ETN Global October Workshop 2024

Driving sustainable pathways forward

08-10 October 2024, Stuttgart, Germany

ETN Global

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Woodward Introduction

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Agenda

- Introduction Woodward Inc.

- The impact of a deterministic control system on Gas Turbine Operations

- Q & A

Goal: Provide the participants a better understanding of how control systems can support increasing output, efficiency and uptime of turbomachinery.

Introduction - Woodward Inc

WE'RE THE GLOBAL LEADER FOR ENERGY CONVERSION & CONTROLS

OUR TECHNOLOGIES INCREASE EFFICIENCY, PERFORMANCE AND SUSTAINABILITY FOR CUSTOMERS

AEROSPACE SEGMENT

We're a leader in integrated turbine engine aircraft control and combustion and flight control systems. We're also helping blaze the path for the future of carbon-free commercial flight.

INDUSTRIAL SEGMENT

We help industries achieve the highest levels of reliability and efficiency, making possible everything from processing materials to producing everyday products.

GROWTH OPPORTUNITIES IN MISSILES AND SPACE

Woodward continues to break technological boundaries as we help solve some of the biggest challenges on this planet and beyond.

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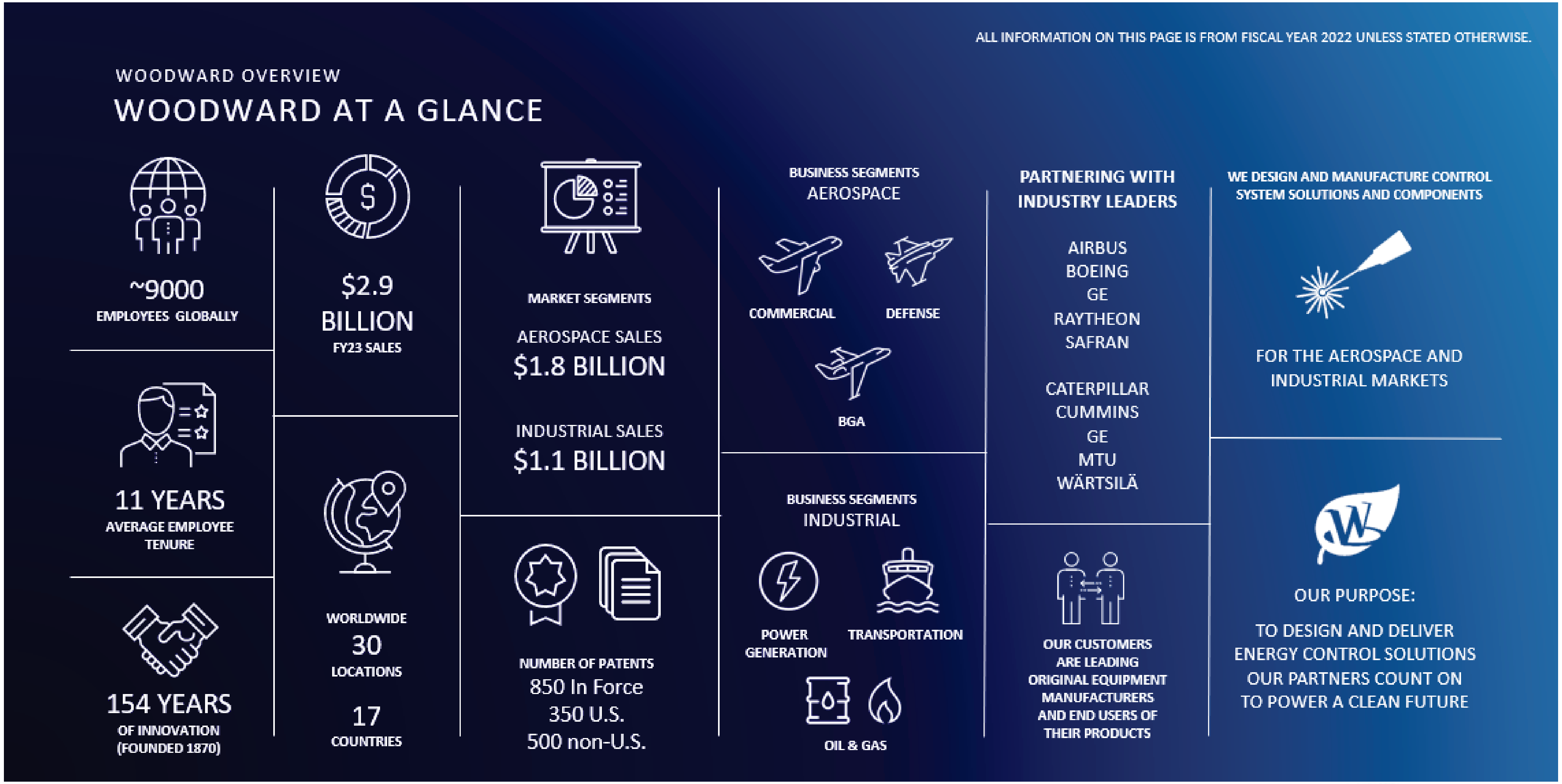
Introduction - Woodward Inc



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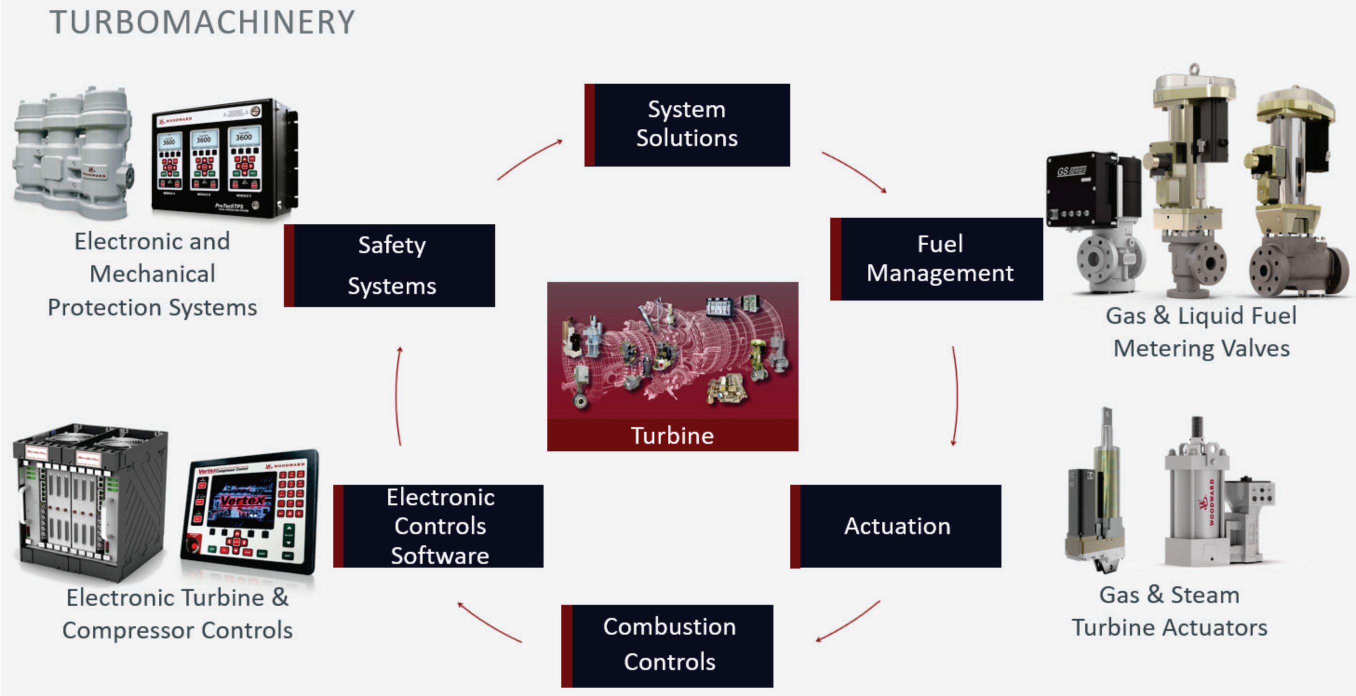
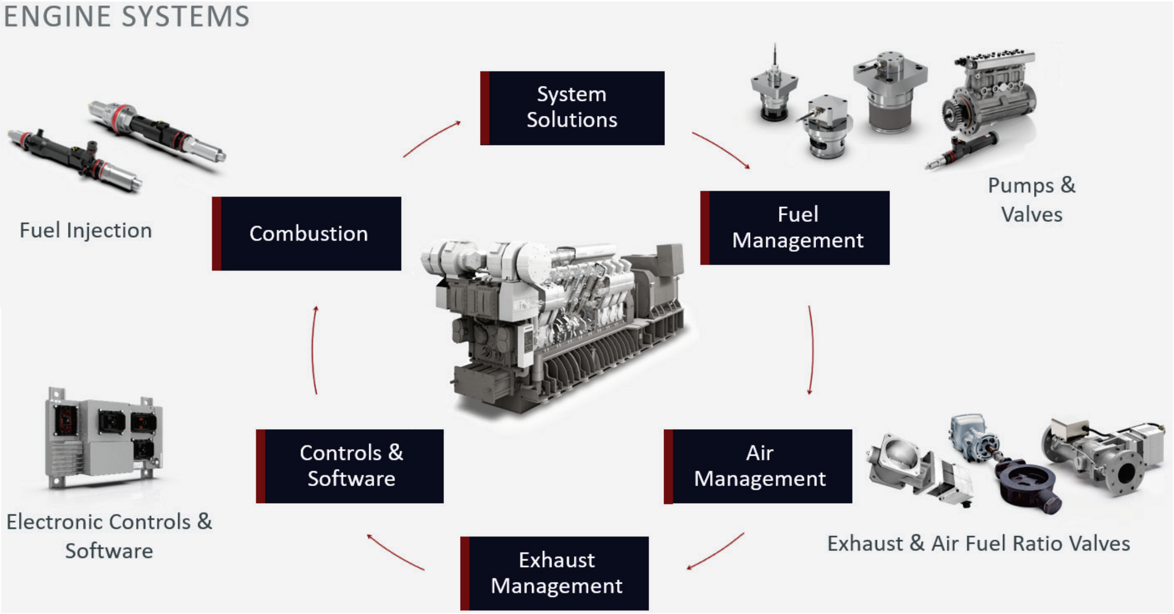
INDUSTRIAL – WHAT WE DO





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SUPPORTING SUSTAINABILITY IN AEROSPACE – ZEROe Airbus Project

Selected by Airbus for balance of plant for ZEROe hydrogen fuel cell demonstrator

