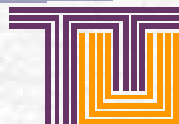




Integrated Intelligent Industrial Process Sensing and Control Demonstrated on Cupola Furnaces

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Tennessee Technological University



Collaborations

- ✔ Tennessee Technological University
 - ✔ Utah State University
 - ✔ Idaho National Engineering Laboratory
 - ✔ American Foundry Society
 - ✔ General Motors
 - ✔ Albany Research Center
 - ✔ US Pipe
- 

Overview

 Introduction

 Objectives

 Object Oriented Framework

 Multi-Modal Sensor Fusion

 Intelligent Controller

 Generalization and User Interface

 Results

 Conclusions

Cupola Furnace



Charging System



View from Tuyere



Control Room

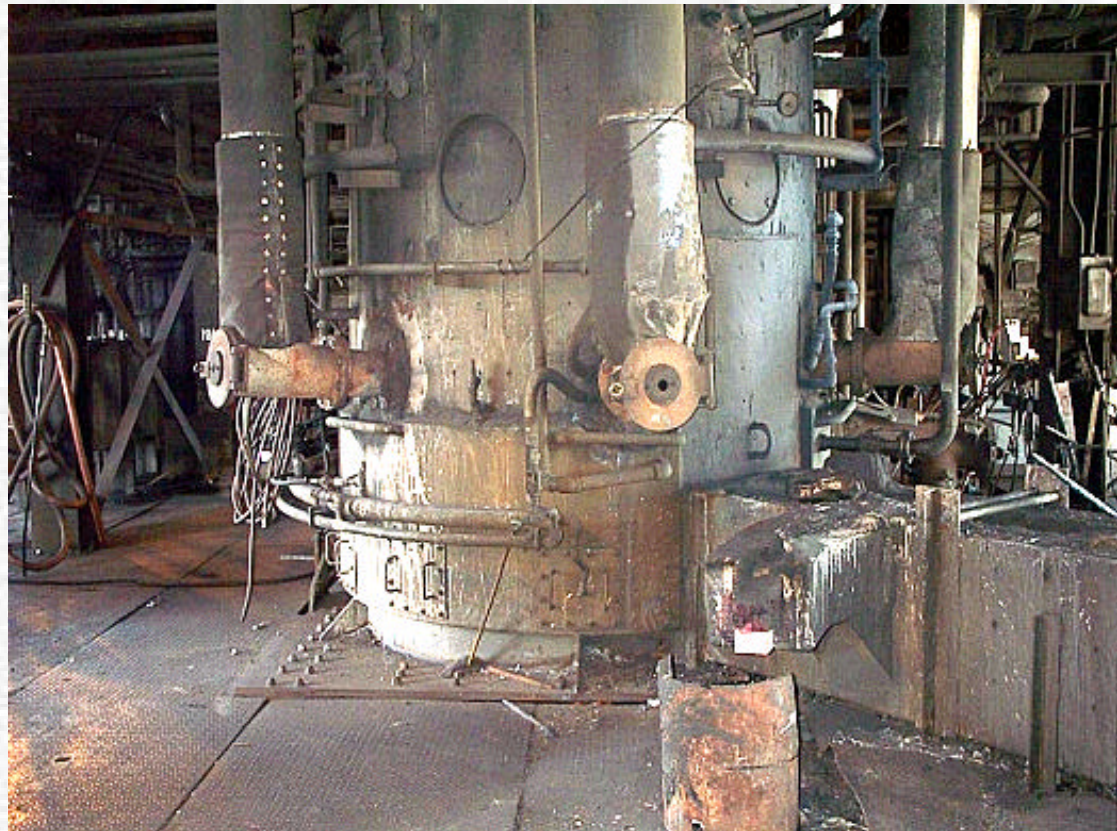


Charging Materials

Cupola Furnace



Tap hole



Cupola Furnace Shaft

Objectives

• Unified Framework for Integration of

- Multi-Modal sensor Fusion,

- Intelligent Controllers, and

- Expert System and Offline Data Analysis Module

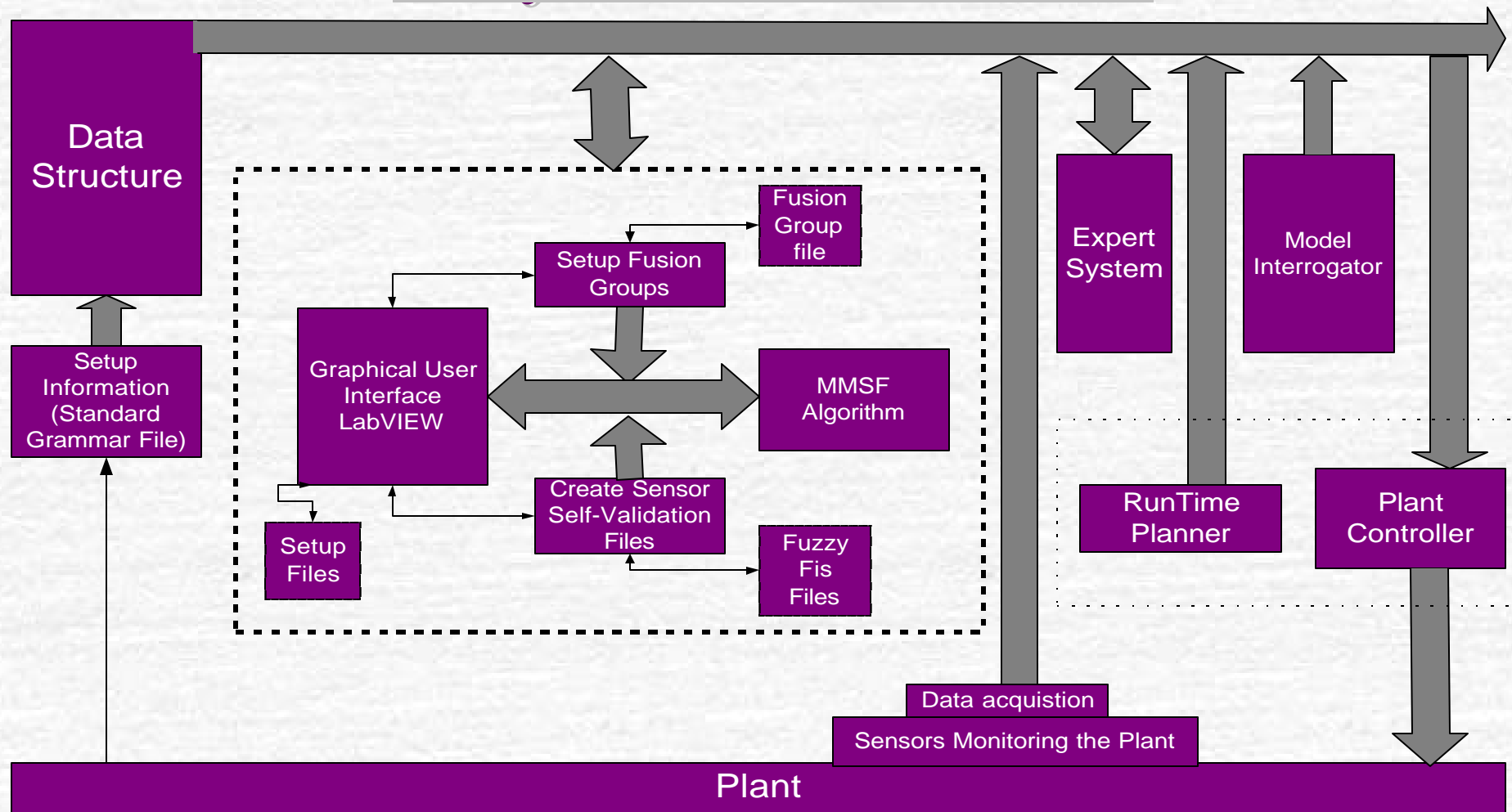
• Generalized, Object Oriented Open System Architecture

• GUI for System Setup and Operation

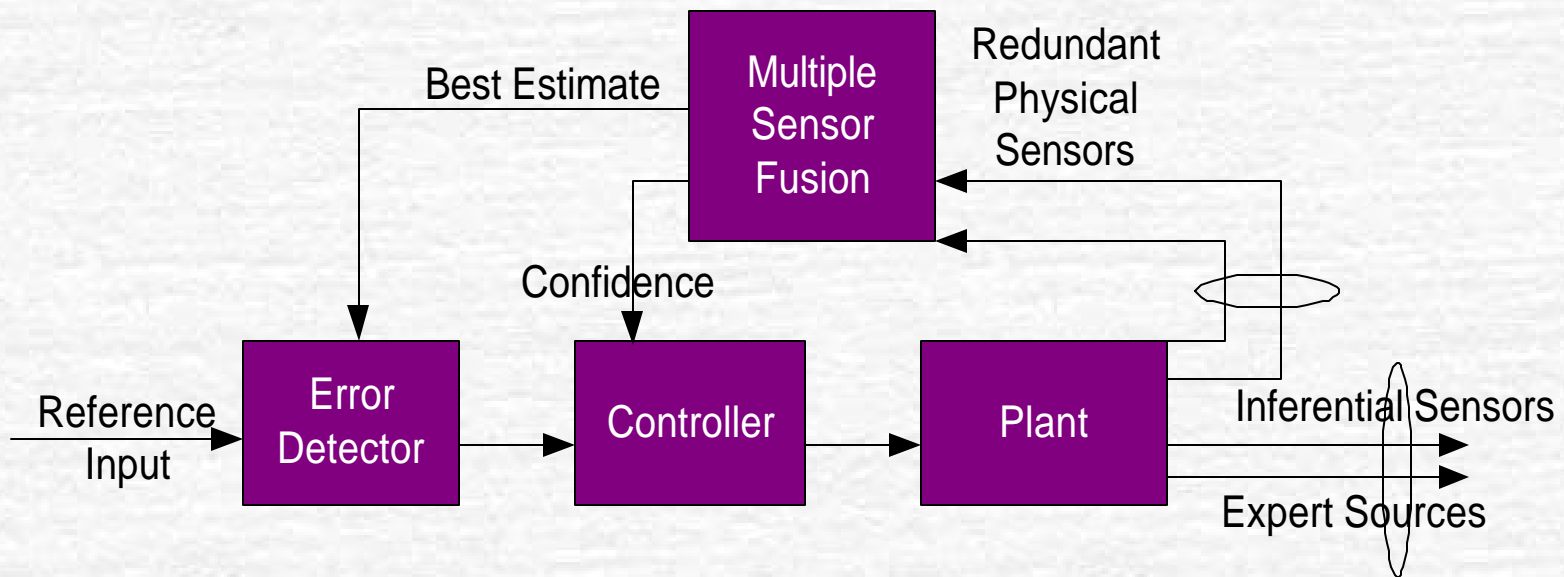
• Proof of Concept of HW Implementation using FPGA

