Sensor Networks & Complex Manufacturing Systems Monitoring Research Lab

School of Industrial Engineering and Management

Satish Bukkapatnam

Ranga Komanduri

Collaborating Faculty - OSU

Chuck Bunting (ECE)
Venkatesh Sarangan (CS)
James Kong (IEM)

Collaborating Faculty - Other

Soundar Kumara (Penn State, advisor)
San-Gook Kim (MIT)
Xiang Zhang (Berkeley)

COMMSENS Lab Accomplishments (2004-06)

55 papers (32 in journals and 23 in refereed conference proceedings)

Current Research Students: 16 (4 PhD, 6 MS, 6 Undergrad)

New Quantitative Tools and Technologies

High throughput RF Vibration sensors for manufacturing and infrastructure integrity monitoring

Nonlinear analysis and customized wavelets-based tools for system performance monitoring

Design and data management solutions for reliable RFID systems

New Course Offerings

Applications of Nonlinear Dynamics and Wavelets

RFID/RF Sensor Applications in Manufacturing and Engineering Systems (one of the first such courses in Industrial Engineering)

Research Funds Secured: $1M

Sponsors: NSF, CELDi, FAA, Tinker AFB, GM, DoT

Research Directions

- **Quality monitoring in manufacturing machines and processes**
  - **Process Type**
    - **Precision machining, Semiconductor polishing, Nanomanufacturing**
  - **Anomaly**
    - **Macroscopic stability analysis using vibration and Acoustic Emission sensors**
    - **Macroscopic quality product variability analysis**

- **Integrity monitoring and coordination of infrastructure and lifeline systems**
  - **Structural Systems**
    - **Large structural sensor networks: Optical strain gage and Wireless sensor networks**
  - **Large-Scale Networks**
    - **Communication networks:**
      - **RFID and RF Sensor Applications**
      - **Intrusion monitoring**
    - **Manufacturing enterprise and logistic systems**
      - **State space modeling and monitoring of manufacturing systems**
      - **Container integrity monitoring using RFID/RF sensor networks**

Current Research Projects	Sponsors
Nonlinear Stochastic Dynamics and Monitoring of CMP of Si Wafers	NSF
Wireless RF/RFID Vibration Sensors for Container Integrity Monitoring	DoT
Pipeline integrity monitoring using Tmote active vibration sensor	NSF, DoT
Zigbee based Active Sensor	NSF, DoT
RFID system testing, read-rate prediction and improvement	NSF, CELDi
Economic analysis of RFID system implementation	NSF, CELDi, FAA, Tinker AFB
Improving Decision Making in Warehouse Search operations using RFID	NSF, FAA
State space modeling and monitoring of manufacturing systems	GM

Experimental Facilities

- Over 1000 sq ft. space at Advanced Technology Research Center for hosting test-beds for RFID and RF Sensing investigations
- Readers from Alien and AWID, and 200 passive tags of various specifications
- Linux servers housing SUN JAVA RFID package with an Application Server and Enterprise Manager with Oracle 10i backend for RFID information management
- RF sensor networks for monitoring vibrations, temperature and humidity using motes with moteiv (IEEE 802.15.4 compliant) system for wireless mesh networking
- New experimental test bays with the latest Gen 2 specific hardware and software are being set up for future applications
- Integration of RFID sensing with tethered sensor networks for AMT of precision production machines and infrastructure

Publications (2004-06)