ENABLING THE ENERGY TRANSITION – P2X

Future solutions will involve:

- Higher temperatures and pressures
- Higher accuracy air, fuel and combustion controls
- Advanced control algorithms
- Safety, cybersecurity, reliability
- Simulation
- Electrification
- Net-zero fuels

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Impact of deterministic control system behavior versus operational gas turbine cost

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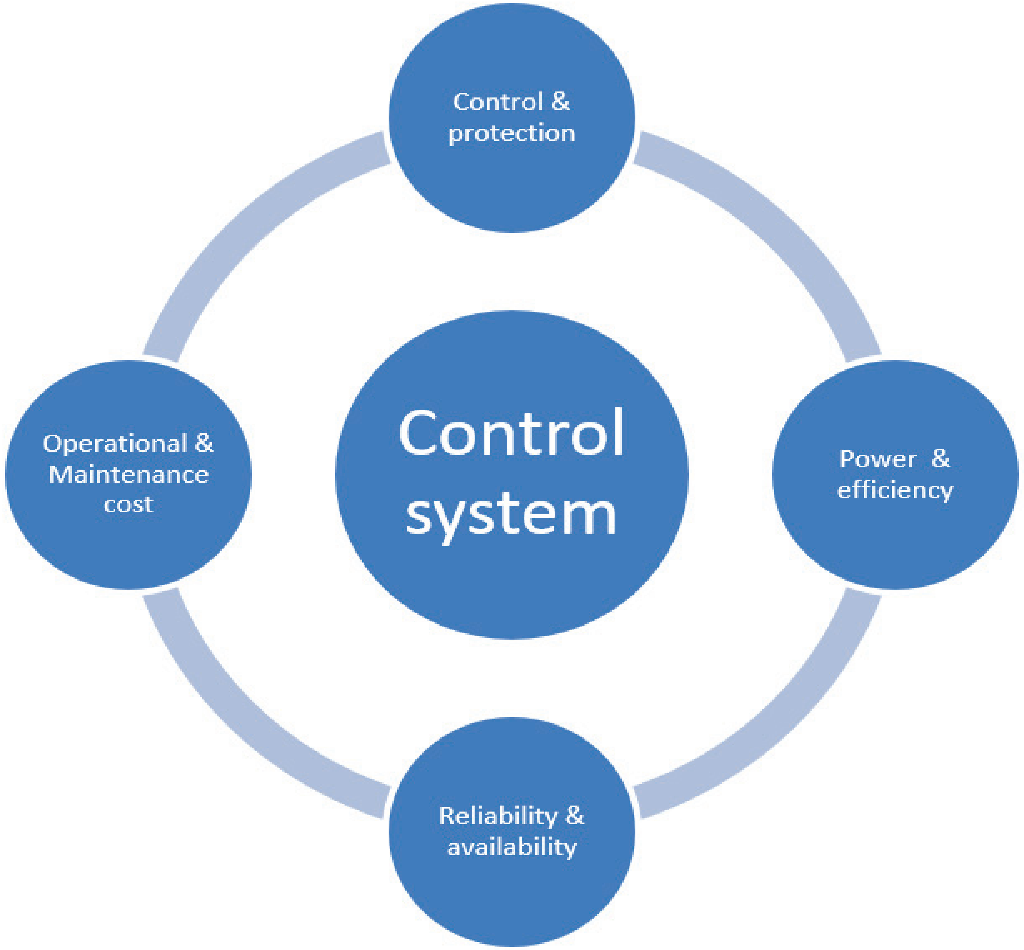
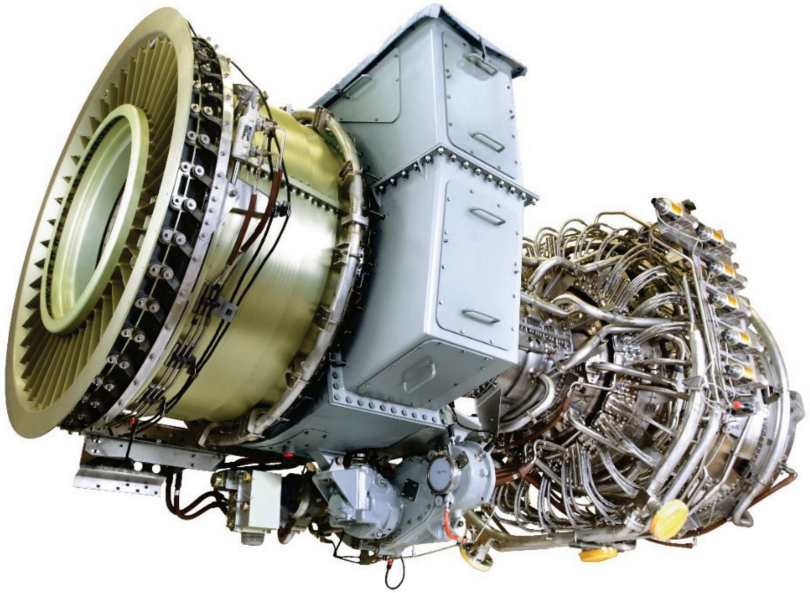
Introduction

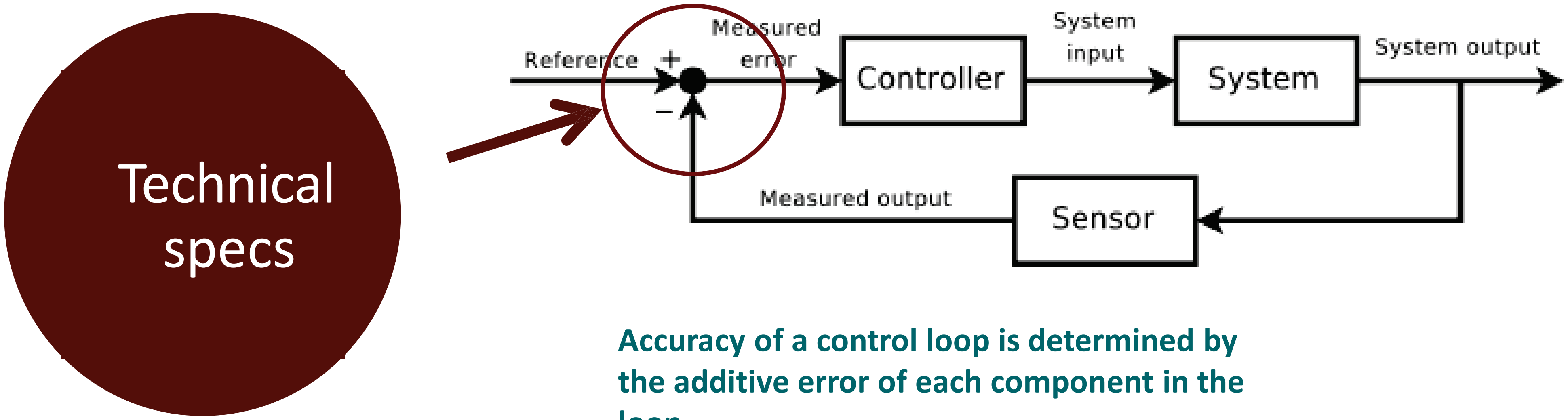




A control system is the heart of each prime mover and has 4 major functions

Control system basics

Definition of a “closed” loop control system :

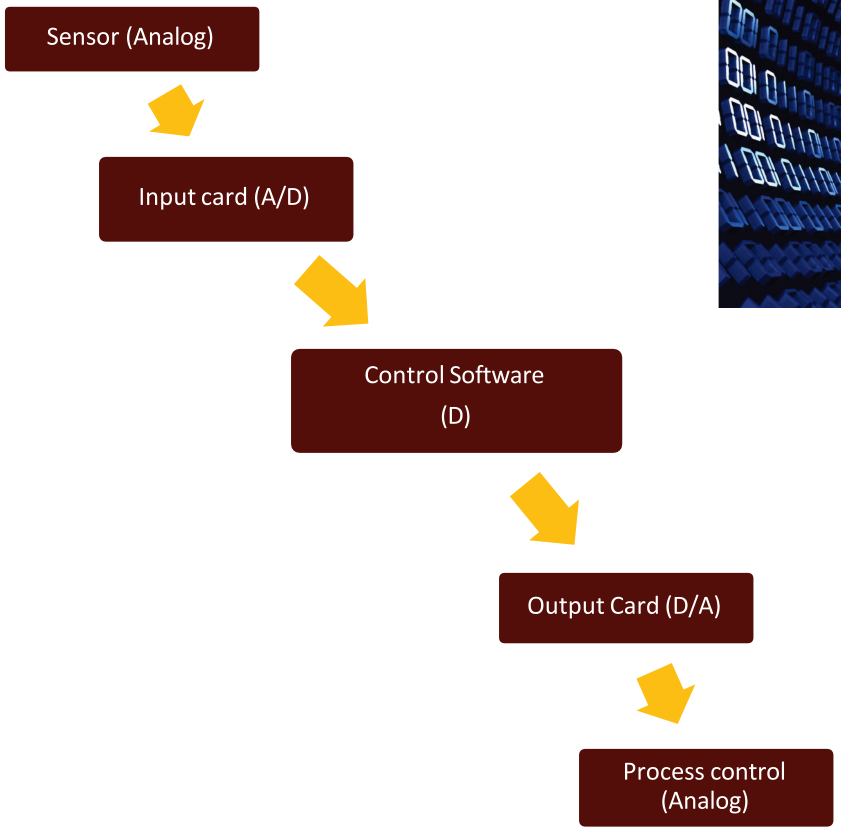


Accuracy of a control loop is determined by the additive error of each component in the loop.