• Demo on Cupola Furnaces

Unified Framework

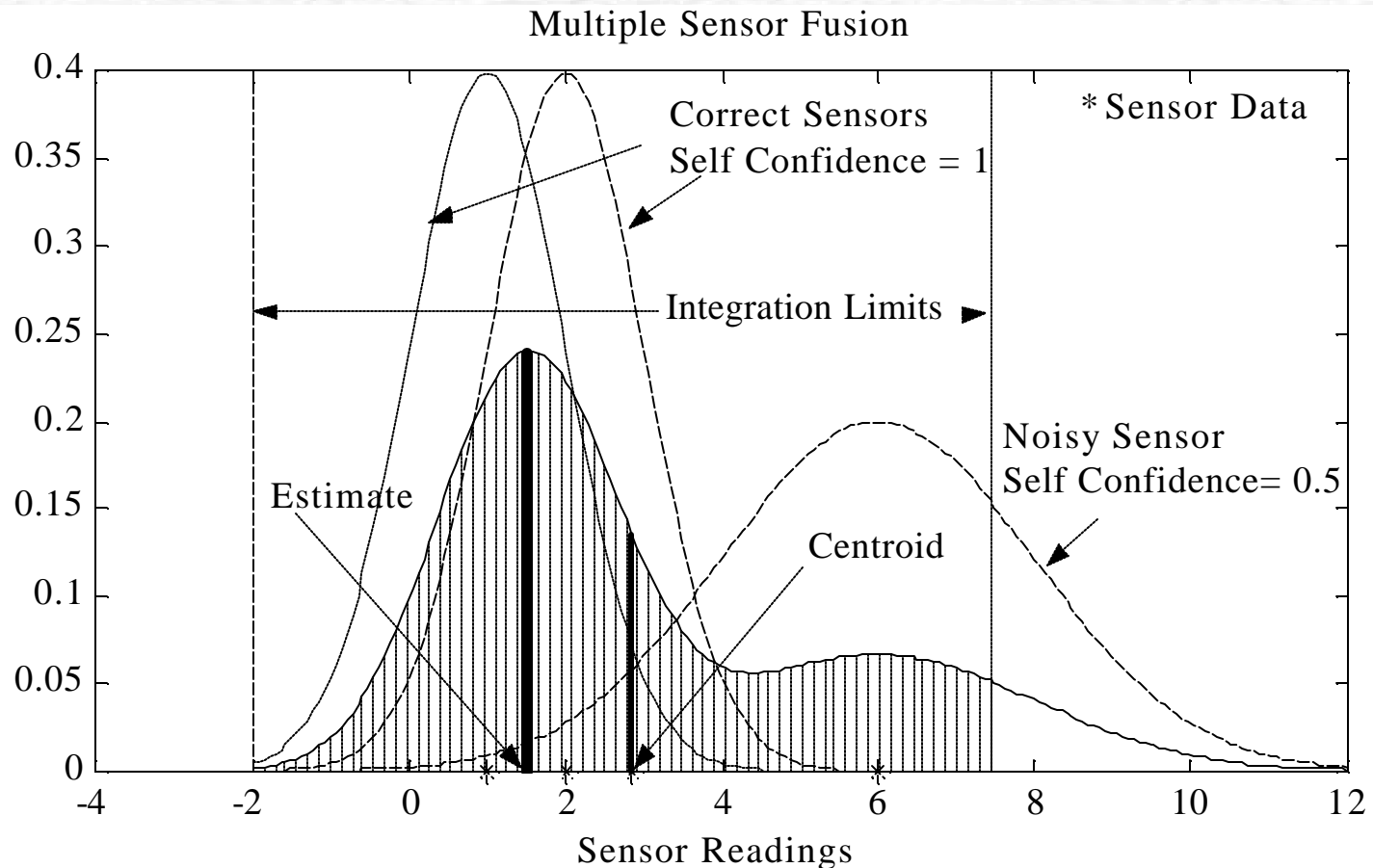


MMSF Fusion: Review MSF

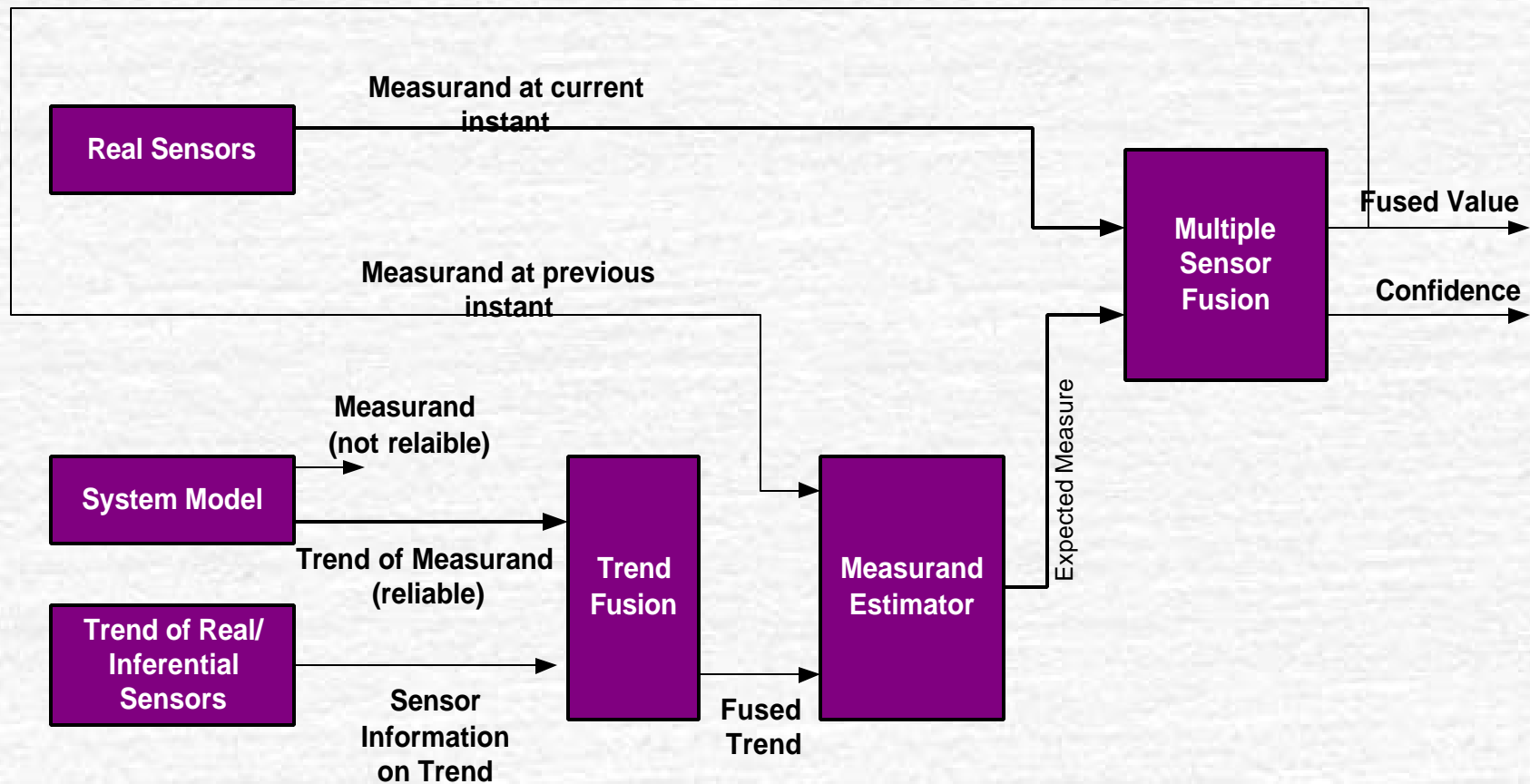


*Trend Information Not
Used*

MMSF Fusion: Review MSF



MMSF Fusion



MMSF::Inferential Sensors

- ❖ Provides Trend/Value Measurand information.
- ❖ Melt Rate Inferential (Virtual) Sensor
 - ❖ ANN Trained using Real Plant Data
 - ❖ Inputs: Blast Rate and Oxygen Enrichment
- ❖ Iron Temperature Inferential (Virtual) Sensor
 - ❖ ANN Trained using Real Plant Data
 - ❖ Inputs: Blast Rate, Oxygen Enrichment, and Bath Temperature
- ❖ Incorporated directly into MMSF algorithm.

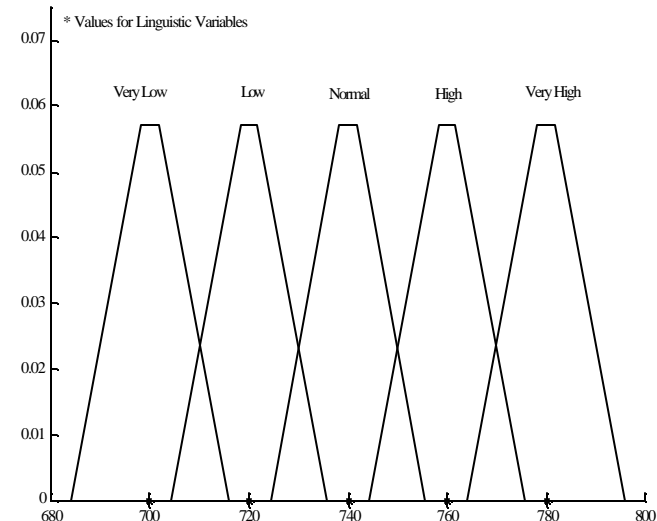
MMSF::Expert Systems

Provide linguistic information on status of operation.

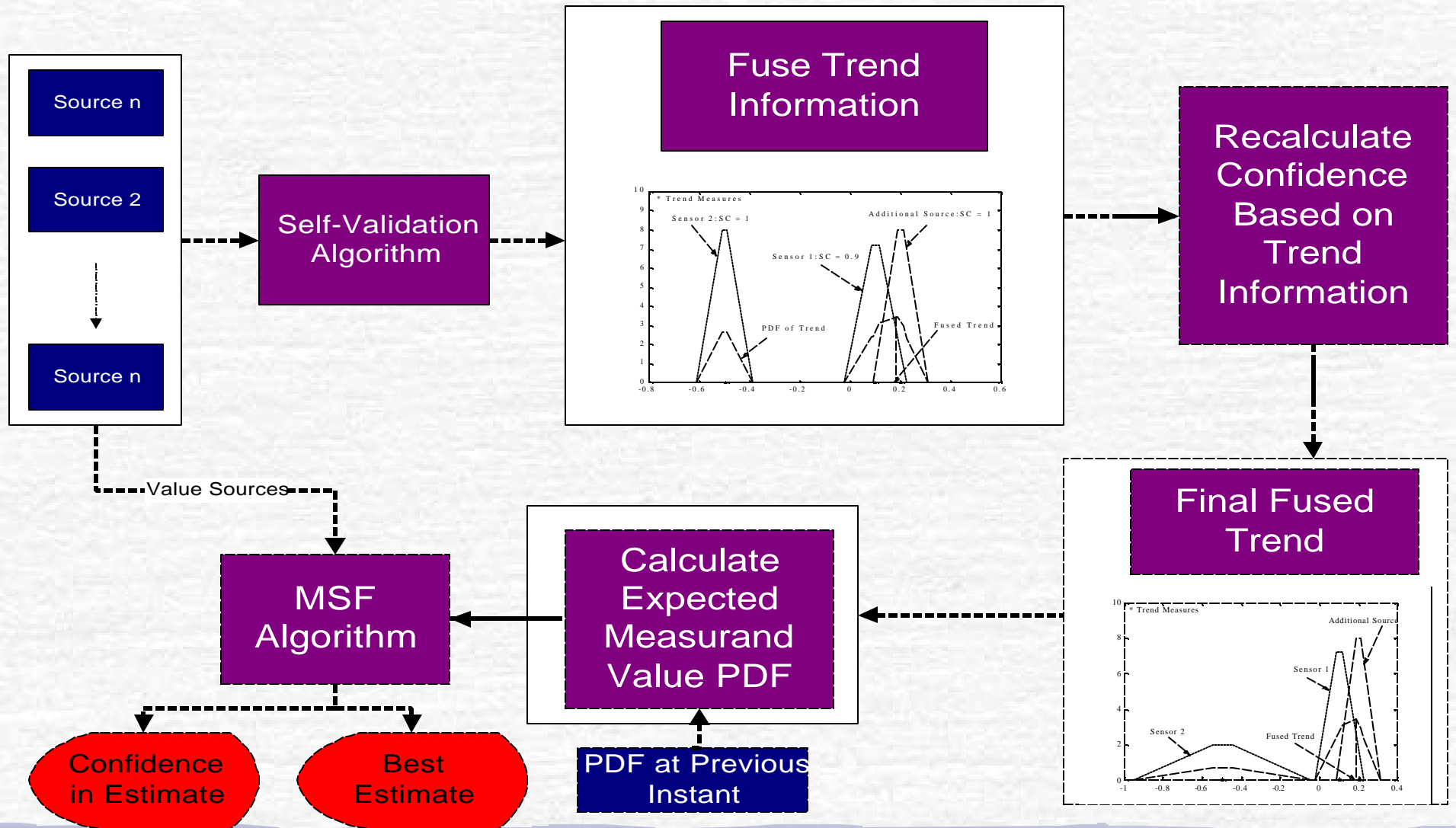
Status of operation of trend/value is classified as:

- Sharply Decreasing/Very Low,
- Decreasing/Low,
- Steady/Normal,
- Increasing/High, and
- Sharply Decreasing/Very High.

Convert linguistic information to PDF
Based on confidence in Source



MMSF Algorithm Summary

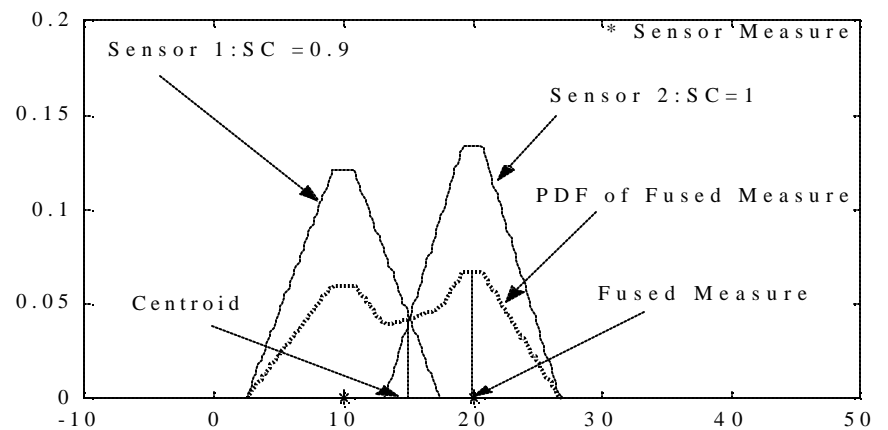
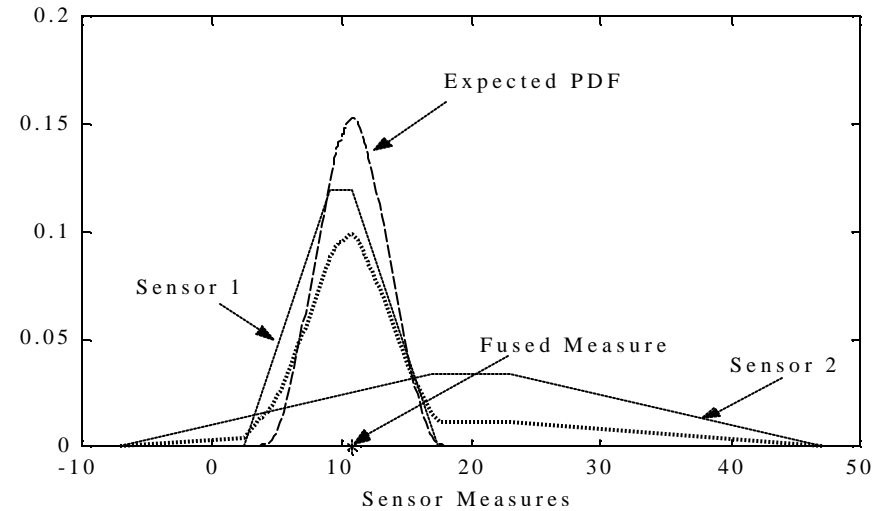


MMSF::Example...