Precision/Nano Manufacturing Machines and Processes

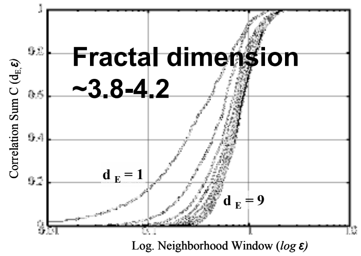
- S.T.S. Bukkapatnam and B. Clark, "Modeling and monitoring of Contour Crafting, a layered manufacturing process," *ASME Transactions Journal of Manufacturing Science and Engineering,* 2006.
- S.T.S. Bukkapatnam, P.M. Agrawal, M.M. Malshe, L.M. Raff, M. Hagan, R. Komanduri, "Parametrization of interatomic potential functions using a genetic algorithm accelerated with a neural network," *Physical Review B,* 2006.
- W. Lih, S. Bukkapatnam, P. Rao, M. Hagan, N. Chandrasekaran, R. Komanduri, "Neural networks and fuzzy inference systems for modeling CMP," *IEEE Transactions on Automation Science and Engineering,*2006.
- S.T.S. Bukkapatnam, "Piecewise eigen-analysis for noise reduction and feature extraction in contaminated chaotic signals," *Physical Review E,* 2005 (under 2nd review).
- P. Rao, S. Bukkapatnam, W. Lih, M. Hagan, N. Chandrasekaran, R. Komanduri, "Statistical analysis of oxide CMP," *Applied Physics A,*2006.
- S.T.S Bukkapatnam, W. Lih, P. Rao, N. Chandrasekaran, R. Komanduri, "Modeling of MRR and WIWNU characteristics in oxide CMP using sparse data," *CMP MIC 06,* San Francisco, March 2006.
- P.M. Agrawal, A.N.A. Samadh, L.M. Raff, M. Hagan, S.T.S. Bukkapatnam, R. Komanduri, "Prediction of molecular-dynamics simulation results using feedforward neural networks: Reaction of a C2 dimer with an activated diamond (100) surface," *Journal of Chemical Physics*, Vol. 123, Article No. 224711, 2005.

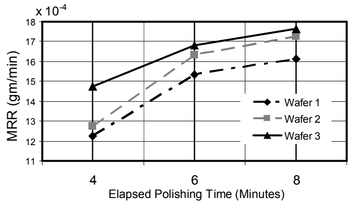
Enterprise Systems Integrity and Performance Monitoring

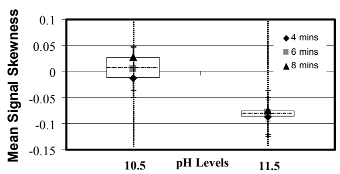
- R. Liao, S. Bukkapatnam, R. Komanduri, "Wireless RFID vibration sensor network for container integrity monitoring," *IEEE Transactions on Automation Science and Engineering,* 2006 (submitted).
- A. Awawdeh, S. T.S. Bukkapatnam, S.R.T. Kumara, C. Bunting, R. Komanduri, "Wireless sensing of flow-induced vibrations for pipeline integrity monitoring," *IEEE SAM 06,* Boston, July 2006.
- J. Govardhan, S. Bukkapatnam, P. Rao, Y. Bhamare, V. Rajamani, "Statistical analysis and design of RFID systems for monitoring vehicle ingress/egress in warehouse environments," *International Journal of RFID Applications,* 2006 (2nd review).
- V. Rajamani, S. Bukkapatnam, C. Bunting, "An experimental study on improving item-level RFID tag readability in the presence of metals and liquids," *International Journal of RFID Applications,* 2006 (submitted).
- J. Govardhan, S. Bukkapatnam, V. Rajamnani, C. Bunting, "Improving read rates of RFID tags in metallic environments using a reverberation chamber," *International Journal of RFID Applications,* 2006 (submitted)
- J. Govardhan, S. Bukkapatnam, "Estimating read-rate probability in backscatter RFID systems," *IEEE Antenna Theory and Applications,* 2006 (submitted).

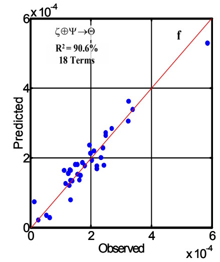
Sensor Networks & Complex Manufacturing Systems Monitoring Research Lab
School of Industrial Engineering and Management

Nonlinear Stochastic Dynamics and Monitoring of CMP of Si Wafers









>90% accurate prediction of material removal rate (MRR) using nonlinear dynamic quantifiers

Benefits/Description/Objectives

Objective: Predict MRR in real-time using features from vibration sensor signals

Advantages and Strengths:

Nonlinear Analysis Approach can capture the dynamics underlying the measured vibration signals, independently of the instantaneous state of the process. This method has been successfully applied to characterize dynamics machining as well as to identify process anomalies.