Without accurate measurements

⇨ **No accurate control**

A/D Conversion

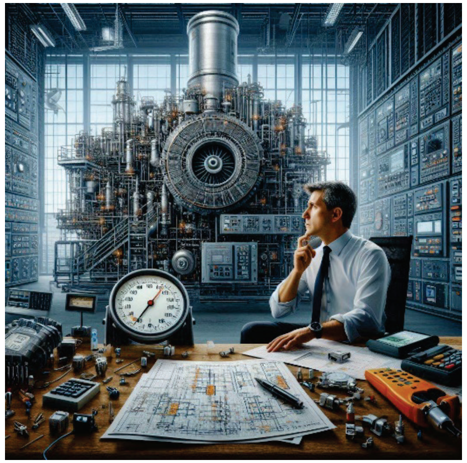


Control systems excel in the digital domain however we will never be able to get rid of the analog part

Analog to digital conversion is a key part of the control system design process

Goal of this presentation

Emphasize the impact of technical specifications on operation cost



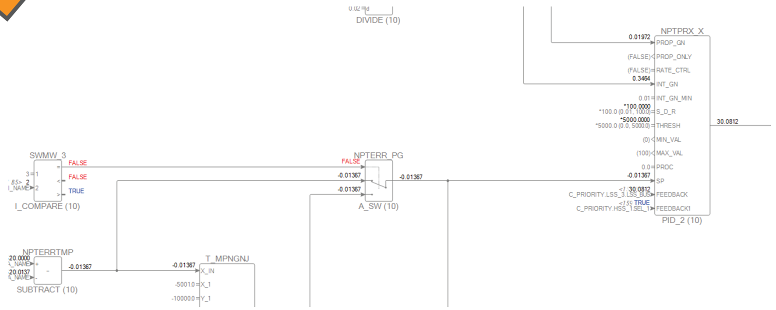
A/D Conversion

Sensor (Analog)

Input card (A/D)

Control Software

(D)



- Well known to everyone
- Low cost impact for manufacturer
- End-user focus

Output Card (D/A)

Process control (Analog)

A/D Conversion

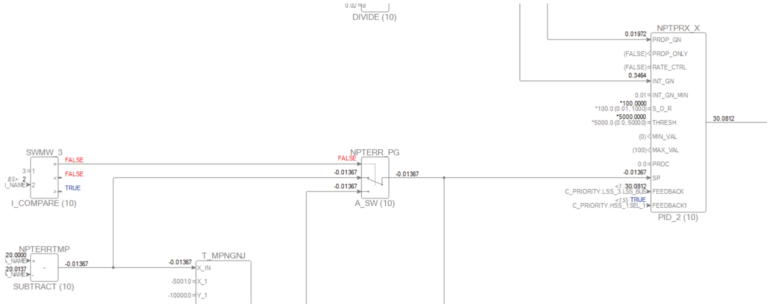
Sensor (Analog)

Input card (A/D)

Technical Specs are Critical

- Often forgotten
- High manufacturing cost impact for vendors
- Little focus from buyers/end-users and/or EPC's
- High impact on operational cost

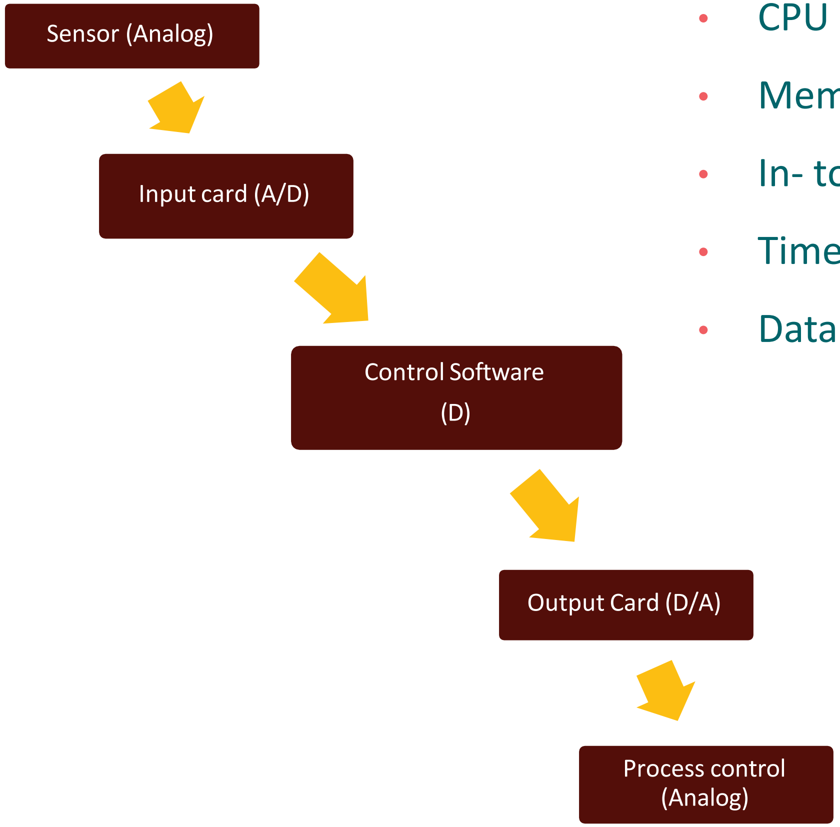
Control Software (D)



Output Card (D/A)

Process control (Analog)

A/D Conversion

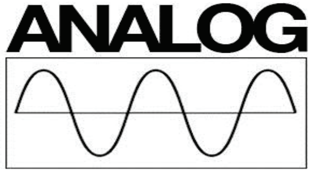


Focus on :

- CPU power
- Memory load
- In- to out processing time
- Time stamping speed / sequence of events
- Datalogging sampling speed

But what about :

- CMRR (Common Mode Rejection Ratio)
- Bit depth
- A/D sampling rate
- Linearity
- Process loop response time



Control Specifications – Gas turbines

Main control parameters/limiters :

- Speed
- EGT (Exhaust gas temperature/power turbine inlet temperature)
- CDT (Compressor discharge temperature)
- CDP (Compressor discharge pressure)

Measure EGT/CDT

↓

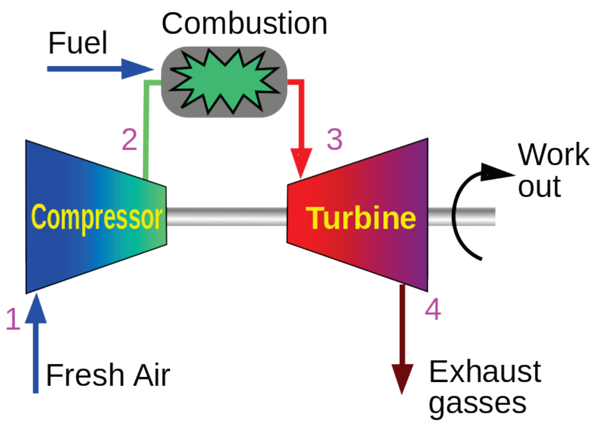
Control/Limit Flame temp

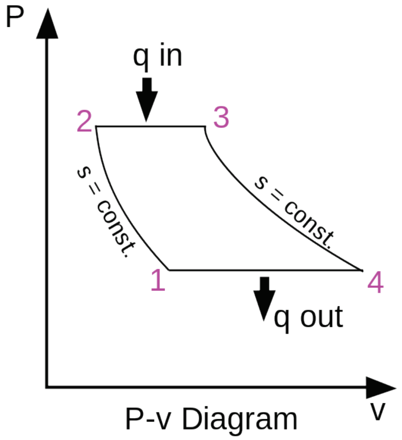
↓

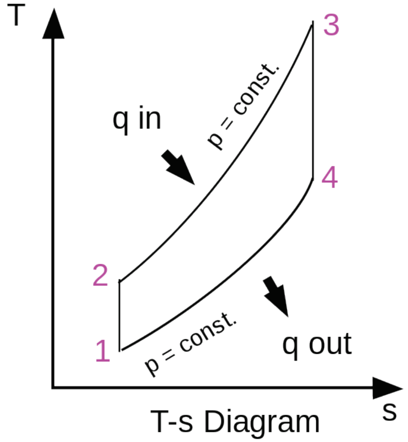
Generate work (MW/heat)

↓

$$







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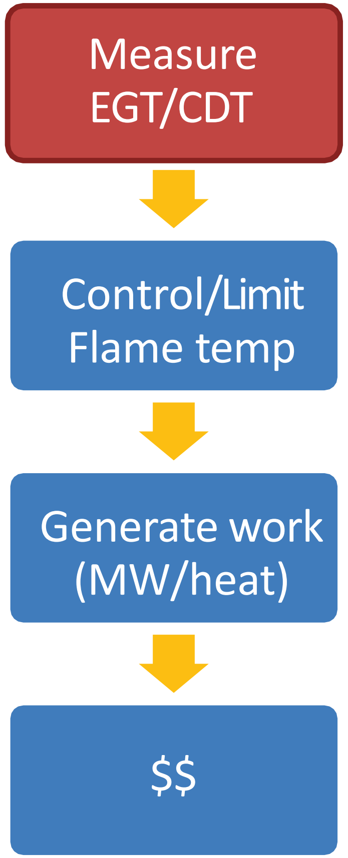
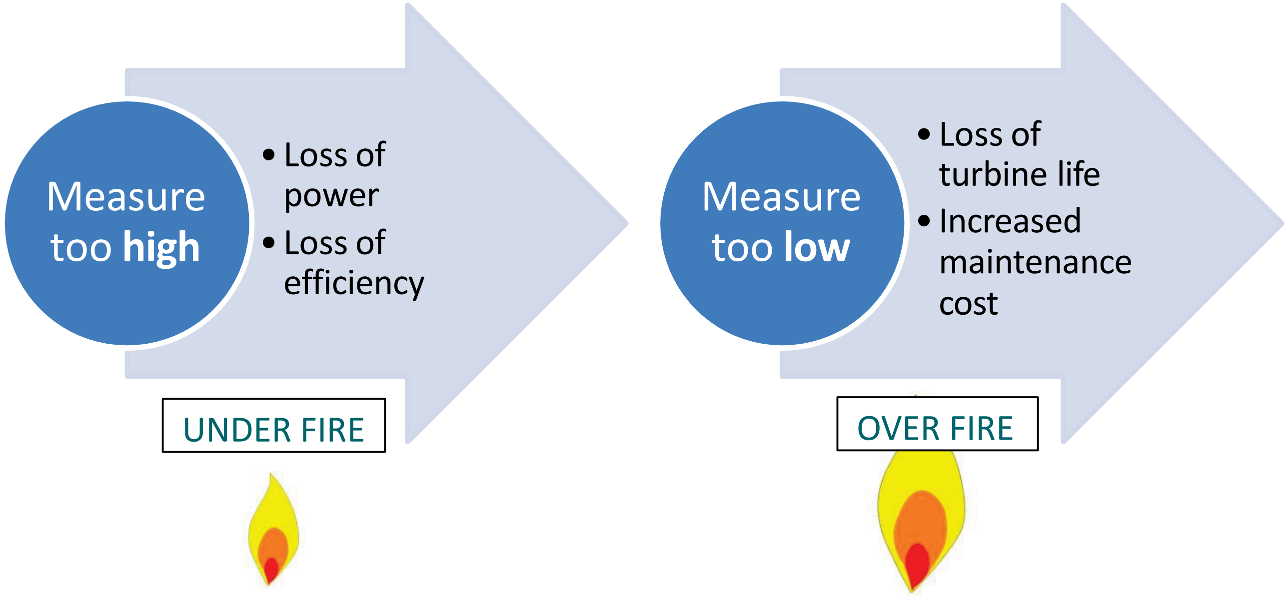
Control Specifications – Gas turbines