Final Result -MMSF

Comparison with MSF algorithm

Plot of PDF of Sensors



MMSF::Hardware Implementation

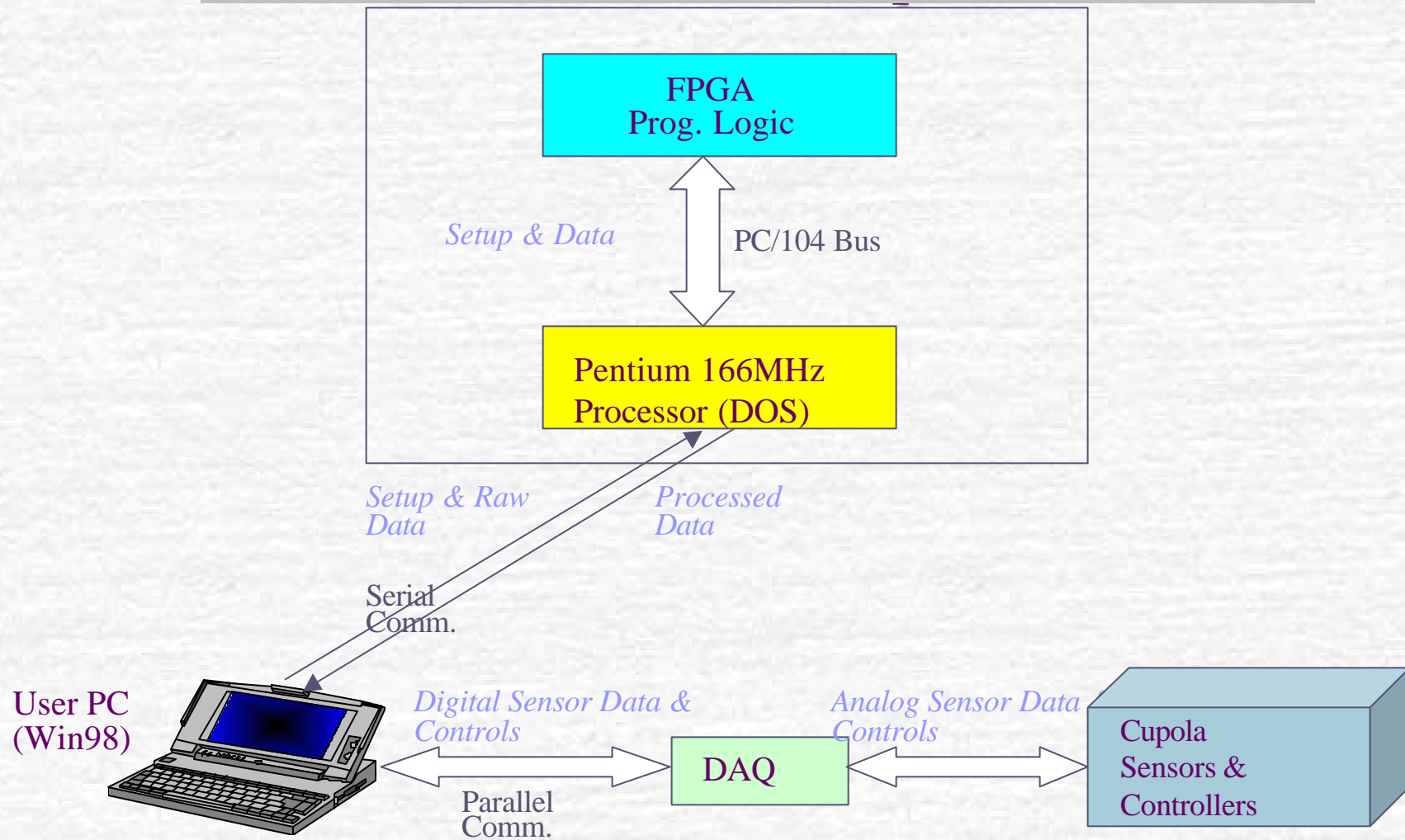
☛ Completed Design and Test

- Allocation of computations between programmable hardware and Processor software implementations
- Programmable hardware for Self-Validation signal processing algorithm
- Hardware/Software interface between Processor board and FPGA board

☛ In-progress Design and Test

- FPGA programmable hardware for Multi-Sensor Fusion signal processing algorithm
- Communication software between User PC and Processor

MMSF::Hardware Implementation



Intelligent Controller

Design Objectives

- Account for non-linearities in the process, and have strategies for handling them.
- Handle noisy measurements appropriately by making use of sensor fusion algorithms.
- Allow operators to define operational parameters, schedule changes, and create heat profiles.

Design Challenges

- Charge Materials have long time delay that makes feedback control very difficult.
- Many aspects of Cupola operation are not modeled, so model based control is difficult.
- Information relevant to control will come from many sources, such as actual sensors, sensor fusion, virtual sensors, AFS model, predictions, and even operators.

Intelligent Controller:: Design Approach

Control is divided into Two Parts

Planner

- User Interface where the operator plans a cupola run. Control variables are declared, setpoints are defined, and transitions are scheduled.
- Cupola Inputs are calculated based on defined setpoint schedule.
- Contingency plans can be developed in case of unplanned events (bridging, production line going down, etc.).

Intelligent Controller

Does not require model to perform control.

- Can incorporate multiple data types and sources to make control decisions.
- Configurable to achieve control of nonlinear and noisy processes.

Intelligent Controller::Creating Heat Plans

Plans are created in segments

- Start Up
- Steady Burn
- Transition
- Shutdown
- others?

The length and the operational points for each segment are defined, as are the overall start and stop time.

Inputs are currently determined from the defined setpoints through an inverse model. Development continues in this area in order to provide accurate as possible values for the cupola inputs.

Intelligent Controller::Creating Heat Plans...

Data Structure

```
graph TD; HP[Heat Plan] --> DS[Data Structure]; C[Controller] --> DS;
```

Heat Plan

- Time Series array of Setpoints.
- Time Series array of Operating State information (transition, steady burn, etc.).
- Time Series array of calculated Cupola Inputs.
- Each point in the Time Series array corresponds to the information for one minute.

Controller

On start up, shut-down, and transitions, the cupola is operated open-loop using the Cupola inputs provided by the Planner & Expert System.

- During Steady Burn segments, feedback control is maintained using Fuzzy Controllers.