Statistical regression with PCA captures the relative sensitivities of various combination of signal features and process parameters on MRR

The use of nonlinear approaches was found to improve predictability up to 20%

Resources/Timing/Deliverables/Impact

Students: Prahalada Rao, WenChen Lih, Upendra Phatak
Leverage: NSF
Timing: Aug 2004 - July 2007
Deliverables:

- Instrumented CMP test-bed
- Wireless miniaturized accelerometer sensor node and software for high-rate data transmission (~500Hz)
- Journal paper detailing the dynamic characteristics of CMP, and prediction of MRR using the dynamic quantifiers

Status/Issues

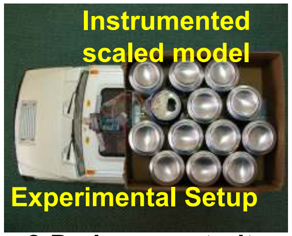
Status

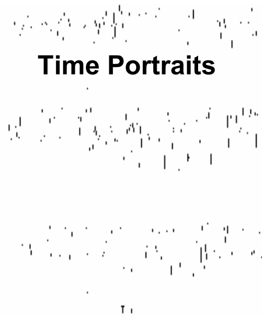
- Experimental setup and instrumentation of CMP done
- More than 90% accuracies (R^2 values) for predicting MRR using features capturing the nonlinear dynamics of vibration signal were demonstrated

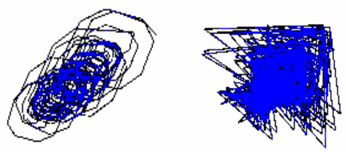
Issues

- Need to optimize the process for WIWNU and Ra
- The methods to estimate MRR and surface roughness need improvement
- Instrumentation of the Strasbaugh CMP tool needs to be undertaken

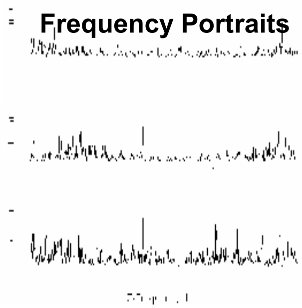
Wireless RF/RFID Vibration Sensors for Container Integrity Monitoring

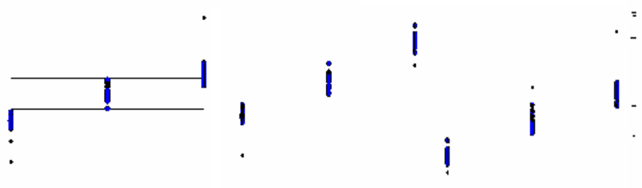






2-D phase portraits reveal a finite dimensional attractor underlying vibration signals





Accurate classification of operating conditions using a feed-forward NN

Benefits/Description/Objectives

Objective: Classify different operating and stability conditions of a container truck using the quantifiers of nonlinear stochastic dynamics of container vibrations measured using high band-width miniature wireless vibration sensors.

Advantages and Strengths of Proposed Approach:

Nonlinear analysis can capture the dynamics underlying the measured vibration signals, independently of the instantaneous state of the process. This method has been successfully applied to characterize dynamics as well as to identify anomalies in precision manufacturing processes.

Neural Networks use nonlinear kernels to classify different operating patterns. Due to the large data pool from experiments, it is suitable for training a NN to make accurate prediction of the operating conditions.

Tmote sensor nodes with Analog Devices vibration sensors allow for high data transmission rates

Resources/Timing/Deliverables/Impact

Students: Yen-Po Liao
Leverage: Oklahoma DoT
Timing: Jan 2006 - July 2007
Deliverables:

- A scaled model of the goods movement on a container truck and experimental benchmarks of the performance of scaled model the to ensure the container integrity.
- A method to classify between the different terrains and other operating conditions of a container truck using vibration signal patterns.
- An RFID sensor based on Tmotes to transmit and process container vibration signals.

Status/Issues

Status

- Acquisition and processing of vibration data from the experiments in scaled model of a container truck and in real car has been demonstrated.
- The procedures for effective signal analysis and classification has been constructed.
- A NN classification of operating conditions has been successful (< 10% misclassifications).
- New sensor that allows much larger data bandwidth development is underway.
- Need to address much larger sets of stability and integrity issues.