Measuring accuracy on temperature has direct impact on :

- Generated power (=$$)
- Turbine life (=Maintenance=$$)
- Emissions(For DLE engines) (=$$)



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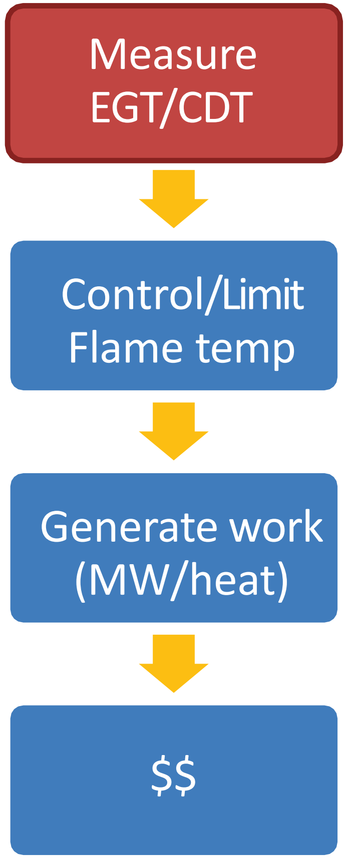
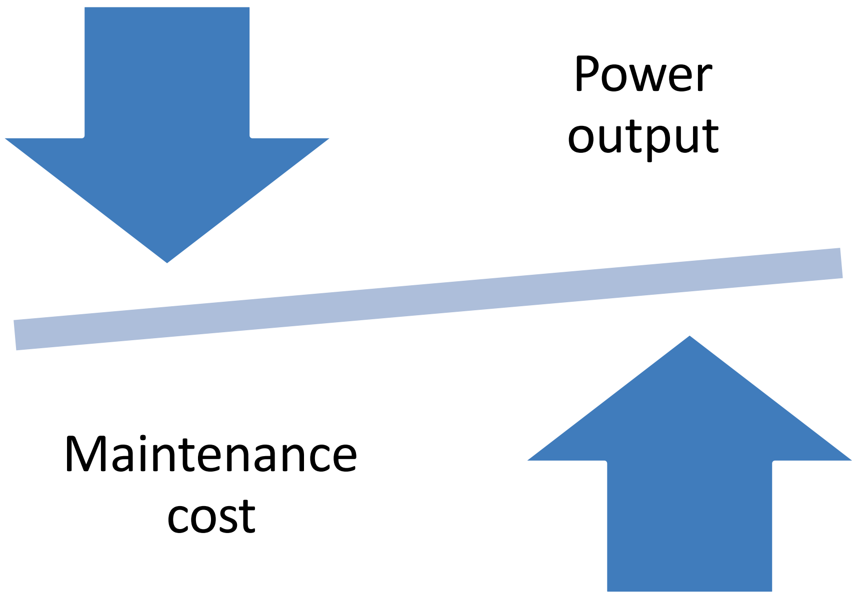
Control Specifications – Gas turbines



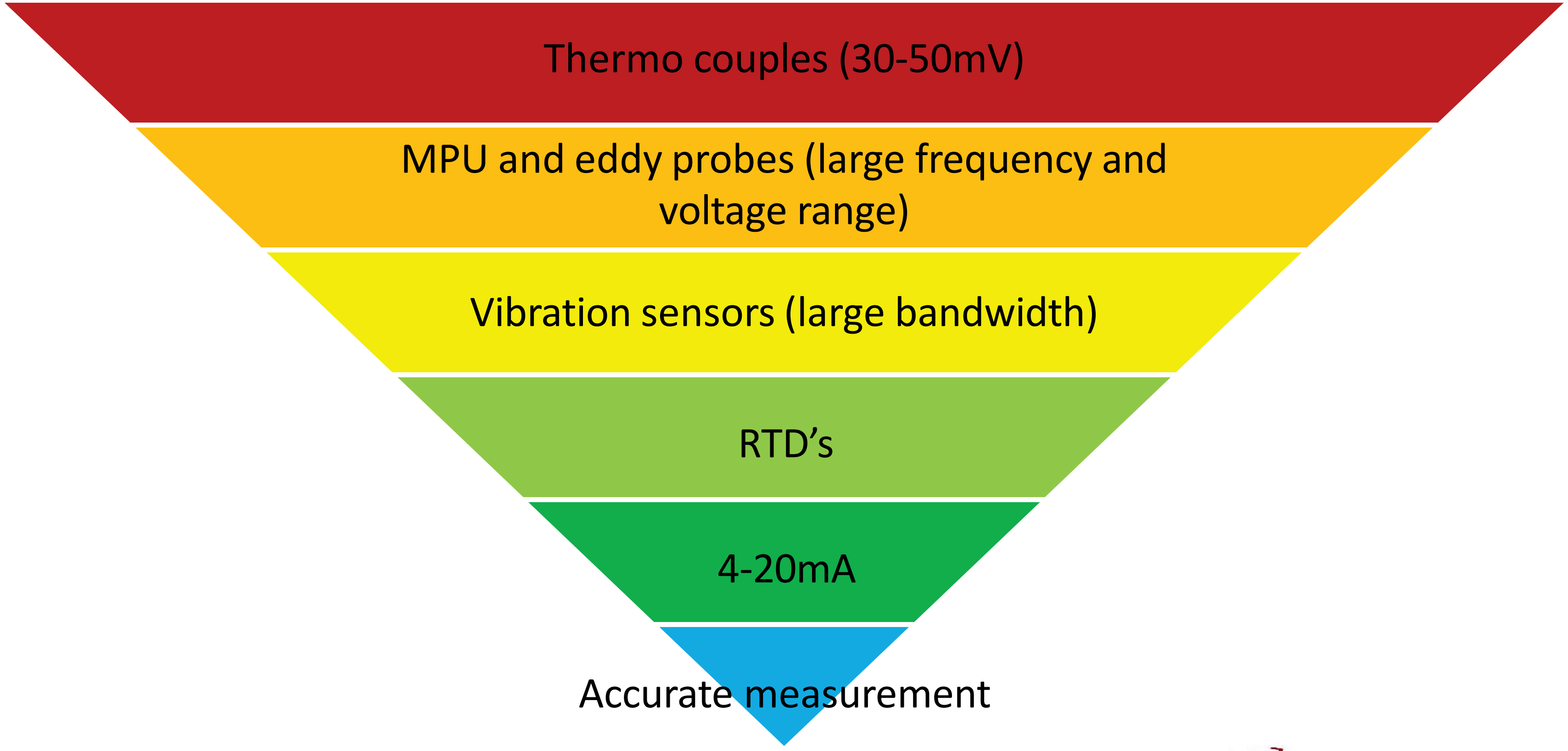
Measuring accuracy on temperature = Best cost efficiency

run GT at design point

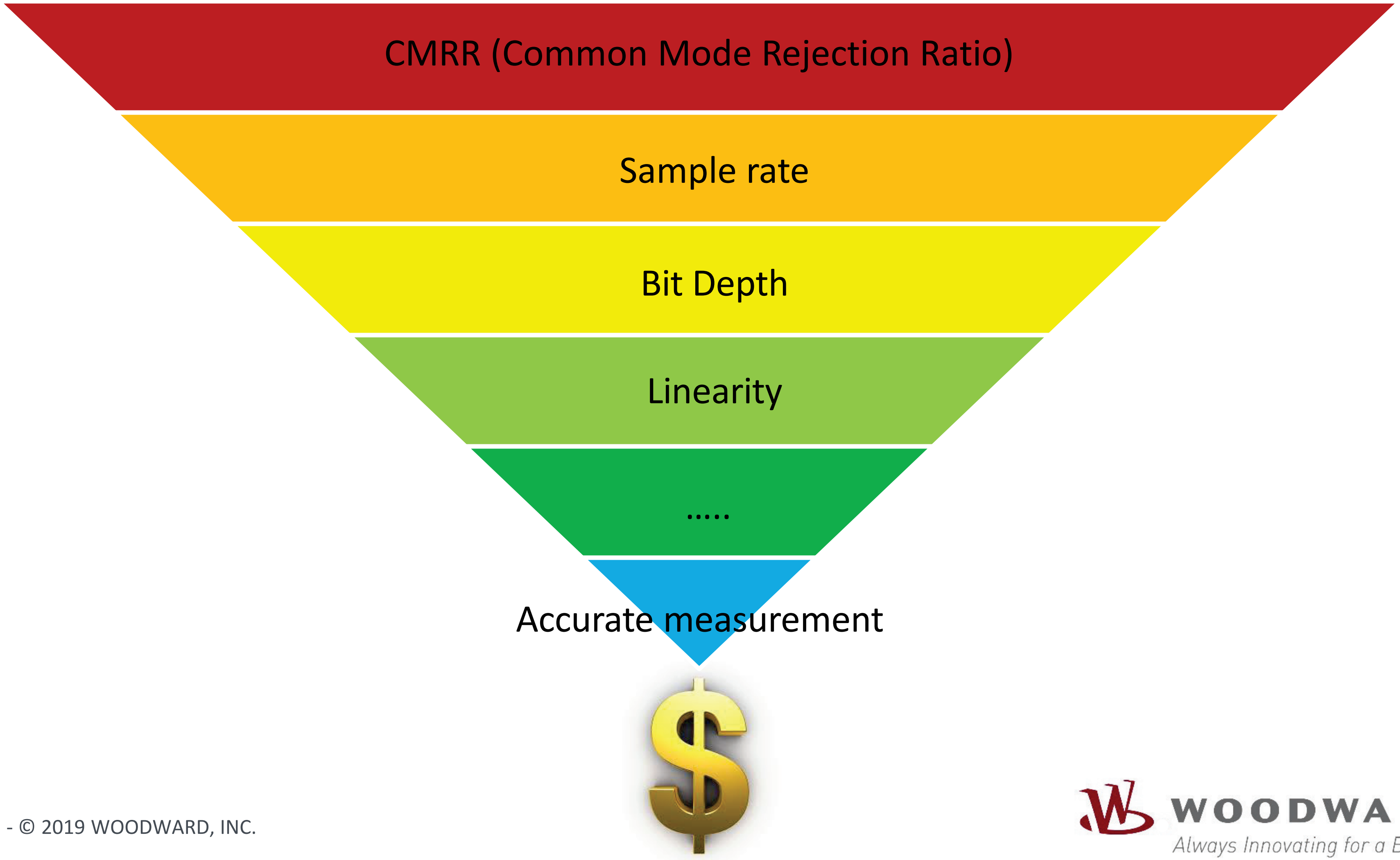


Complexity funnel / Measurement type

Voltage measurements are sensitive in industrial environments.
High quality specs needed for accurate measuring (EMI, shielding, twisted pairs, etc)



Complexity funnel / Measurement type



Control Specifications – CMRR

What is CMRR ?