Preliminary AFS-Model-Based Expert System

Expert System 2.vi

File Edit Operate Tools Browse Window Help

18pt Application Font

O/P->I/P I/P->O/P

Stop

1.593 0.787 2.485

Select Output To Change

melt rate

Current Inputs

Input Names

Y1	coke ratio	Y1	9.55
Y2	blast rate	Y2	0.24
Y3	oxygen addition rate	Y3	0.006

Suggested Inputs

Select Controllable Inputs

- coke ratio
- blast rate
- oxygen addition rate

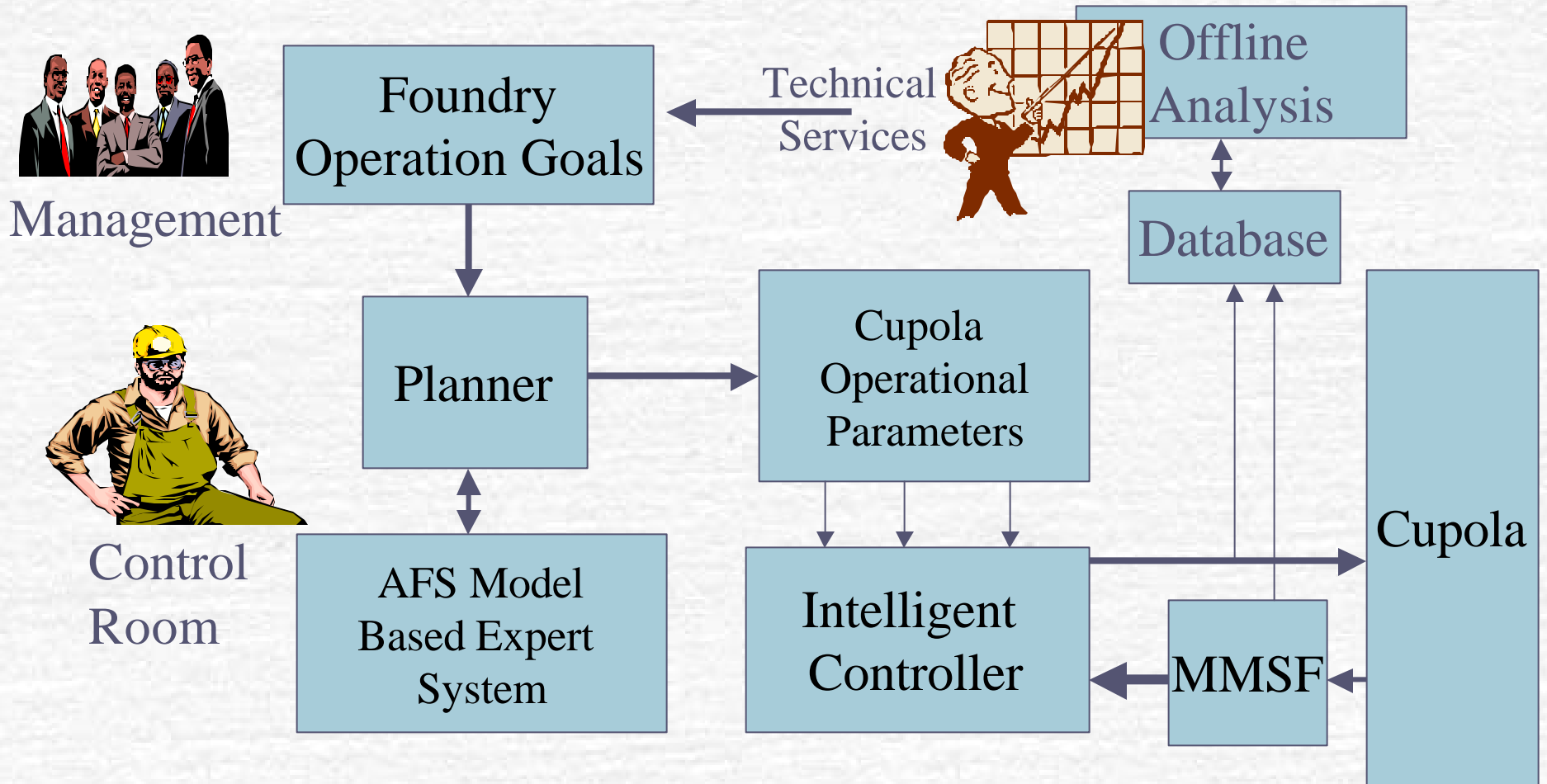
Optimization Method

Variable of Interest Only

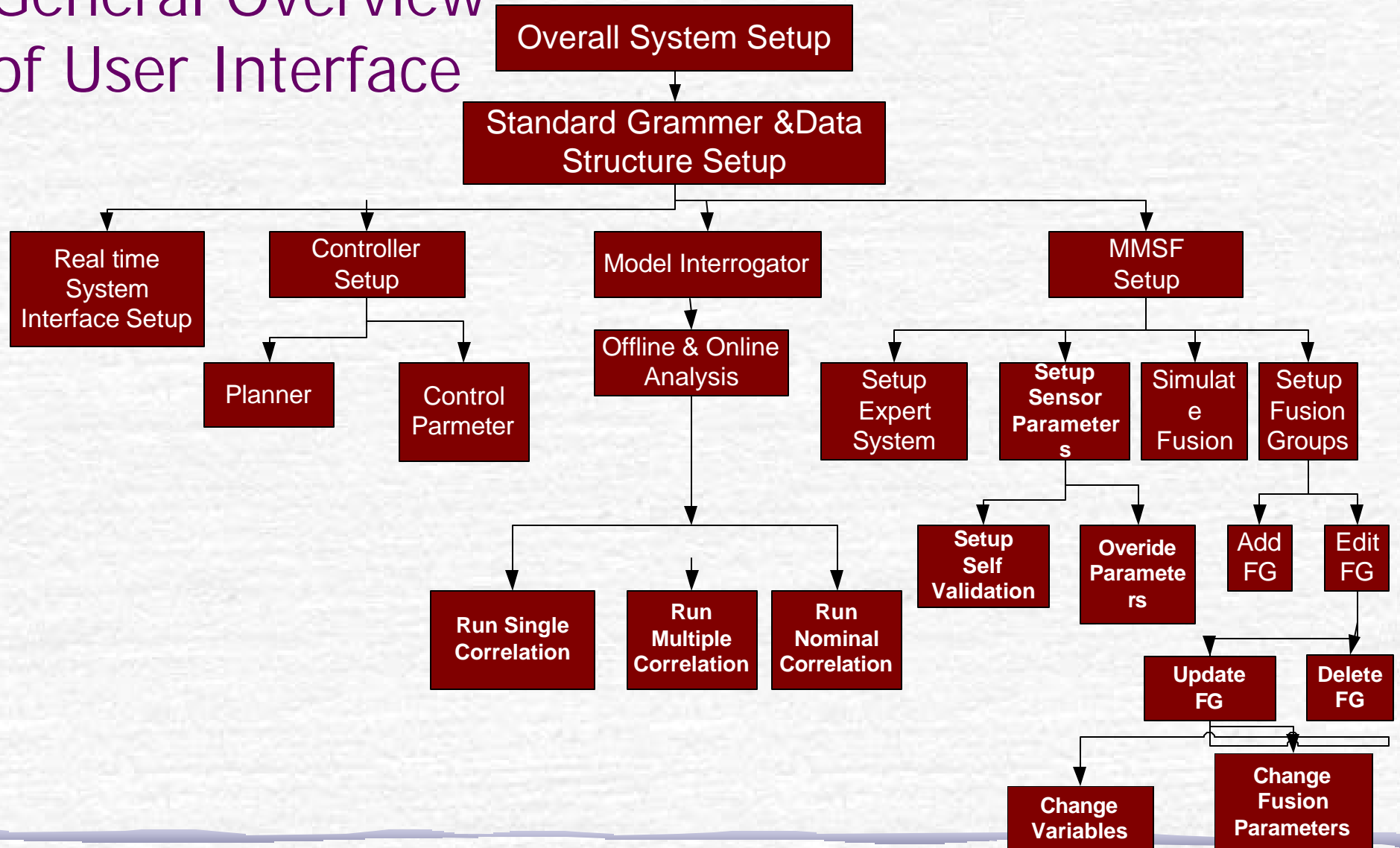
Current Outputs	Achievable Outputs	Desired Outputs	Deviation from Desired
x1: 14.01	x1: 11.69	x1: 19.76	x1: 0.69
x2: 14.16	x2: 13.89	x2: 9.67	x2: -0.30
x3: 0.57	x3: 0.58	x3: 0.56	x3: -0.04
x4: 0.50	x4: 0.53	x4: 0.34	x4: -0.37
x5: 1.62	x5: 1.51	x5: 1.29	x5: -0.15
x6: 1743.79	x6: 1682.08	x6: 1745.06	x6: 0.04
x7: 1743.70	x7: 1681.93	x7: 1745.05	x7: 0.04
x8: 3.03	x8: 3.01	x8: 3.19	x8: 0.06
x9: 1.13	x9: 1.14	x9: 1.05	x9: -0.08
x10: 0.33	x10: 0.33	x10: 0.28	x10: -0.14
x11: 435.57	x11: 442.00	x11: 470.54	x11: 0.06

- Based on Model Interrogator for AFS Cupola Model
- Suggests Input Changes for Major Operational Transitions in Cupola
- Allows for Optimization and Constrained Operation

Summary of Controller Architecture



General Overview of User Interface

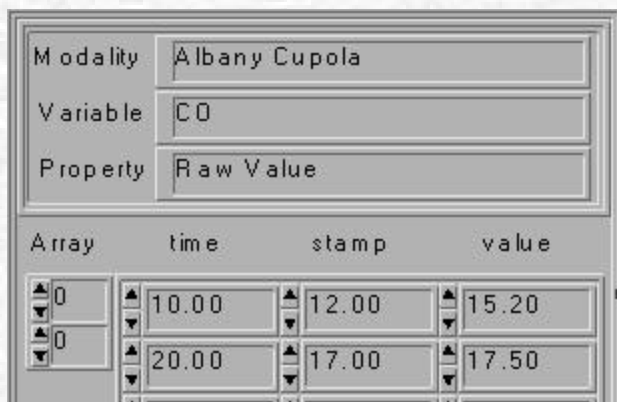


User Interface::Standard Grammar

- ✦ Backbone of the Datastructure and User Interface.
- ✦ ASCII text file.
- ✦ Lists all Modalities and Variables (Sensors).
- ✦ Different Sensor Names in Different Modalities
- ✦ Structure governed by strict rules.

User Interface::Data Structure

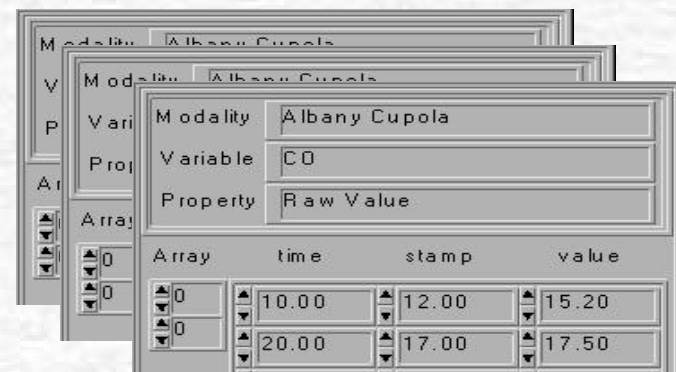
- 📦 Built on Standard Grammar
- 📦 4-Dimensional array
- 📦 Data storage Unit is a “Node”
- 📦 Allows for Access by Multiple Objects
- 📦 Allows for Distributed Computing



A screenshot of a software window titled 'Albany Cupola' showing a data structure. The window has three input fields: 'Modality' (Albany Cupola), 'Variable' (CO), and 'Property' (Raw Value). Below these is a table with columns 'time', 'stamp', and 'value'. The table contains two rows of data.

Array	time	stamp	value
0	10.00	12.00	15.20
0	20.00	17.00	17.50

Structure of A Single Node



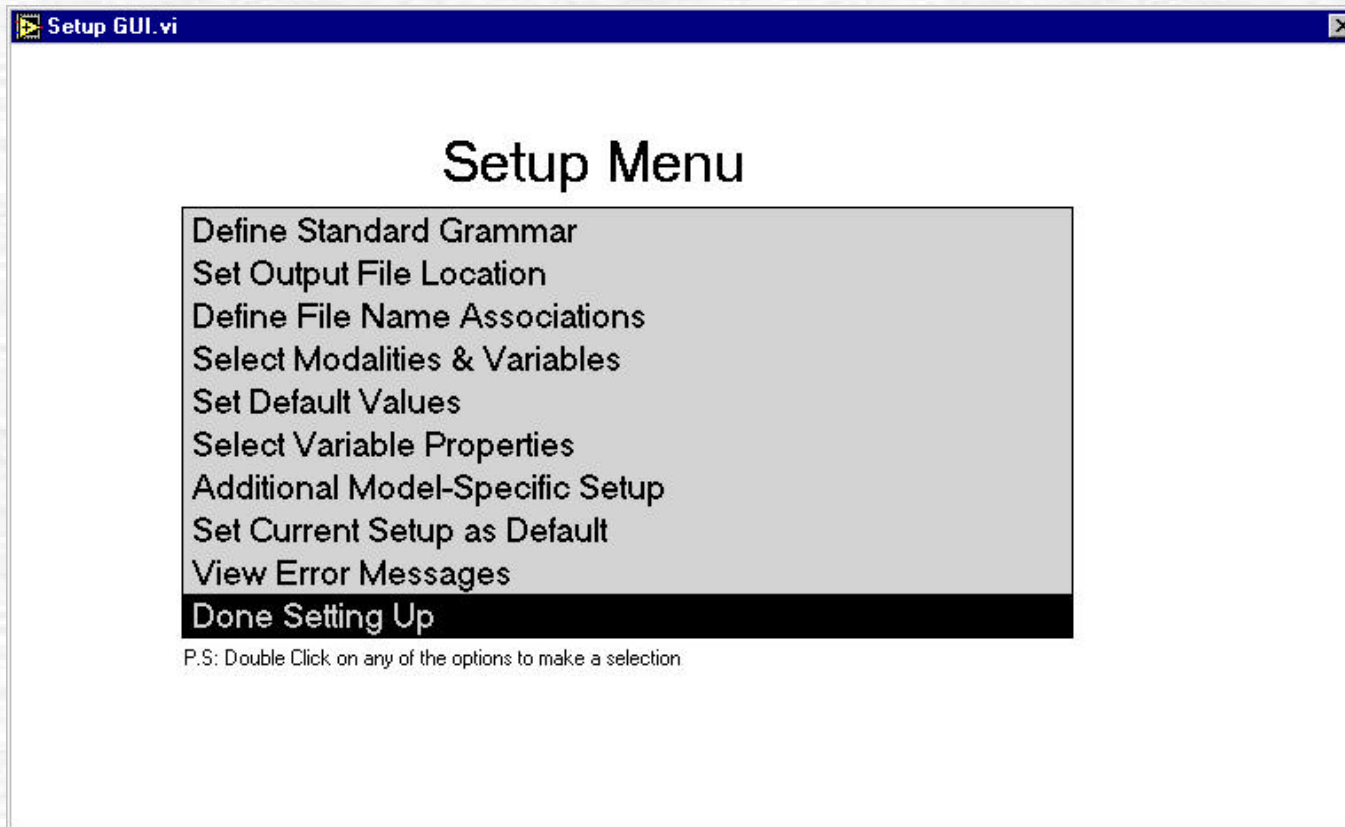
A screenshot showing multiple overlapping windows of the same data structure as the single node, illustrating a 4-dimensional array structure. The windows are stacked, with the top one showing the same data as the single node window.

Array	time	stamp	value
0	10.00	12.00	15.20
0	20.00	17.00	17.50

Data Structure Made-up of Nodes

User Interface::System Setup

Main Menu



Main Menu
for setting up
or Modifying
overall
System
Structure

User Interface::System Setup...

Screens for Defining Variables, Modalities and Properties

The image displays four screenshots of a software interface for system setup, arranged in a 2x2 grid.

Top Left: Select Variables.vi
This window shows the process of selecting variables. It has three main sections: "Modalities" (listing AFS model variable, ANN Model variable, Real Albany sensor, and Other Model 1-5), "AFS model variable" (with a list of inputs like coke in charge, coke ratio, cupola diameter, cupola well diameter, blast rate, normalized mass of amount of moisture, normalized oxygen, oxygen addition rate, blast temperature, and blast fraction), and "Real Albany sensor" (with a list of inputs like blast rate, sensor1, sensor2, sensor3, blast temperature, total oxygen in blast, ambient temperature, relative humidity, and time). A "Selected Variables" list at the bottom contains "coke ratio" and "blast rate". A red "Continue" button is at the bottom center.

Top Right: Select Parameters.vi
This window shows the "Parameter List" and "Selected Parameters". The "Parameter List" includes "value", "trend", "mean value", "standard deviation", and "confidence". The "Selected Parameters" list contains "trend". There are "Add to List" and "Return to Menu" buttons.

Bottom Left: Model Specific Setup.vi
This window shows the "Declare Model Setup Files" section. It includes a "Return to Menu" button, a "Define" button, a "Model" dropdown menu (set to "Metal Data GUI.vi"), and a "Run Setup VI" button. There are also "error in (no error)" and "error out" status indicators.

Bottom Right: Update Values.vi
This window shows the "Done Making Changes" section and a table titled "Selected Model Variables and Defaults".

INPUTS		
coke in charge	4.672	kg
coke ratio	10	%
cupola diameter	0.559	m
cupola well diameter	0.457	m
blast rate	0.1399	m ³ /s at 0C
normalized mass of	0.7087928	kg/s/m ²
amount of moisture	0.004166713	kgH ₂ O/kg dry air
normalized oxygen	0.0182721	kg/s/m ²
oxygen addition rate	0.003125	m ³ /s at 0C

User Interface::Fusion Groups...