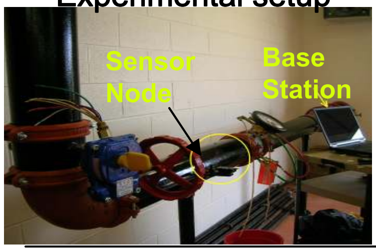
Issues

- Improve the data denoise technique.
- In the future, more sensitive vibration sensor can be used to improve the accuracy of the model this research addresses.

Pipeline integrity monitoring using Tmote active vibration sensor

Tmote Sensor

Experimental setup



Methodology

Data Capture by Tmote
Tmote sensors in two locations
7 settings and 2 configurations

↓

Wavelet De-Noising
Filter out lowest and highest scales, Threshold on other

↓

Feature Selection
PTP, STD and Entropy result in 18 vector matrix

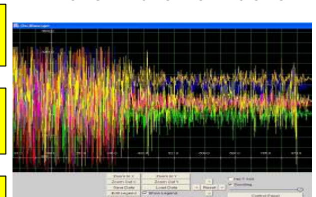
↓

Feature Extraction
Singular Value Decomposition (SVD) 1-4 Principal

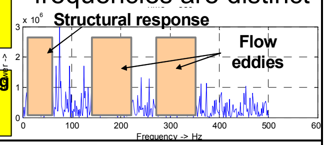
↓

Step-wise Regression Mapping
Determination of mean square value

Tmote vibration data

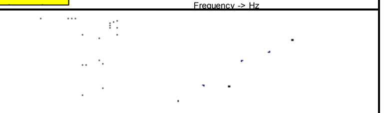


Structural and flow induced vibration frequencies are distinct



Results

Finite 5-dimensional pipeline vibrations dynamics evident after wavelet denoising



80-90% accurate flow rate estimates using PCs of entropy & other features

Benefits/Description/Objectives

Objective: To develop a wireless sensor system for continuous and unintrusive monitoring of flow rates and integrity of a pipeline network

Advantages and Strengths :

–The system utilizes wireless sensors which replace wired sensors and hence lower the number sensor deployment and maintenance cost.

–Enables broad-based deployment of wireless networks with low cost, low power solutions.

–Uses statistical models and mathematical functions to analyze the data collected by the wireless sensors thus resulting in high accuracy prediction.

Resources/Timing/Deliverables/Impact

Students: Jakkrit Kunthong, Roger Liao, Amjad Awawdeh

Sponsor: NSF, Oklahoma DoT

Timing: August 2004 - July 2007

Deliverables:

- Implementation of a Tmote sensor with 3-axis vibration sensor to monitor flow rate on both vertical and horizontal pipelines at sampling rate of 500Hz.
- A wavelet approach to decipher information from noisy wireless sensor signals.
- Validating the prediction of flow rates by combining classical statistical features with nonlinear dynamic quantifiers of sensor data resulted in 80-85% prediction accuracies.

Status/Issues

Status

- The Tmote wireless sensor has been installed and tested on both vertical and horizontal pipe setup at OSU Fire Protection and Safety Laboratory.
- Software written for data capturing and Graphical User Interface (GUI)
- Statistical and mathematical techniques were utilized to extract data from the sensor noisy signal.

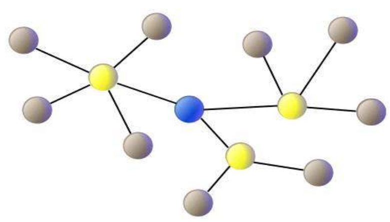
Issues

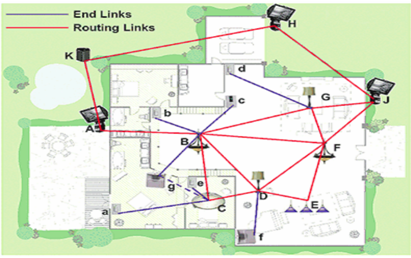
- Need to improve pipeline integrity detection method.
- Need to improve capturing rate of the sensor (sampling rate) which result in more data extraction and useful information.
- Need to lower overall system cost including installation, device, and maintenance cost.