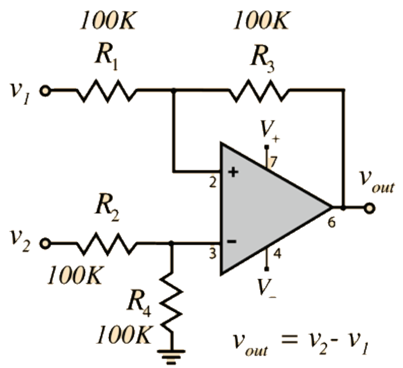
Majority of accurate input signal modules/cards are based on a differential amplifier principle (floating power supply principle)

GOAL :

AMPLIFY the differences of inputs and REJECT the common signals(like noise, EMI induced currents and voltages)

CMRR = Electronical able to reject the common signals (expressed in dB), ratio = Adm(differential mode gain) / Acm (common mode gain)

CMRR dB = 20 log 10 Adm/Acm



Adm = Differential mode voltage gain

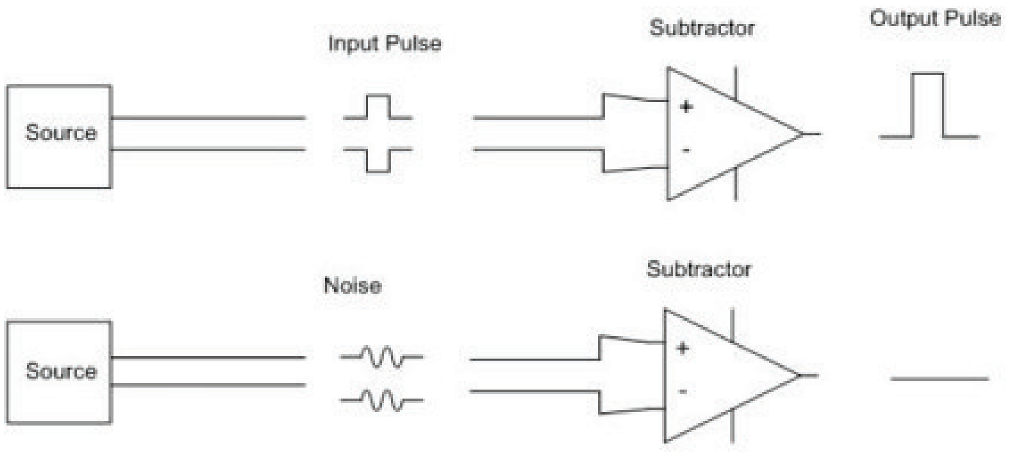
Acm = Common mode voltage gain

Ideal CMRR = infinite dB

(Adm, very high, Acm, close to 0)

Reality Acm < 1

CMRR(dB) = 20 log10 CMRR		
CMRR		CMRR dB
10	-->	20 dB
100	-->	40 dB
1000	-->	60 dB
10000	-->	80 dB
100000	-->	100 dB
1000000	-->	120 dB
10000000	-->	140 dB



Control Specifications – CMRR

What is CMRR and why is it so important ?

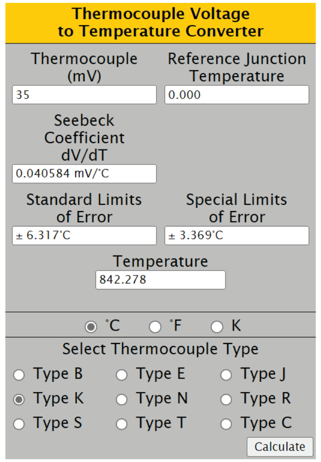
Majority of accurate input signal modules/cards are based on a differential amplifier principle (floating power supply principle)

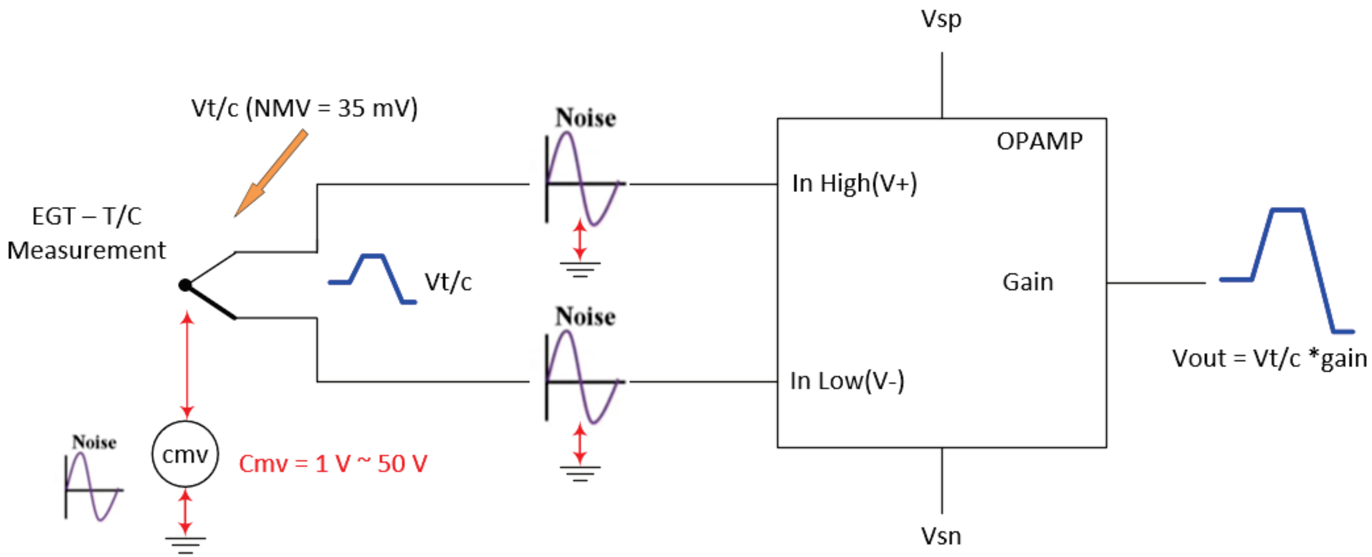
EXAMPLE :

NMV=35mV (~842.2 dgr.C, Fluke T/C converter, https://us.flukecal.com/Thermocouple-Temperature-Calculator)

EGT T/C measurement

Common mode rejected





Floating input measurement

Floating system

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Control Specifications – CMRR

What is CMRR and why is it so important ?

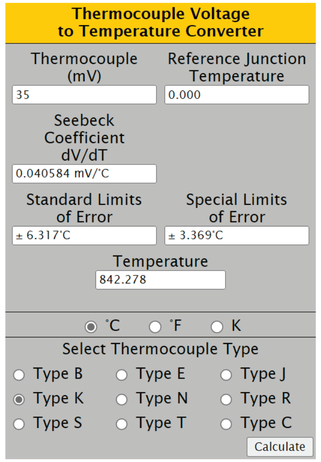
Majority of accurate input signal modules/cards are based on a differential amplifier principle (floating power supply principle)

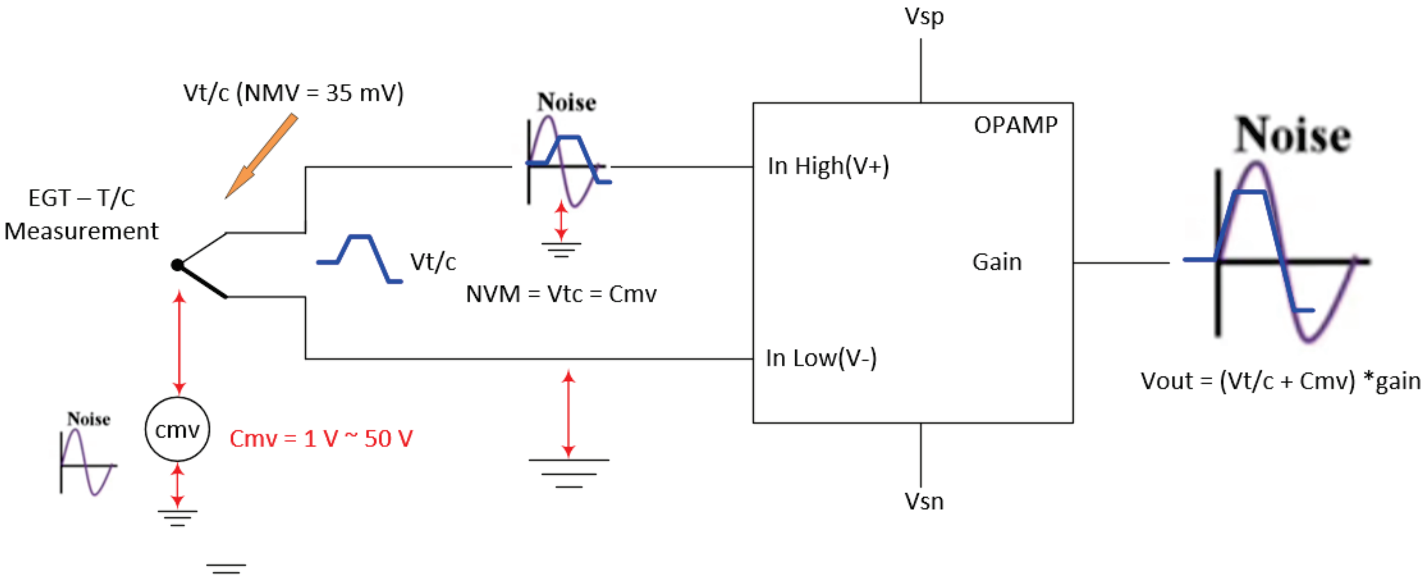
EXAMPLE :

NMV=35mV

EGT T/C measurement

Common mode amplified and extrapolated on measurement





Non-Floating(grounding issues)
input measurement = inaccuracy

Grounded system

Control Specifications – CMRR

What is CMRR and why is it so important ?

- In the example we are amplifying a sensitive T/C measurement (Which is in mV's) in an EMI harsh environment
- Common mode signal up to 50V can be expected in industrial and high voltage environment
- Main goal is to amplify only the measured mV's (NMV) and not the common mode voltages.

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Control Specifications – CMRR (GT example)

What is CMRR and why is it so important ? Case #1

- High difference between control systems/PLC's : CMRR between 60dB up to 140 dB.