Create Fusion Groups

Available List

Variables

- coke in charge
- coke ratio
- cupola diameter
- cupola well diameter
- blast rate
- normalized mass of air in b
- amount of moisture in air
- normalized oxygen additio

Properties

- value
- trend
- mean value
- standard deviation
- confidence
- time base

Modalities

- AFS model variable
- ANN Model variable
- Real Albany sensor

0 Relative Instant

Add Variable

Add Group

Fusion Groups List

- coke ratio : AFS model variable : value at 0
- coke ratio : AFS model variable : trend at 0
- blast rate : ANN Model variable : trend at 0

PS Double Click on any of the elements in the Fusion Group:
List above to modify it

Back to Main Menu

Group Name

Fusion.Group.1

Association

Variable: coke in charge

Modality: AFS model variable

Property: fused value

Relative Instant: 0

Variables associated with this fusion group

Threshold: 0

Trend Influence: 0.25

Factor: 1.00

Weightage of Expected Value: 0.5

Weightage of Previous Fused Confidece: 0

Path of VI that executes Fusion

C:\My Documents\wpn\Thesis\temp\Doc-labview\MSF&Datastructure\MMSE Fusion.vi

Nodes to be fused

Modality	Variable	Property	Relative Instant
AFS model variable	coke ratio	value	0
AFS model variable	coke ratio	trend	0
ANN Model variable	blast rate	trend	0

Add Group

Cancel

Change Variable.vi

Variable: blast rate

Property: time base

Modality: AFS model

Relative Instant: 0

Change

Delete

Cancel

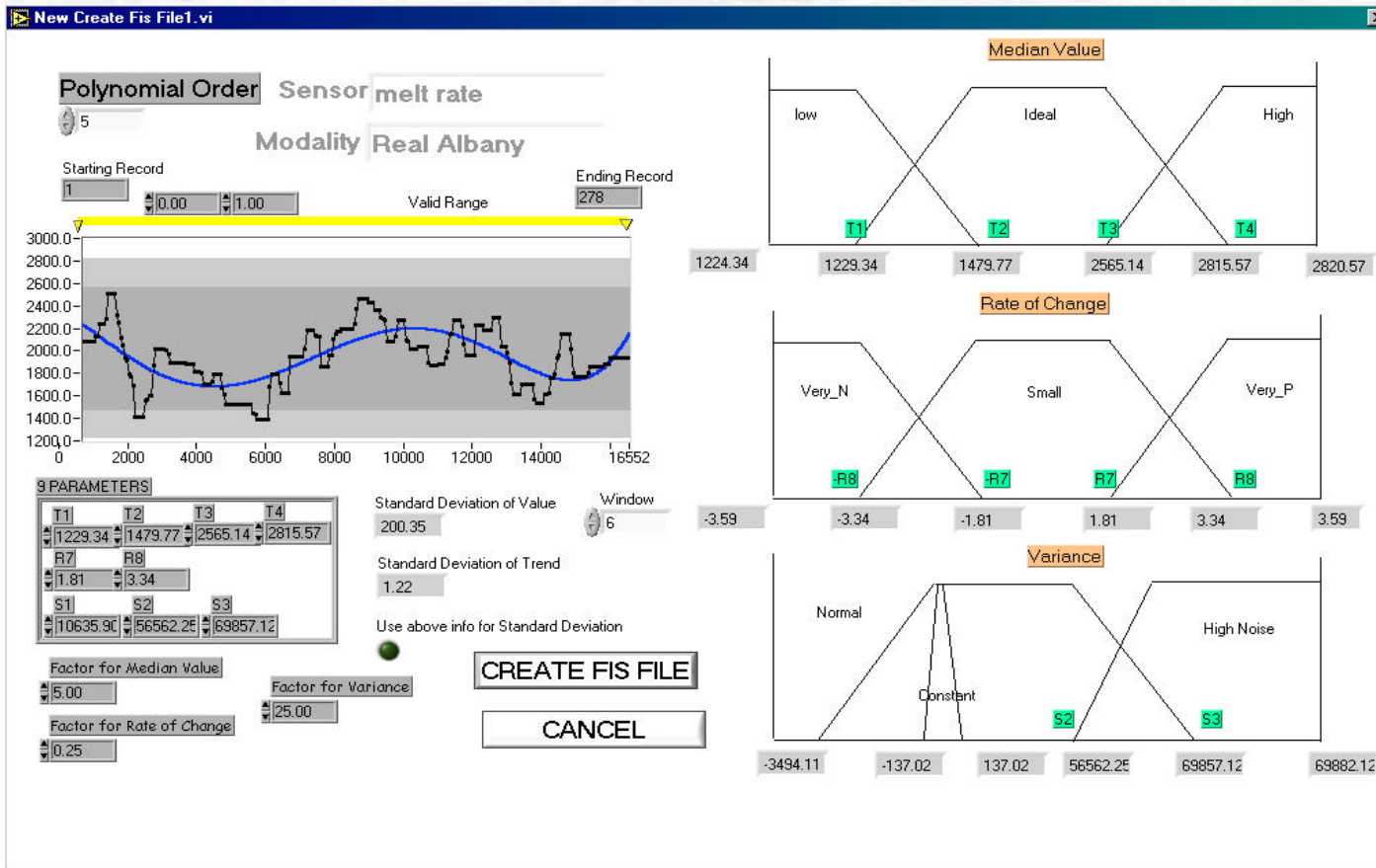
User Interface::Fusion Groups...

Edit Fusion Groups

The image displays two side-by-side windows from a software application. The left window, titled 'Update Group.vi', contains a menu titled 'Update Group' with three options: 'Change Variable List', 'Change Parameters', and 'Done Updating'. The right window, titled 'Delete or Update Group.vi', features a 'Groups' list with 'Fusion Group1' selected. To the right of this list are 'Delete Group' and 'Modify Group' buttons, both with 'OK' labels. Below these is a 'Back To Main Menu' button. On the far right, a 'Fusion Group Details' panel is visible, showing fields for 'Group Name' (Fusion Group1), 'Nodes to be fused' (Modality: AFS model variable, Variable: blast rate, Property: value, Relative Instant: 0), 'Node to associate fused value with' (Modality: AFS model variable, Variable: coke in charge, Property: fused value, Relative Instant: 0), and 'Variables associated with this fusion group' (Threshold: 0, Trend Influence Factor: 0.25, Weightage of Expected Value: 1.00, Weightage of Previous Fused Confidence: 0.25). At the bottom, the 'Path of VI that executes Fusion' is listed as 'C:\W\Documents\vipin\Thesis\user\Doc\labview\A...'.

User Interface::Sensor Parameters...

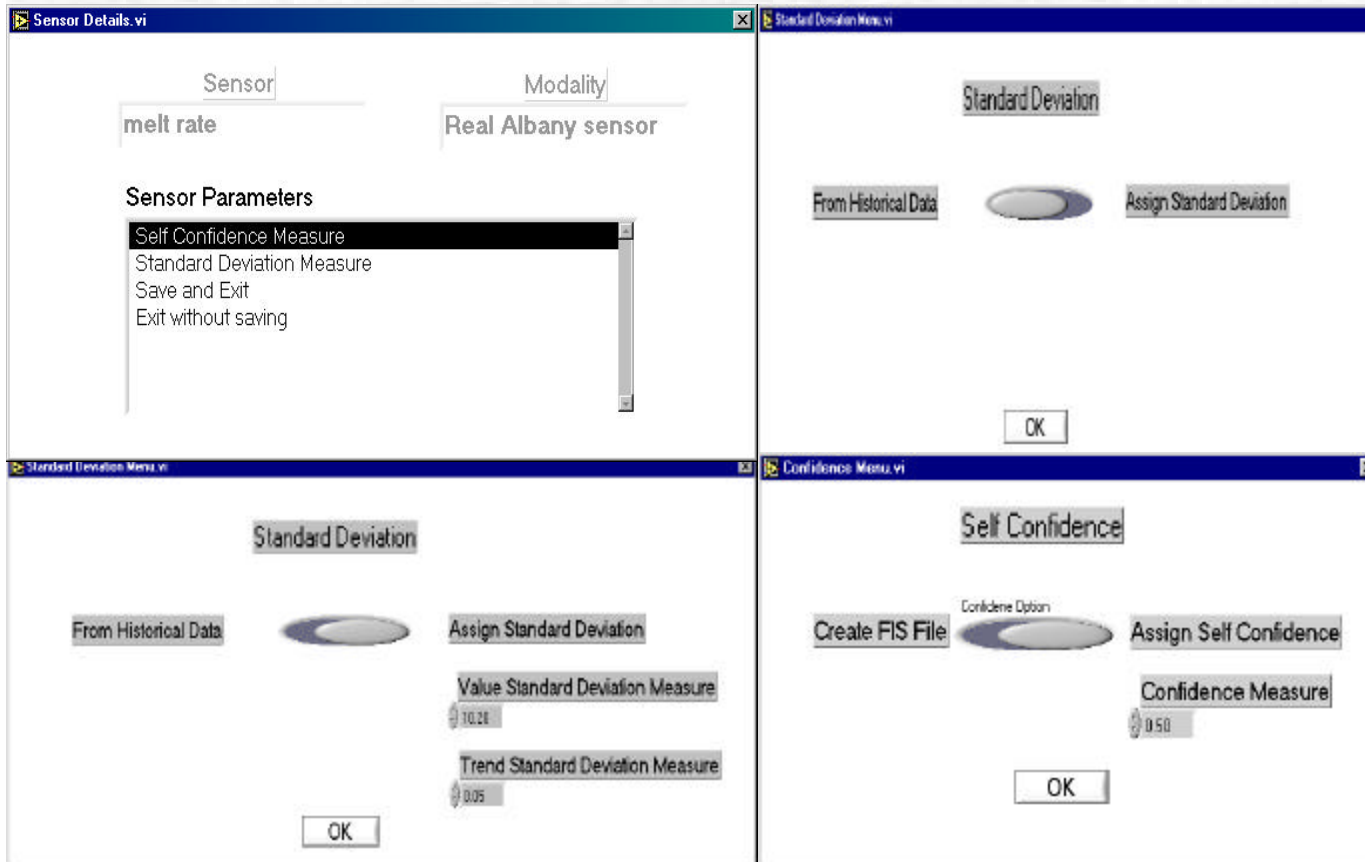
Interface to Setup Self Confidence Parameters



Uses Historical Data to Evaluate Self Confidence parameters

User Interface::Sensor Parameters...

Interface to Setup Self-confidence Parameters



Screens Provide a User Override to automatic settings for self-confidence Parameters

User Interface::Expert System Expert System Setup

Setup
Linguistic
Ranges for an
Operational
System
Variable

The screenshot shows a window titled "Expert Menu.vi" with a header "sensor 3-value". It contains a table of linguistic variables and their associated values and standard deviations. An "OK" button is visible on the right side.

Linguistic Variable	Value	Standard Deviation
Very High	600.00	10.00
High	620.00	10.00
Normal	640.00	10.00
Low	660.00	10.00
Very Low	700.00	10.00

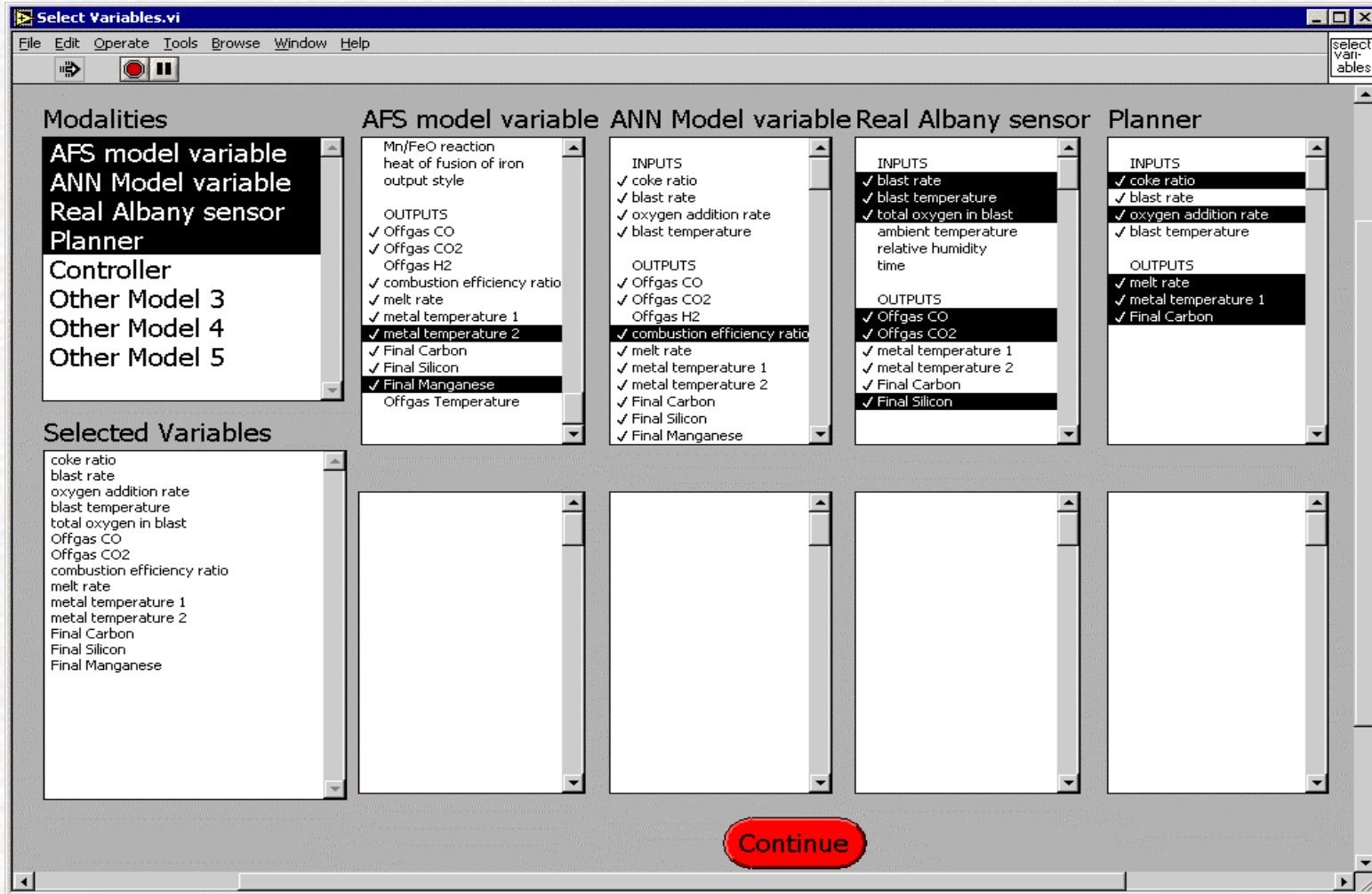
Expert System Run Time Interface

On Demand
Run Time
Screen for
Operator
Input

The screenshot shows a window titled "Expert System Interface" with a header "sensor 3::value". It displays five linguistic variables: Very High, High, Normal, Low, and Very Low. Each variable has a green dot above its name, a "Value" field, and a "Standard Deviation" field.