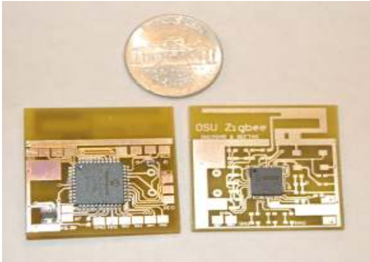
OSU Zigbee based Active Sensor

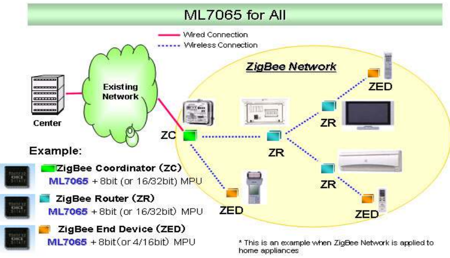
Zigbee Network

Cluster Network









Benefits/Description/Objectives

Objective: To develop Smart Active Sensors based on Zigbee technology with extremely low power consumption.

Advantages and Strengths of Proposed Approach:

• Uses ZigBee, a unique wireless standards-based technology that addresses the unique needs of remote wireless monitoring and control network applications.

• Enables broad-based deployment of wireless networks with low cost, low power solutions.

• Provides the ability to run for years on inexpensive primary batteries for a typical monitoring application.

• Miniature design for dense deployment

• Allows for large sampling and transmission rates

Resources/Timing/Deliverables/Impact

Students: Jakkrit Kunthong, Roger Liao, Steven Welch
Leverage: Oklahoma DOT, NSF
Timing: May 2006 - August 2007
Deliverables:

- A prototype implementation of a Zigbee active sensor system for Pipeline vibration and temperature monitoring at 10 times faster sampling rate compared to the previous system (Tmote)
- A prototype implementation of a wafer polishing roughness monitoring system.
- A comparison study of Zigbee's RF propagation for indoor environment based on Ray tracing and Finite Different Time Domain (FDTD).

Status/Issues

Status

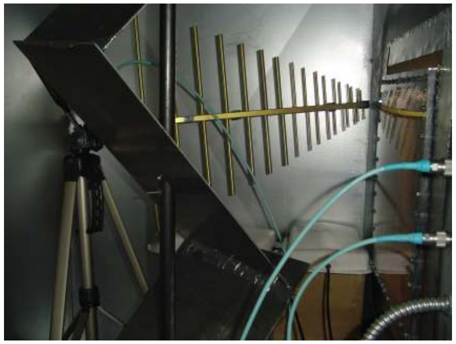
- The new Zigbee prototype board has been designed from ground up and being tested
- Software for the prototype board is being developed for multiple monitoring applications, such as pipeline integrity, container integrity and Chemical Mechanical Planarization (CMP).
- The RF propagation model and prediction software for this Zigbee device are also being studied to address issues related to the full deployment of the system

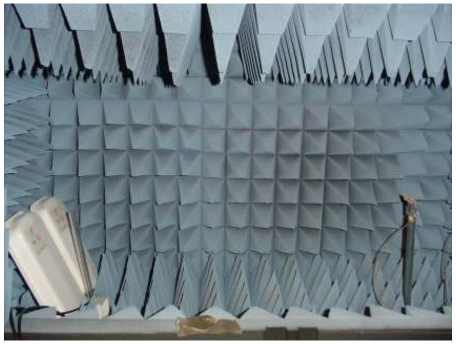
Issues

- Need to improve sensor's speed, range and power consumption with minimum hardware and size.
- Need for smart and easy to use active sensor software.
- Accuracy RF prediction model for low power active sensor.

RFID system testing

Experimental Setup





Benefits/Description/Objectives

Objective: Predict and improve read-rates in RFID environments through a rigorous characterization of the uncertainties in the EM fields.

Experimental approach is followed to test the existing RFID systems and a novel method to increase the readability in highly metallic environments is being developed.

