IP (CWM).

Results:

- Scan based execution model of PLC was chosen for its determinism.
- Reconfigurable MFSM control code was translated into LabVIEW state diagram toolkit.
- Reversible and irreversible modules were used for integrating manual mode error handling.
- Methodologies for flexible manufacturing system control code were adapted for LabVIEW finite state machine. Multiple parts and part-rerouting were implemented.
- The LabVIEW control logic proved to be reconfigurable. The seven finite state machines used for modeling part type 1 were re-used for part type 2.
- The control code of one of the work stations of the rotary test bed was re-used for other work stations.
- The linear test bed was integrated into the RFT as the wheel processing station.

Fig 3. Results of execution trace toolkit before and after implementing scan based execution model.

Future work

- Model based design of Logic control for PAC.
- Auto generation of logic control code for PAC.

Acknowledgement

This research was sponsored in part by National Instrument and ERC/RMS

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[2] S. Lee and D. M. Tilbury, A modular control design method for a flexible manufacturing cell including error handling. In *Proceedings of IEEE Conference on Decision and Control and European Control Conference*, 2005.
[3] S. Lee, A cell controller design methodology including error handling for flexible manufacturing system, PhD thesis, Department of Mechanical Engineering, University of Michigan, Jan 2006.
[4] E.W. Endsley, Modular Finite State Machines for logic control: Theory, verification and applications to Reconfigurable Manufacturing Systems, PhD Thesis, Department of Mechanical Engineering, University of Michigan, 2004.

Reconfigurable Factory Testbed (RFT)

The Reconfigurable Factory Testbed (RFT) is a comprehensive platform that enables research, development, education, validation and transfer of Reconfigurable manufacturing system (RMS) concepts.

By providing a collaborative mix of hardware/software and real/simulation components distributed across a web-enabled network, the RFT serves as excellent environment to consolidate and showcase results of the University of Michigan's Engineering Research Center for RMS. More importantly, it provides an environment to envision, rapidly prototype, and verify in a factory operation environment those solutions that result from the combination of the RFT components. Further it will provide a mechanism for pre-qualification of factory reconfiguration strategies.

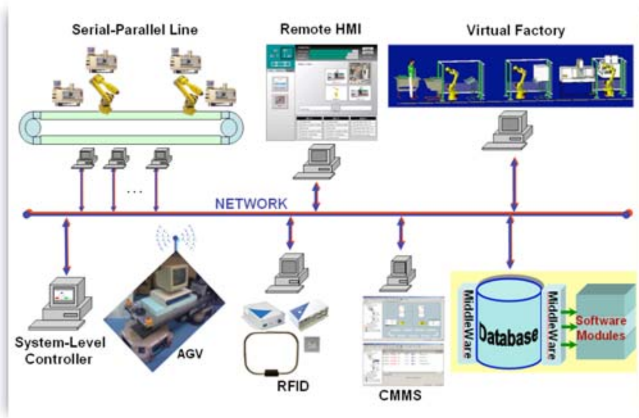

Figure: Reconfigurable Factory Testbed Schematic

RFT Components

The envisioned testbed is schematically represented in the figure. The primary components of the testbed are:

Serial-Parallel Line: This line consists of two cells with two table top CNC machines and a robot each, connected in series by a conveyor. This line will be utilized in the study of planning and scheduling as it relates to reconfigurable manufacturing.

Remote Viewing and Collaboration Tools: The RFT employs a remote Human Machine Interface (HMI) to provide connectivity for diagnostics, maintenance, and order placement, utilizing data gathered from sensors/machines using OPC and XML. These web-based tools also give researchers and partners at other universities and commercial sites access to this state-of-the-art facility.

Virtual Factory: A commercial factory simulation software package is used to simulate not only the serial-parallel machining line and the assembly cell, but also additional factory components that do not exist in hardware. The virtual factory is actually linked into the system to enable real + virtual simulations.

***Radio Frequency Identification (RFID)*:** It is integrated to RFT for process, product, and people traceability. The system uses high frequency 13.56 MHz with write/read transponders.

Safety System: The RFT system employs state-of-the-art safety components, to accomplish a level of standardized safety equal to the most advanced manufacturing facilities. Further research is being conducted on the advantages of such safety systems interacting with control networks to provide for a more optimized network.

Software Infrastructure: The infrastructure has a data centric architecture where it uses OPC and XML for communications. It has plug-n-play capability for module deployment. The current framework supports modules with Java, Matlab, C++, and Visual Basic 6.0 platform.

RFT Applications and Benefits

Research

- Networks: Multi-tier networking, Quality of Service and Quality of Performance for controls and diagnostics.
- Control rules and event-based control; modular logic control; factory-wide consolidated control strategy
- e-diagnostics and e-manufacturing.
- Part program reconfiguration based on actual and/or virtual inspection
- Combining/collaborating research efforts on a single platform
- Virtual + Real" real-time simulation and prediction
- Logic controllers
- Network time synchronization (IEEE 1588)

Education

- Web-distributed system allowing for collaboration with other universities.
- Exposing students to real-world environments.

Technology Transfer

- Web-distribute real + virtual environment allows users to apply "what-if" analysis and test potential transfer solutions prior to adoption.
- Industrially relevant solutions utilizing off-the-shelf technologies wherever possible, standards (official and de-facto), conforming to industry trends, guided by industry partners.
- Solutions for industrial network management to support control, diagnostics and safety information distribution; consolidated HMI methodology
- Graphical method for control strategy reconfiguration
- RFT designed for technology transfer.

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