Linguistic Variable	Value	Standard Deviation
Very High	600.00	10.00
High	620.00	10.00
Normal	640.00	10.00
Low	660.00	10.00
Very Low	700.00	10.00

User Interface: Setup Modalities



Variables from many different sources can be compared.

Selecting a variable in one model will also show that the same parameter in another model is also selected.

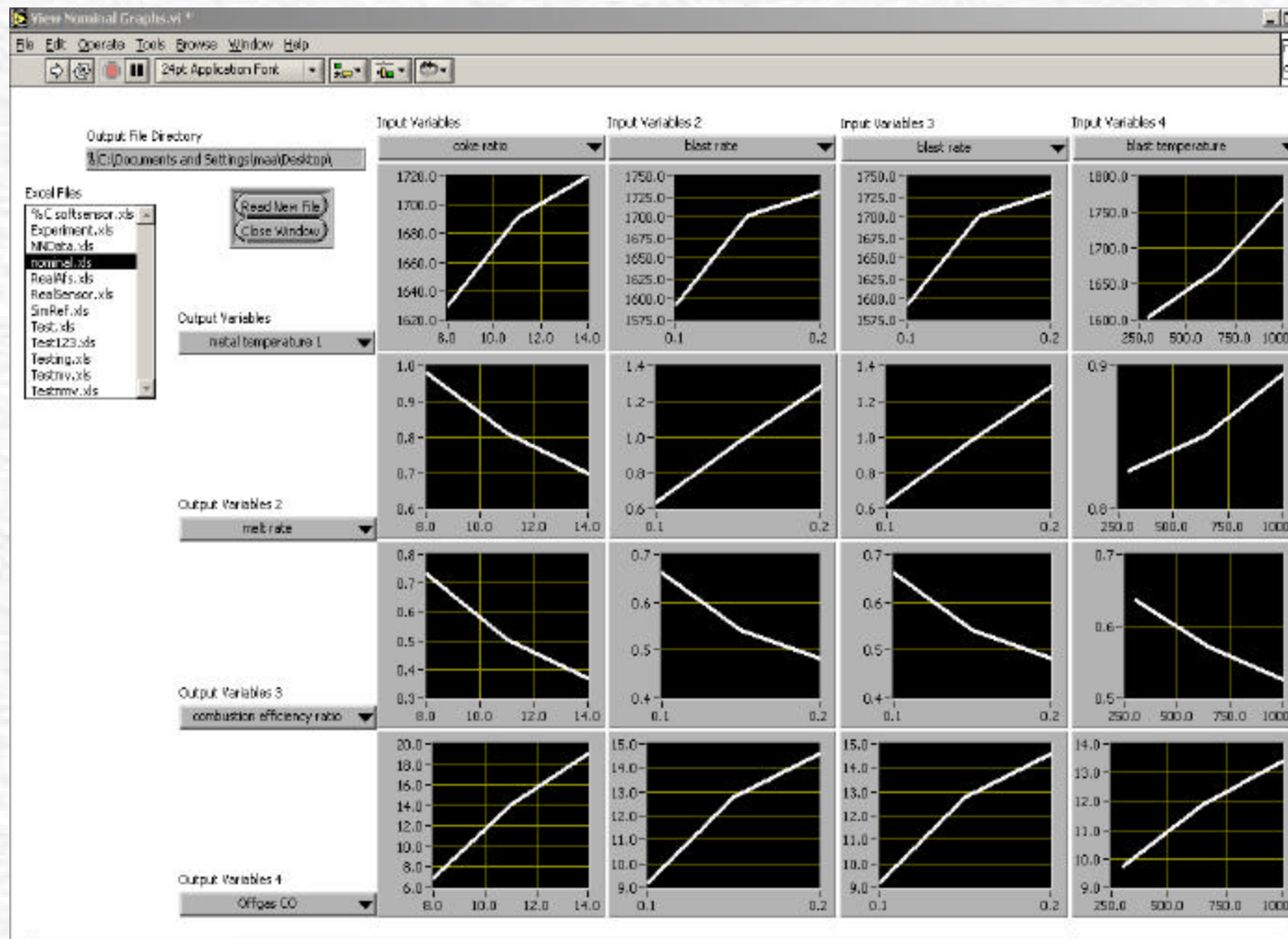
This setup also allows models to only use the variables that pertain to them, and not the entire set.

User Interface: Model Interrogator

Variables are chosen and a range defined for each.

The model is executed a number of times and the results are collected so that trends can be compared.

User Interface: Data Analysis- Model Interrogation



Analysis of
relationship
among various
cupola
Parameters using
Model
Interrogator with
AFS Model

Simulation and Results

📖 Data for simulation : ALRC cupola

📖 Variables considered for testing

📖 Melt Rate.

📖 Iron Temperature.

📖 Water Drum Temperature.

📖 Modalities considered for testing

📖 Real Albany Sensors (Pyrometers, MR and Thermo couples)

📖 Virtual Sensors (ANN Inferential sensors)

📖 Expert Source

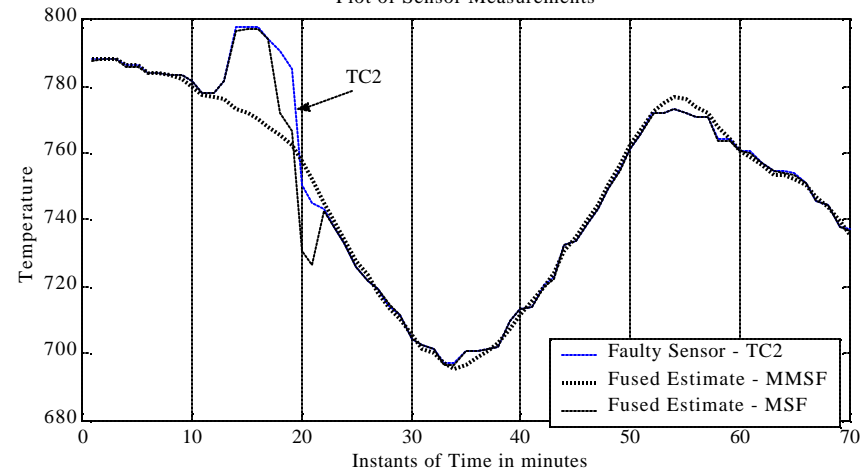
Simulation and Results...

Thermocouples: Case2

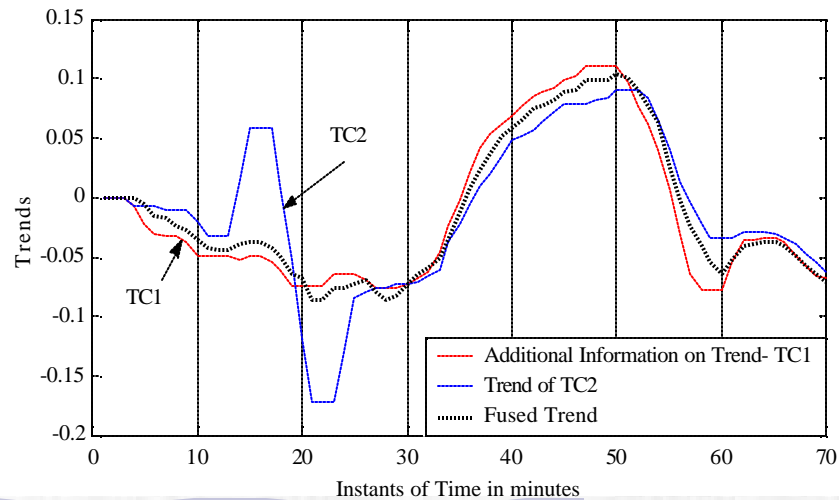
Simulation Parameters:

- TIF = 0.25
- PVC = 0
- EVI = 1.5

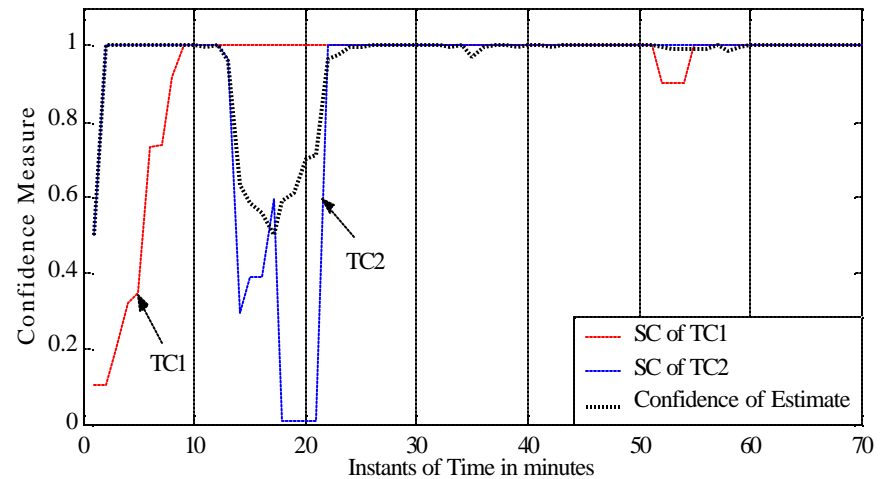
Plot of Sensor Measurements



Plot of Sensor Trends

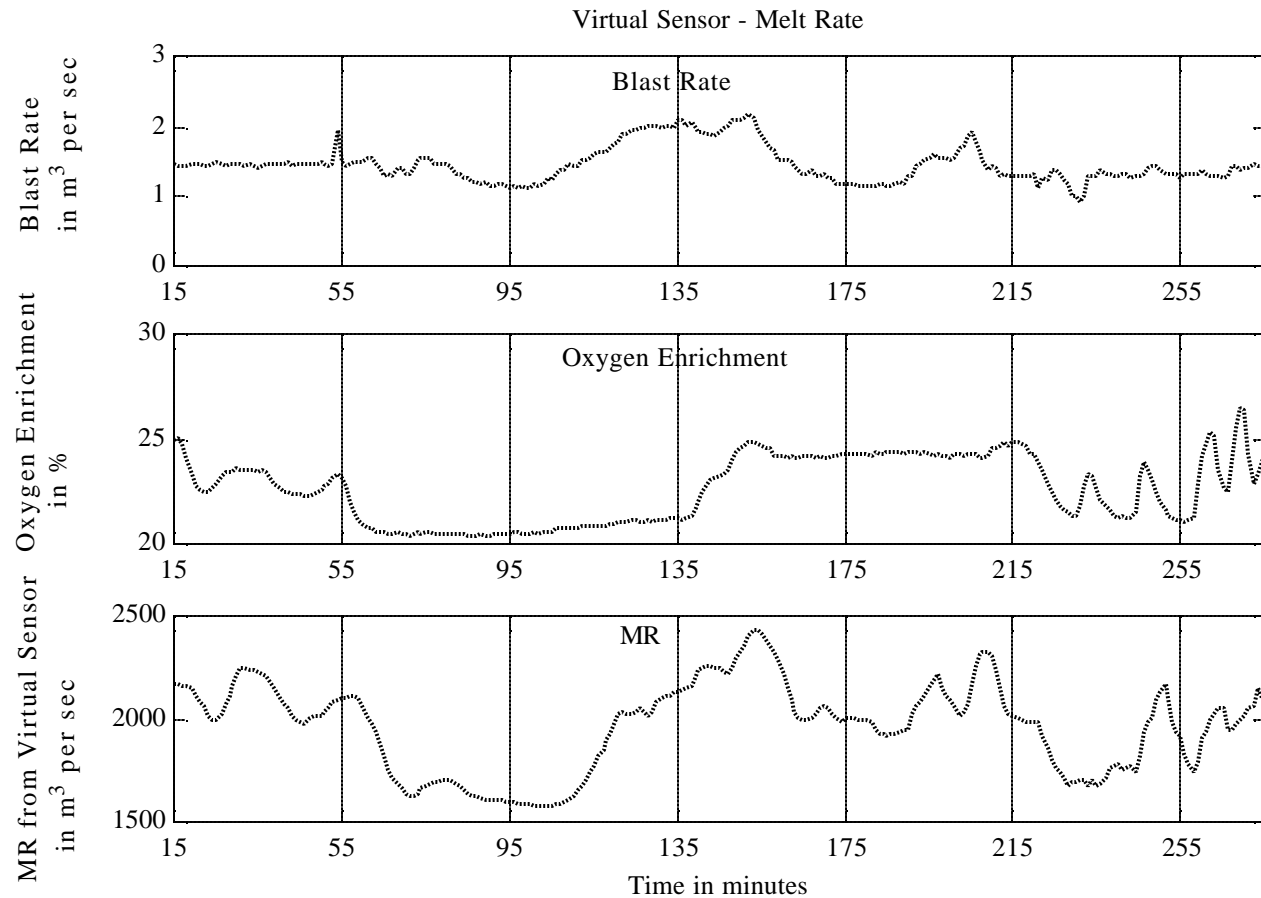


Plot of Sensor Confidences



Simulation and Results...