Common issues that occur while using RFID in a factory environment and measures to reduce some of these have been investigated using statistically designed experiments

Advantages and Strengths :

The results show that the physical principles that are at the root of the problem of poor readability in the presence of metals can be turned around for higher readability in metallic environments

Resources/Timing/Deliverables/Impact

Students: Vignesh Rajamani, Jayjeet Govardhan
Sponsors: NSF, NSF CELDi
Timing: August 2005-July 2006
Deliverables:

- A novel method to improve the read rates in factory environments
- Validation of the experimental results with theory
- Statistical design and analysis of experiments to yield in better understanding and improvement of the setup
- Papers discussing the above mentioned issues and Journals discussing the solutions and the experimental results

Status/Issues

Status

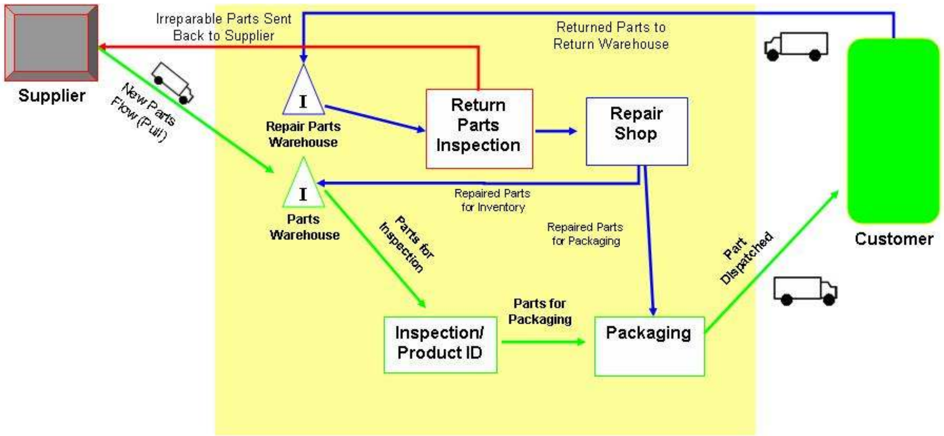
- Proof of concept of the proposed approach has been validated
- More experiments are in progress to analyze some of the issues
- Mapping the field around the RFID reader and the tag is in progress

Issues

- The sweep mode operation of the reader makes it hard to accurately determine the threshold power for the tag
- Different RFID reader specifications serve as a problem in developing a general standard method of testing

The Value of RFID in a Depot Environment

Mapping of Depot Environment



Benefits/Description/Objectives

Objective:

Develop a spreadsheet framework to determine the value of RFID in a depot environment using industrial engineering concepts such as value stream mapping and engineering economics

Advantages and Strengths:

Allows for the capture of soft savings such as reduced scanning times

Provides a framework to determine cost of a passive RFID tag that will create savings for an organization performing depot tasks

Presents a systematic approach for determining soft savings that one may expect from the implementation of passive RFID

Resources/Timing/Deliverables/Impact

Student: Brandon Gardner
Sponsor: NSF I/UCRC-CELDi, FAA, Tinker AFB
Timing: September 2005-December 2006
Deliverables:

- A model and a spreadsheet implementation to determine the economic value of RFID over a given time period (includes soft savings)
- A report explaining the various calculations and values used in the model to determine the value of RFID

Status/Issues

Status

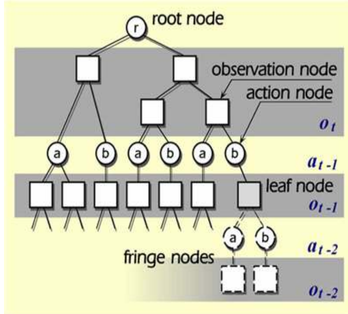
- A draft of the framework has been created
- Research has been done in the area of cost benefit analysis of passive RFID in a manufacturing and depot environments
- A draft of the report detailing the calculations and values in the framework has been created
- A fairly detailed mapping of the depot environment has been completed

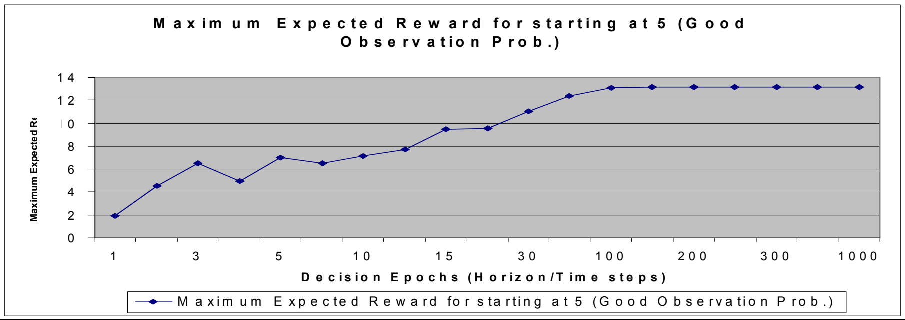
Issues

- Need to review the model to verify that it accurately predicts the value of RFID in a depot environment
- Prepare a document finalizing the details of the framework