Example 1:
NMV = **35mVDc** (EGT thermocouple)
Amplifier gain = 1
CMV = 7 V (very common)
CMRR = **80dB**

80dB = 20 log (CMV in / CMV out)
80dB = 20 log (7Vdc / CMV out)
4 = log (7Vdc / CMV out)
10000 = 7 Vdc / CMV out
CMV = 0.7 mV

Result: 35mVdc + 0.7 mV

→ **2 % inaccuracy (80dB)**

Example 2:
NMV = **35mVDc** (EGT thermocouple)
Amplifier gain = 1
CMV = 7 V (very common)
CMRR = **100dB**

100dB = 20 log (CMV in / CMV out)
100dB = 20 log (7Vdc / CMV out)
5 = log (7Vdc / CMV out)
100000 = 7 Vdc / CMV out
CMV = 0.07 mV

Result: 35mVdc + 0.07 mV

→ **0.2 % inaccuracy (100dB)**

Control Specifications – CMRR (GT example)

What is CMRR and why is it so important ? Case #1

- High difference between control systems/PLC's : CMRR between 60dB up to 140dB.

Example 1:
CMRR = **80dB**
→ **2 % inaccuracy (80dB)**

T48 Temp. limiter (LM6000PC, S50TF330 S7.4.0)
Max temp = 1600 dgr.F (871.1 dgr.C)

- **- 2 % inaccuracy results in 1632 dgr.F (888.8 dgr.C)**
- **+ 2 % inaccuracy results in 1568 dgr.F (853.3 dgr.C**

Example 2:
CMRR = **100dB**
→ **0.2 % inaccuracy (100dB)**

T48 Temp. limiter (LM6000PC, S50TF330 S7.4.0)
Max temp = 1600 dgr.F (871.1 dgr.C)

- **- 0.2 % inaccuracy results in 1603.2 dgr.F (872.8 dgr.C)**
- **+ 0.2 % inaccuracy results in 1596.8 dgr.F (869.3 dgr.C**

TEMP is directly linked to MW

32 dgr.F too low can lead to loss of :
> 3.5 MW

3.6 dgr.F too low can lead to loss of :
~ 0.1 MW

Note: depends on ambient conditions and several other GT parameters.
Data taken from a LM6000PC Sprint (T2=59 dgr.F, 15 dgr.C)

Control Specifications – CMRR (GT example)

What is CMRR and why is it so important ? Case #1, T48 measured too high.

- High difference between control systems/PLC’s : CMRR between 60dB up to 140 dB.

Example 1:
CMRR = 60-80dB
→ **2 - 5 % inaccuracy**

Example 2:
CMRR = **100-140dB**
→ **0.02 - 0.2 % inaccuracy**

Unit runs 365/year, 24/7 Power Generation

Control Specifications – CMRR (GT example)

What is CMRR and why is it so important ? Case #1, T48 measured too low.

Unit runs 365/year, 24/7 Power Generation

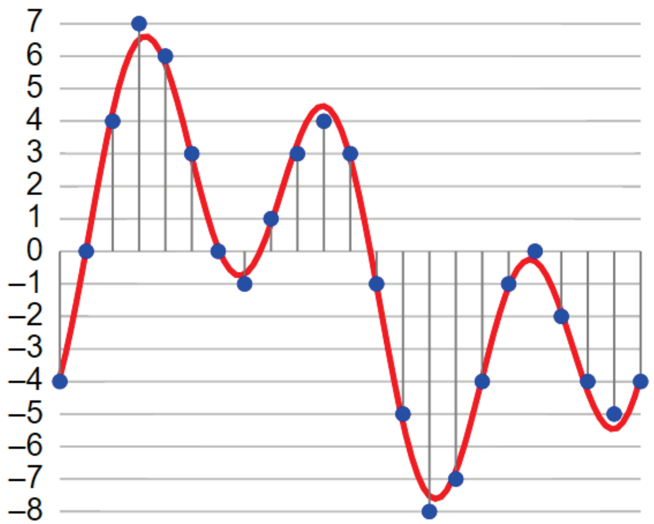
Running T4.8 32 dgr.F higher as expected will cause hot section damage and could lead to major maintenance costs

Control Specifications – Bit Depth

What is bit depth?

The number of bits used to represent the information in a sample is known as the bit depth or resolution.

The bit depth determines the number of possible values that can be assigned to each sample, and therefore affects the accuracy and fidelity of the digital representation of the analog signal. For example, a 16-bit depth allows for 65,536 possible values, while a 24-bit depth allows for over 16 million possible values. Higher bit depths typically result in higher quality sampling, but also require more storage space and processing power.



Example : Analog I/O card with Full scale input differential range of -5 Vdc to + 5 Vdc.

Bit Depth – 4 Bits
Sample dissection – 16 slices
Dead band of 0.625V
Accuracy – 6.25%

Lube Oil Temperature
Combustion Control
Speed Control

Bit Depth – 16 Bits
Sample dissection – 65536 slices
Dead Band of 0.0001525V
Accuracy – 0.00152%

Combustion Control
Speed Control

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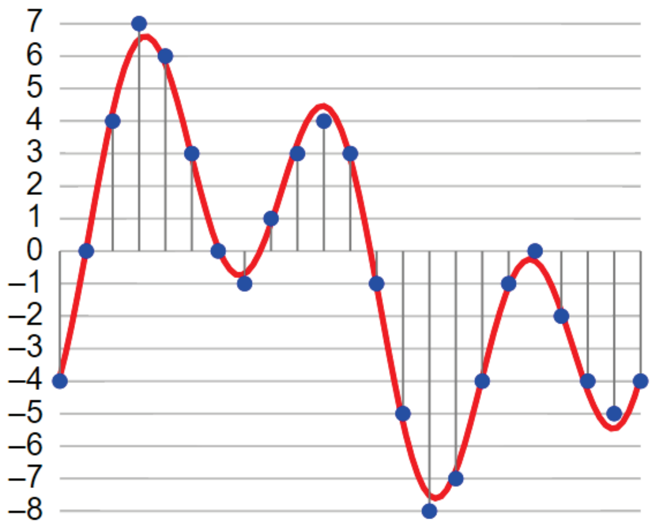
Control Specifications – Sampling Rate

What is sampling rate ?

The number of samples used to represent the information in a digital format, expressed in samples/sec or Hertz.

Typical sampling rate on control systems/plc is in the rang of 4 to 300 Hz.



How would that relate to ?

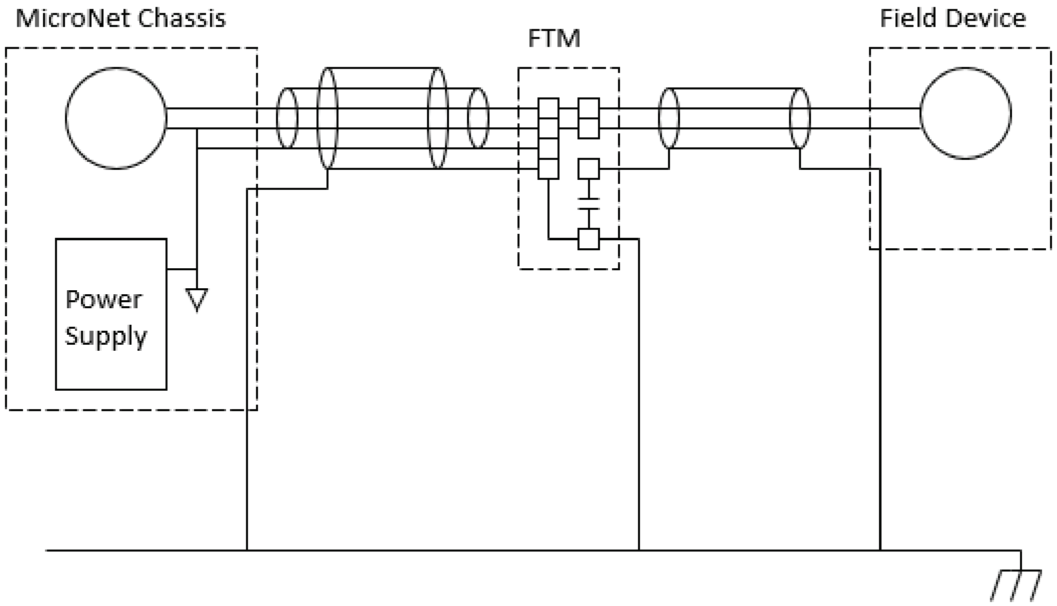
- Stall detection
- Speed control
- Temperature control
- Does the software processing time matches with the I/O time?

Control Specifications – Comparison

	PLC	MOST CONTROLS	DCS SYSTEMS	DEDICATED HIGH END CONTROLS
CMRR	60dB	80dB	90-130 dB	140dB
BIT DEPTH	12 Bits	16 Bits	16 Bits	16 Bits / 20 Bits
SAMPLE RATE	4Hz	120Hz	10 Hz	200Hz (5ms)

When selecting an automation system for specific prime mover, the technical specifications of I/O cards should be considered keeping the basic principle of the control loops in mind.