Melt Rate Virtual Sensor



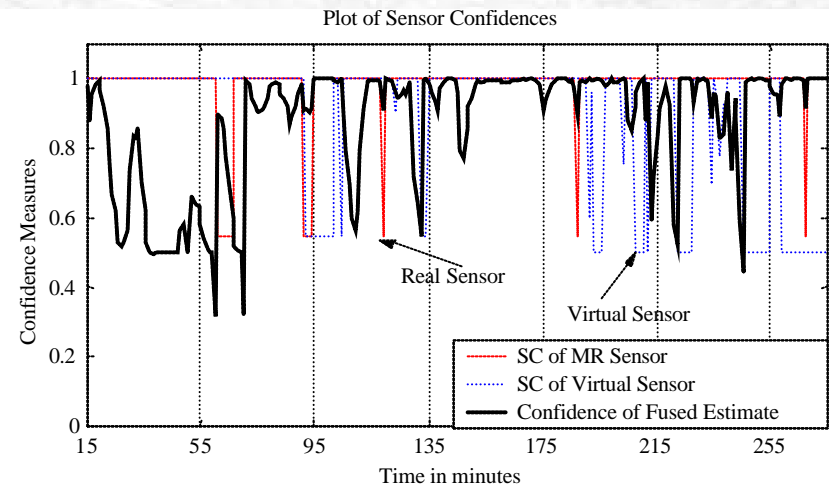
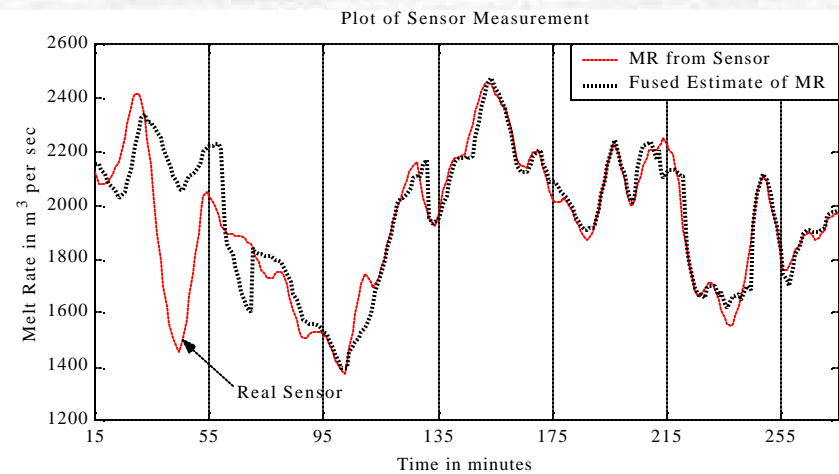
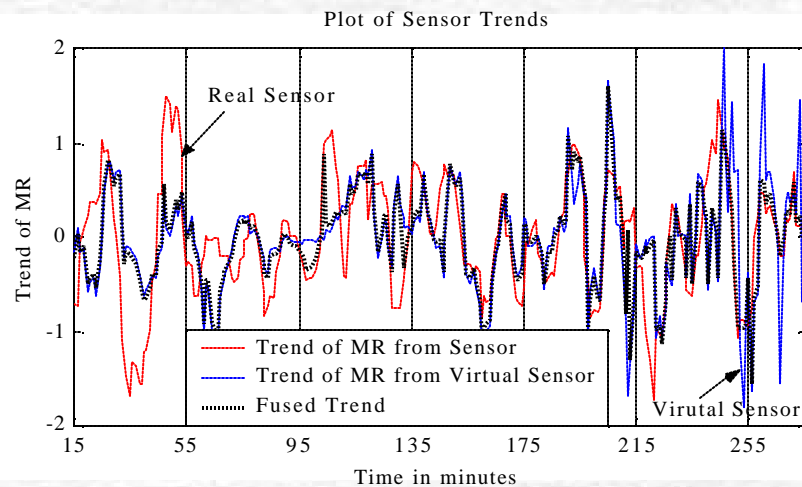
Simulation and Results...

Melt Rate: Case 1

Virtual Sensor as Trend Source

Simulation Parameters:

- TIF = 0.10
- PVC = 0.75
- EVI = 1.5

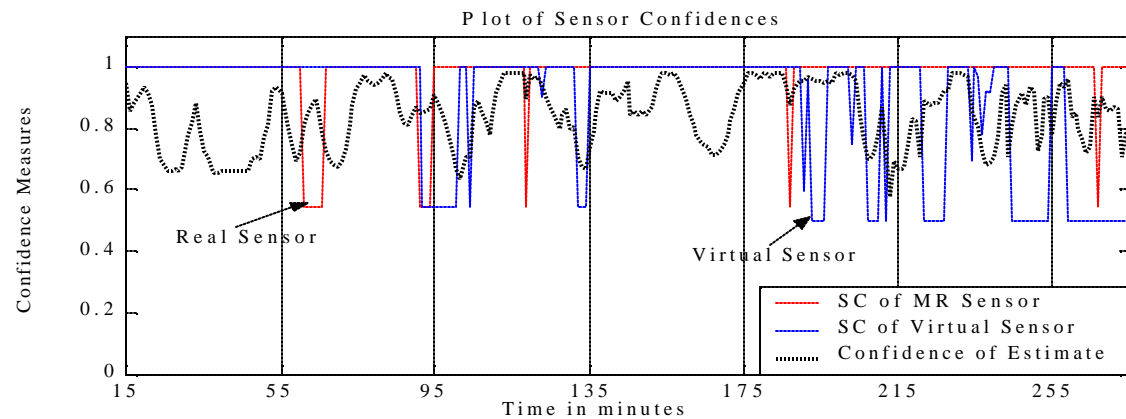
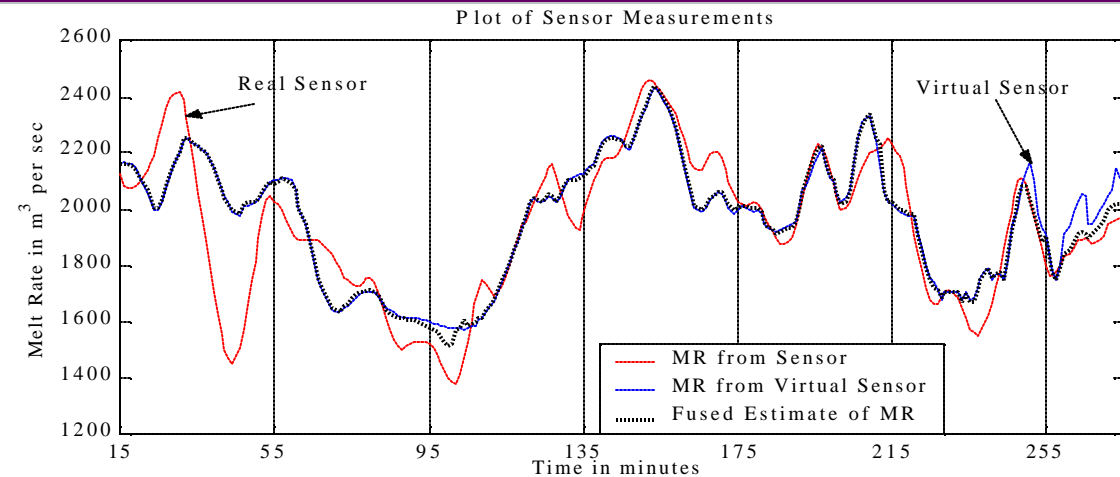


Simulation and Results...

Melt Rate: Case 2 Virtual Sensor as Trend and Value Source

Simulation Parameters:

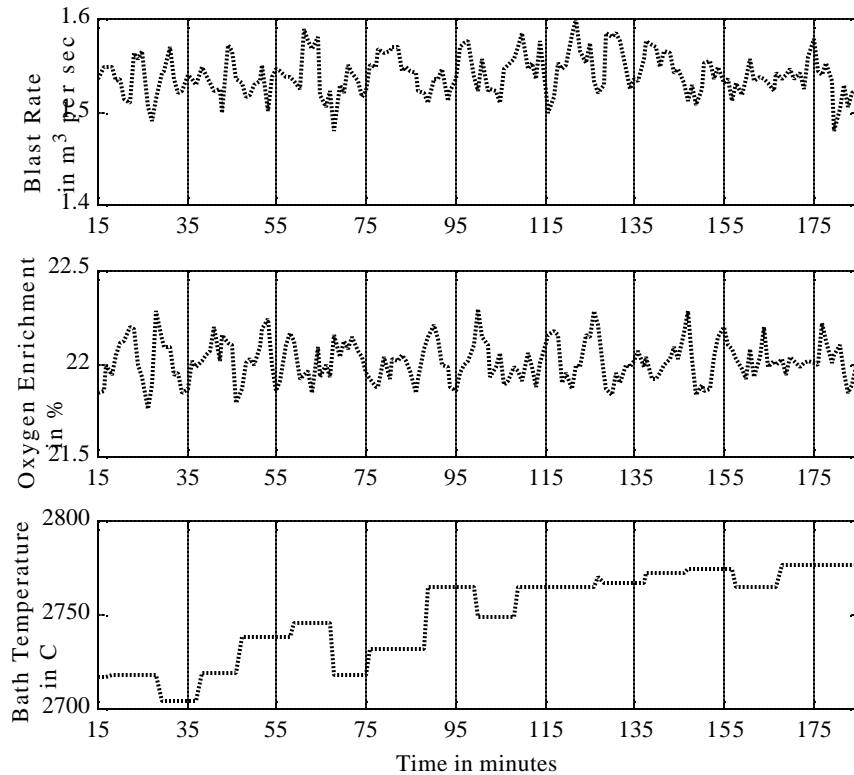
- TIF = 0.25
- PVC = 0
- EVI = 1.5



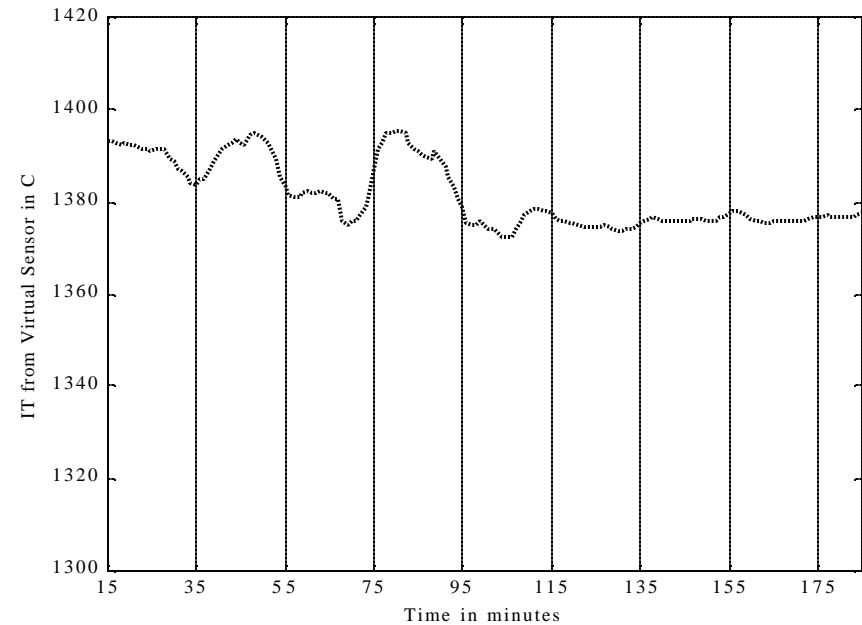
Simulation and Results...