RFID-POMDP Warehouse Search Model

POMDP Warehouse State Space formulation
↓
Observation function definition
↓
Reward/cost specification
↓
Computation of expected maximum reward
↓
Policy graph and optimal policy calculation





Benefits/Description/Objectives

Objective

Model and solve the problem of searching for misplaced/lost items using POMDP, in a storage environment, using information from RFID signals

Strengths of Proposed Approach

- Incorporates uncertainty in RFID system due to false negative reads resulting in varying read rates in a warehouse environment
- Minimizes the order picking time considerably when items are often lost or misplaced within the warehouse
- Ensures almost 100% visibility of inventory levels in the warehouse

Resources/Timing/Deliverables/Impact

Student: Sharethram Hariharan
Sponsor(s): NSF (CELDi), FAA
Timing: January 2005- September 2006
Deliverables:

- A comprehensive model for using RFID to improve the searching process for misplaced items in storage environments
- Incorporate read rate variations due to presence of metals or liquids into the model formulation
- Report detailing the performance of the POMDP algorithm with different levels of uncertainty in RFID information
- Optimal policy interpretation of the result of the algorithm in C code in a Linux platform

Status/Issues

Status

- Warehouse Search model formulated
- Formulated 4 different scenarios with different belief states and observation probabilities
- Implemented the scenarios using POMDP incremental pruning algorithm
- Compared the performance of the algorithm with varying observation probabilities for each model
- Plotted the performance and quantified them with expected maximum reward values

Issues

- Larger state space formulations very slow with existing algorithm
- As uncertainty increases, policy becomes more and more sub-optimal

Sensor Networks & Complex Manufacturing
Systems Monitoring Research Lab
School of Industrial Engineering and Management

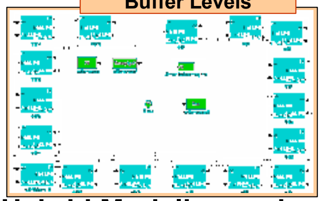
Continuous Flow Modeling of Manufacturing System Dynamics

Comparison of Line Statistics

Time Series
Throughput
Buffer Levels

Assembly line

Time Series
Throughput
Buffer Levels



Hybrid Modeling and Simulations

What are the various entities doing?
Data Visibility
Not Actionable
Sensor and Data Logging Technologies

What and How are the various entities doing?
Performance Visibility
Actionable
Sensor and Data Loggin
+
Complex System Dynamic Modeling

Benefits/Description/Objectives

Objective: Investigate a continuous state space approach founded on nonlinear dynamic systems principles to model assembly line operations.

Advantages and Strengths:

- Captures nonlinearity, noise
  - Can capture significantly more information from noisy data
- Allow reconstruction of low-order prediction models from real-time sensor data
  - Reflect the complexity exhibited by real production systems
  - Allow fast prediction of performance

Resources/Timing/Deliverables/Impact

Students: Yang Hui, Utkarsh
Leverage: GM Research Center
Timing: August 2005 - August 2007
Deliverables:

- A prototype implementation of a hybrid model
- A prototype implementation of a continuous flow model
  - Validation of the implementations relative to an 18 machine line segment and a larger segment
  - Report detailing the dynamic characteristics of GM assembly operations

Status/Issues

Status

- Continuous-DES Hybrid modeling approach applied to model 18 station line segment
- Statistics of throughput compared with historical data from GM
- DES model of the operation implemented in arena
- Initial validation of DES model completed (~90% accuracy of model wrt actual line observations demonstrated)
- Nonlinear analysis of the model underway

Issues

- Need to improve computational speed of the hybrid model
- Make the model continuous for long-term prediction of system characteristics
- Investigations needed for deriving real-time model-based performance prediction