Iron Temperature Virtual Sensor

Input for Iron Temperature ANN



Plot of Iron Temperature from Virtual Sensor

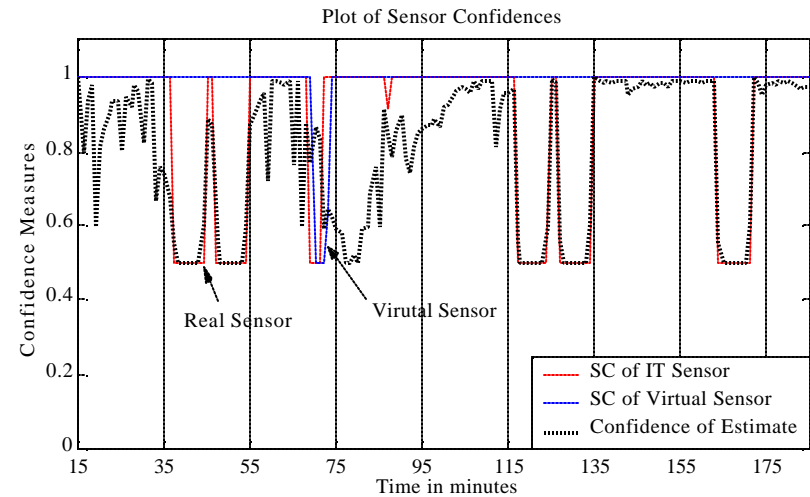
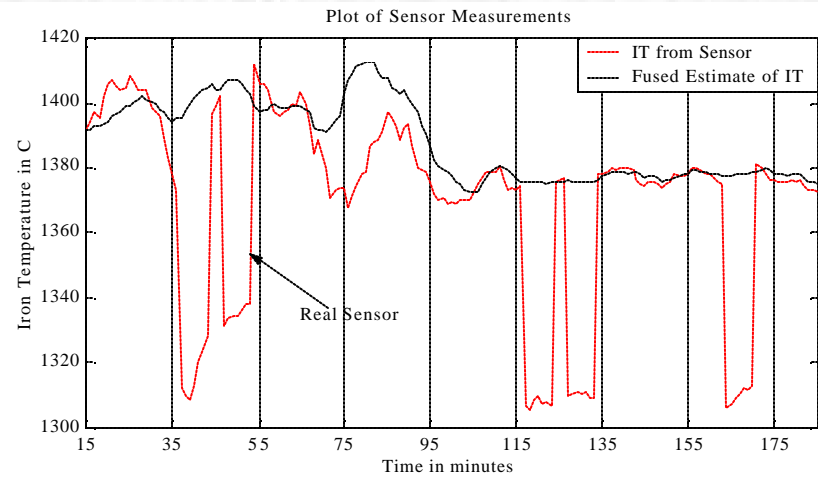
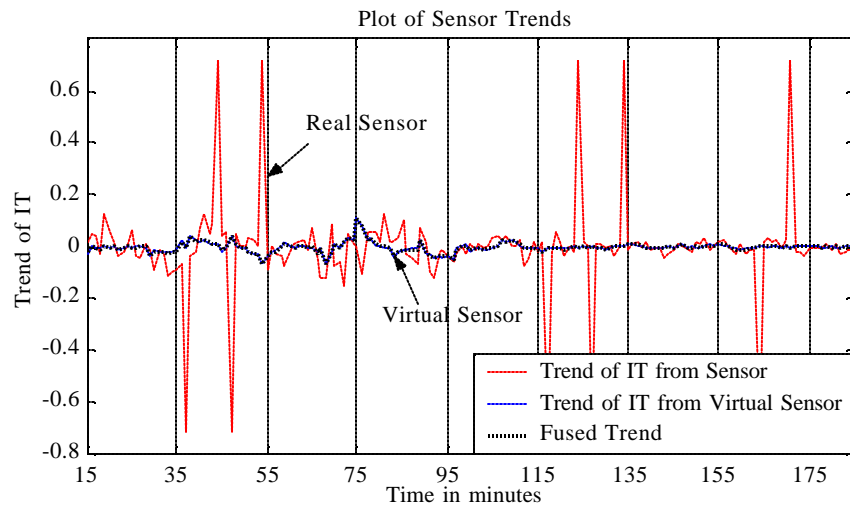


Simulation and Results...

Iron Temperature: Case 1 Virtual Sensor as Trend Source

Simulation Parameters:

- TIF = 0.25
- PVC = 0
- EVI = 1.5

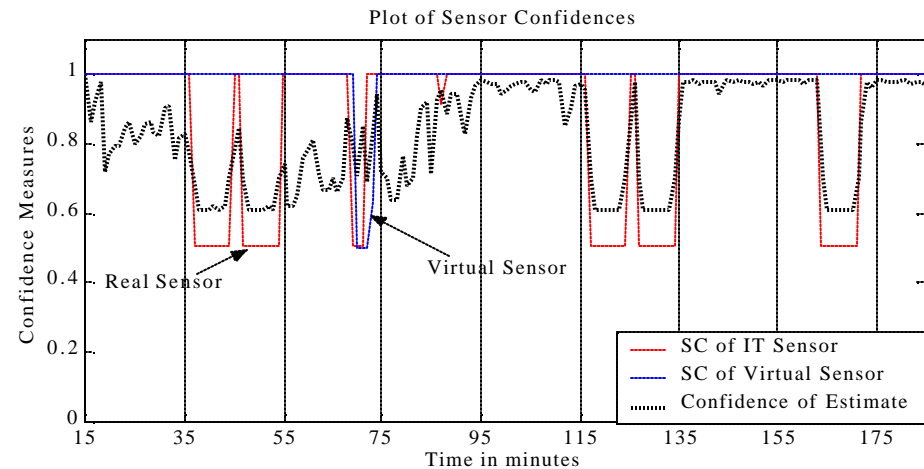
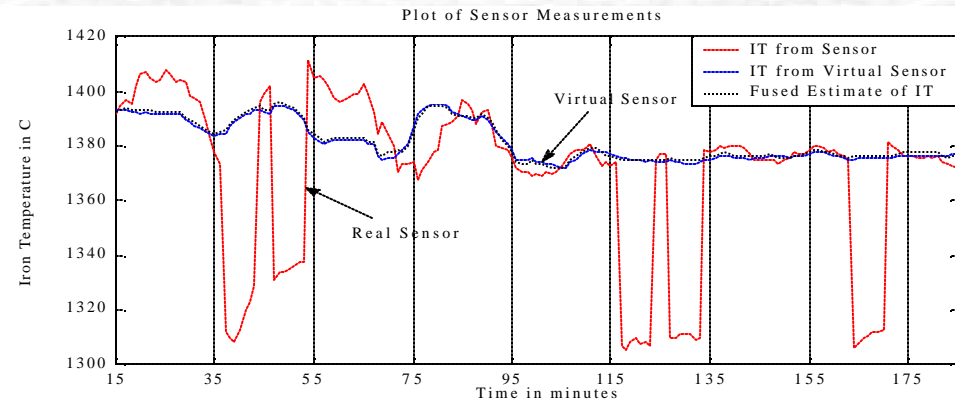


Simulation and Results...

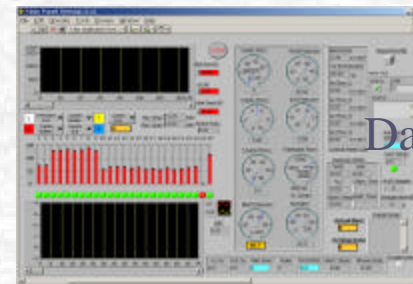
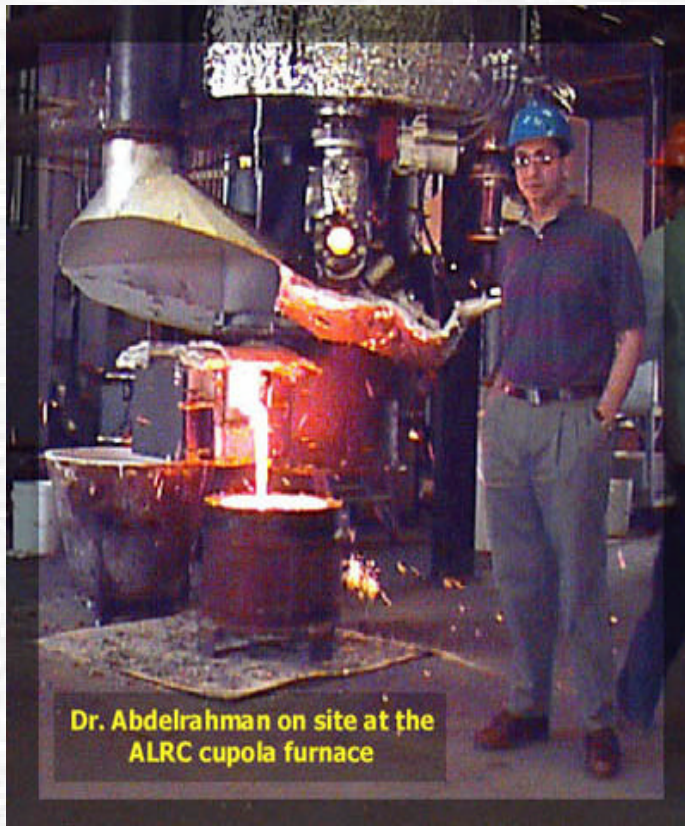
Iron Temperature: Case 2 Virtual Sensor as Value & Trend Source

Simulation Parameters:

- $TIF = 0.25$
- $PVC = 0$
- $EVI = 1.5$

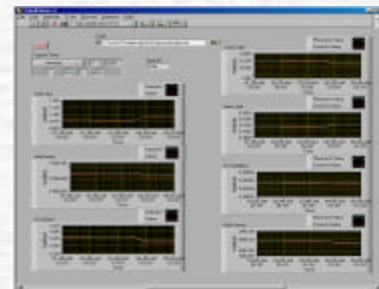


Demonstration Plans



Data Acquisition Software on cupola computer

Ethernet interface



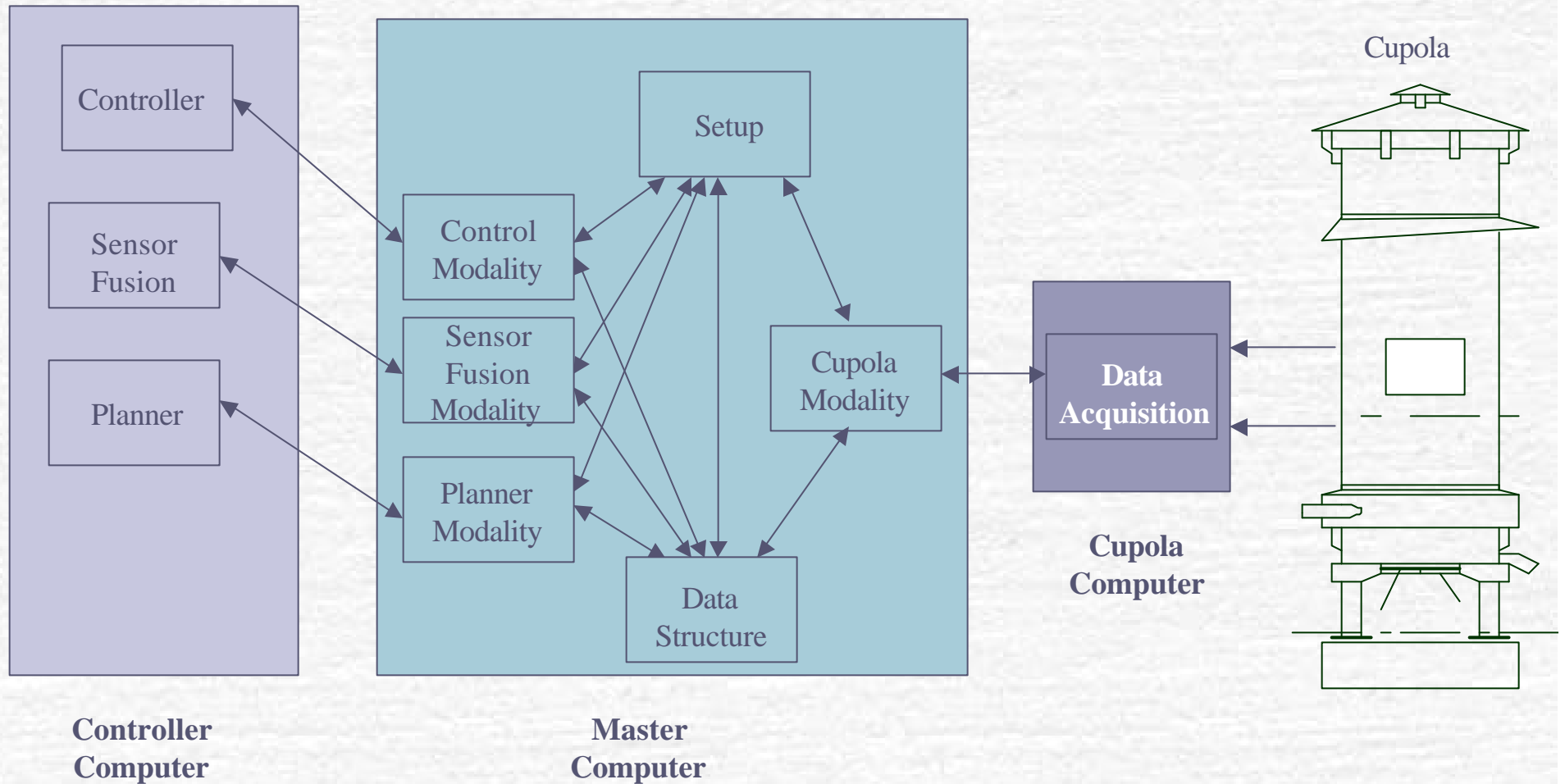
Sensor Fusion, Planner and Controller

Ethernet interface



Data Structure on Master Computer

Computer Architecture for Demo Plans



Demo Plans

- Independent Control of Molten Iron Parameters (Melt rate, Temperature and Iron Composition) under practical situations suggested by Industrial Advisory Board.
- Testing Performance of Virtual Sensors and Fusion Algorithms.

What has been Accomplished So Far?...

- ✔ Interfacing with Computer System in Albany Research Center,
- ✔ Preliminary Planner and Cupola Controller
- ✔ A Pool for Selection of Demonstration Plans in Consultation with Industrial Advisory Board.

What has been Accomplished So Far?

- ❖ A Methodology for Multi Modal Sensor Fusion (Best Estimate, Confidence in the Estimate)
- ❖ A Generic Open Architecture that allows for Easy System maintenance and reconfiguration and Distributed Computing,
- ❖ A Generic Model Interrogator with special focus on AFS Cupola Model (Data Analysis, Expert Rules, Operator Training),
- ❖ GUI for Setup of System Components

Future Work

- ✔ Complete Development of Intelligent Controller
- ✔ Preparation for Demo Plans in September, 2001
- ✔ Continue Testing & Debugging
- ✔ Complete System Integration
- ✔ Marketing the Technology