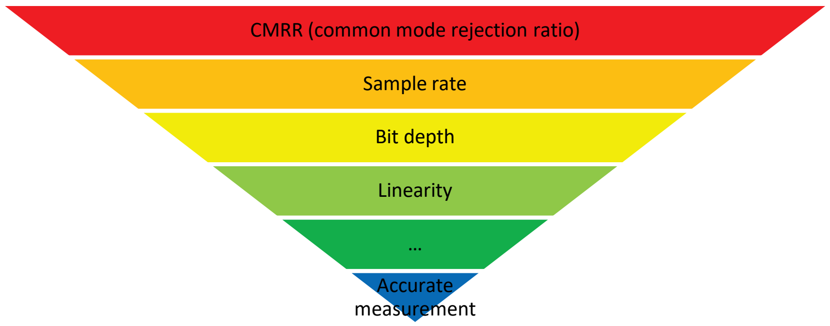
Control Specifications – Grounding/Shielding



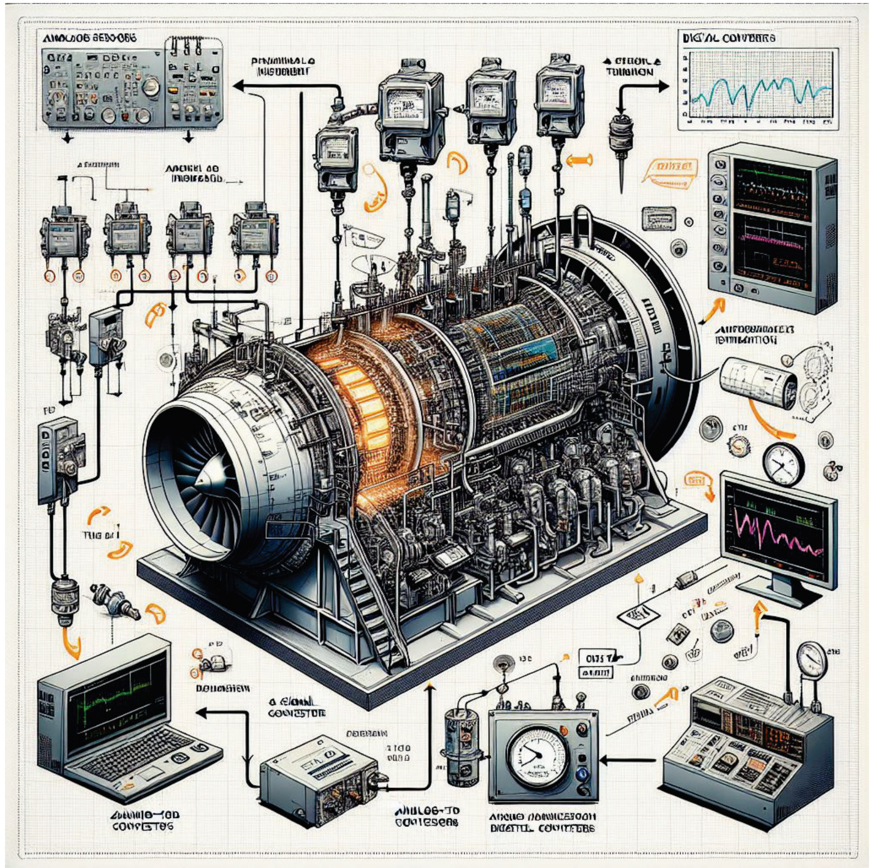
- Keep sensitive I/O cables separate from noisy power wires to the control or to other devices
- Separate incoming power wires from 24VDC to control
- Use suppressors on all inductive devices (relays, pumps, motors, etc.)
- Keep shield terminations as short as possible (1” is barely acceptable, ½” is better) - 1” of shield termination acts like 10 ohms at 60 MHz.
- Solder sleeves cause reflections. For best shielding, terminate shield itself, not an added wire.

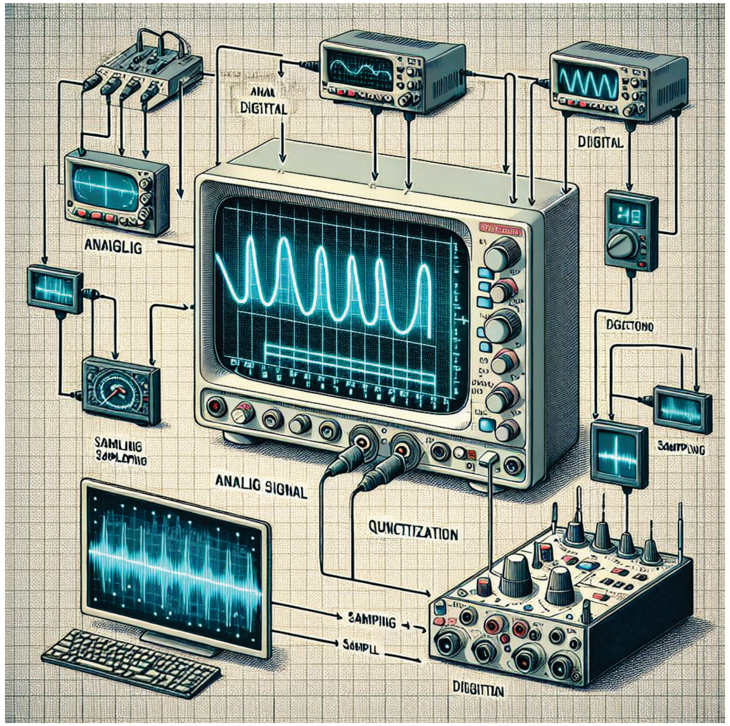
Control Specifications – Conclusions

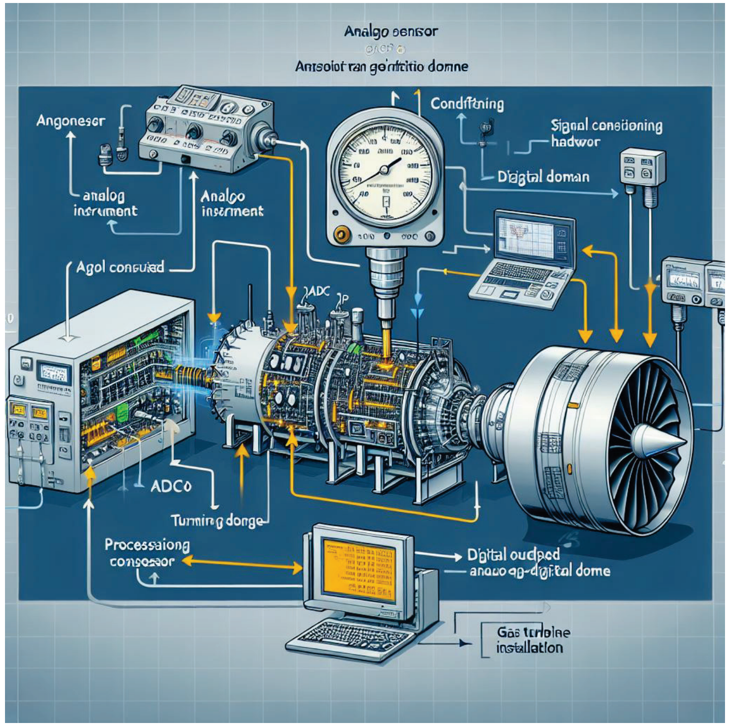
- Technical specifications of control systems have a crucial impact on the controlled process!
- Not only control algorithms but also control hardware has direct impact on operational cost
- Input card specifications (A/D) are often forgotten, yet critical
- Accurate measuring is key to protect and maximize efficiency of your rotating equipment
- Control systems have tremendous impact on reliability and availability
- There is a substantial difference between a PLC, DCS and a dedicated control system
- Proper grounding/shielding philosophy decreases risk of EMI



Control Specifications – Analog to Digital Domain







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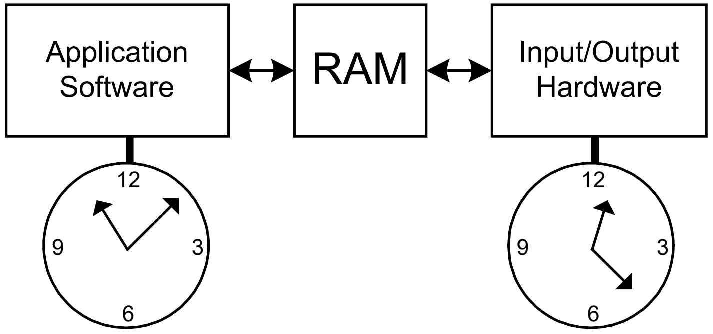
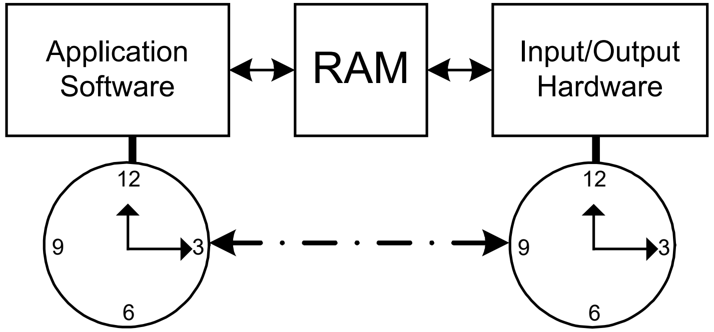
Control Code Execution - Deterministic

Synchronization:

- Locking Hardware I/O updates to software Execution rates resulting in a fixed and determined throughput
- Throughput: The time for a continuous time analog input signal to pass into the digital software realm, get processed, and re-directed back to an analog input(Same applies for a Boolean signal).
- Synchronization also applies to communications for networked I/O even more important due to added communications delays to an analog output
- Synchronized controls offers best performance
- A-Synchronous systems results in variable and random throughput delays or "Jitter"
- Random nature of the delay is difficult or near impossible to compensate for in control loops
  - it is not deterministic
  - Results in performance degradation
- Yet asynchronous systems are easily engineered and do save cost



Asynchronous I/O

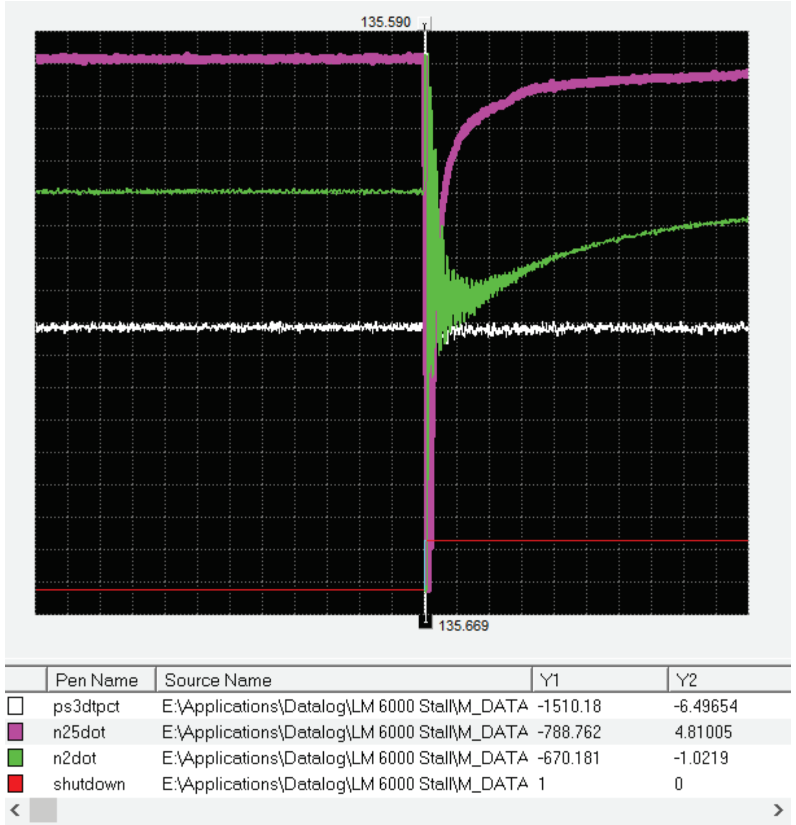


Synchronous I/O

Control Code Execution - Deterministic

Synchronization:

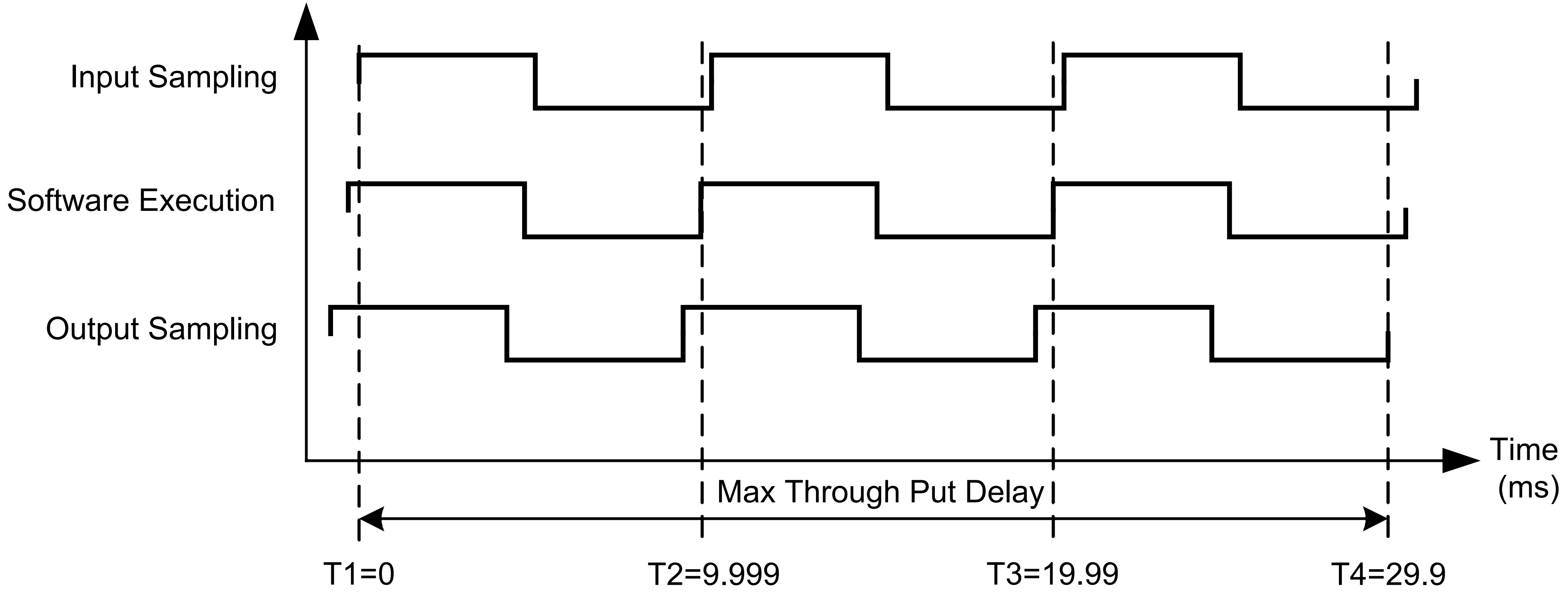
- Application requirements determine the need for synchronous versus asynchronous
- Especially critical on fast aero-derivative gas turbines
- Just 5 to 10 msec can make difference in prevention of overspeed during load rejection transients.
    - Example, a power generation gas turbine :
    - Critical isochronous power load of 10 %
    - 90 % utility grid export
    - Utility tie breaker trips, resulting in a load-rejection from 90 to 10 % power, turbine will tend to overspeed.
    - To keep the isochronous load of 10 % alive the unit must not trip on overspeed
- Accel/Deceleration limiters (dNGG/dt, dnPT/dt), Stall detection, etc



LM6000 Stall detection

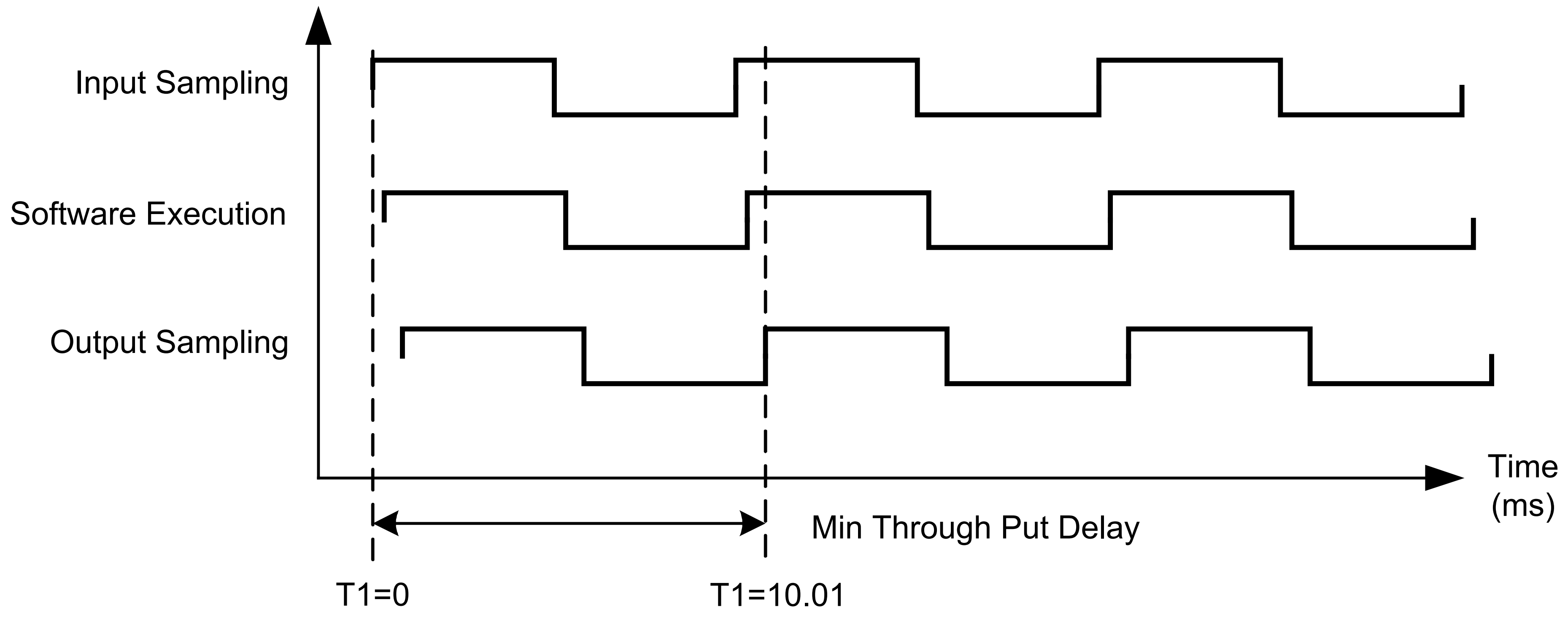
Control Code Execution – Deterministic

TECHNICAL BASICS & BACKGROUND:
A-SYNCHRONOUS I/O (Maximum Delay)



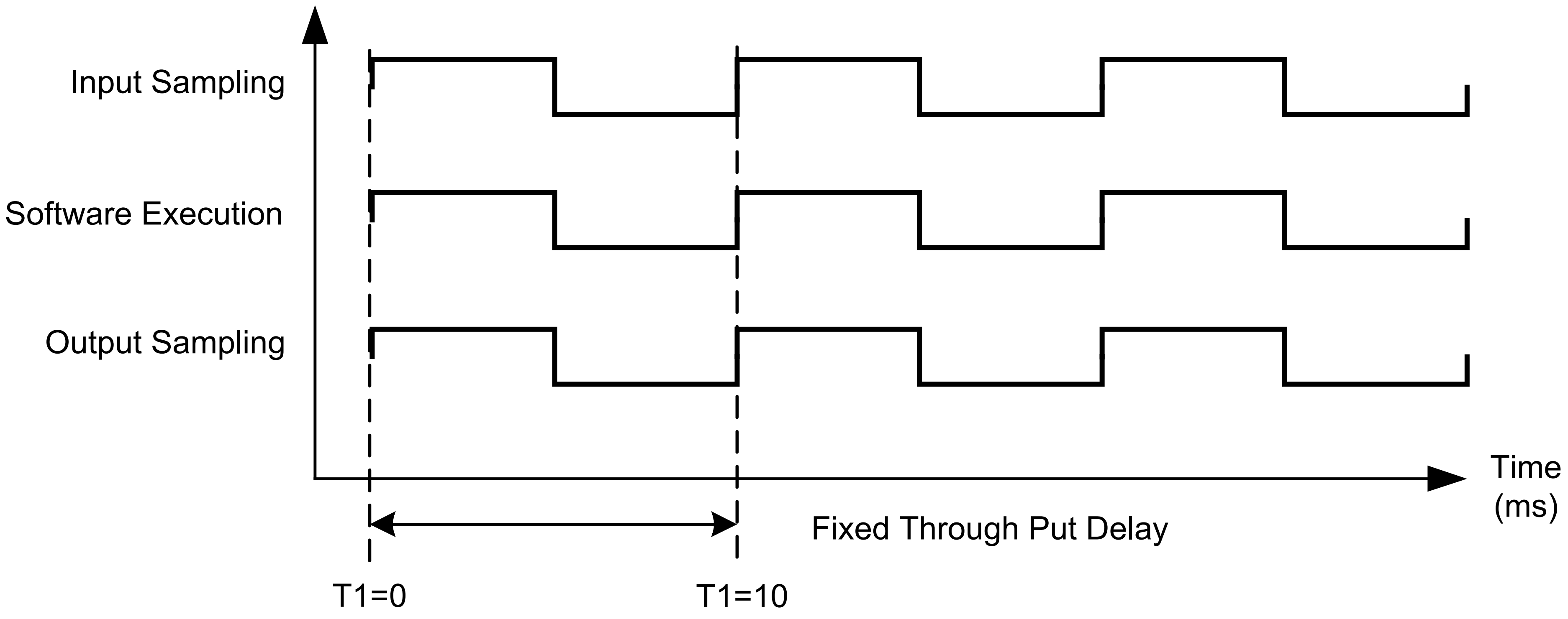
Control Code Execution – Deterministic

TECHNICAL BASICS & BACKGROUND:
A-SYNCHRONOUS I/O (Minimum Delay)



Control Code Execution – Deterministic

TECHNICAL BASICS & BACKGROUND: SYNCHRONOUS I/O (Fixed Delay)



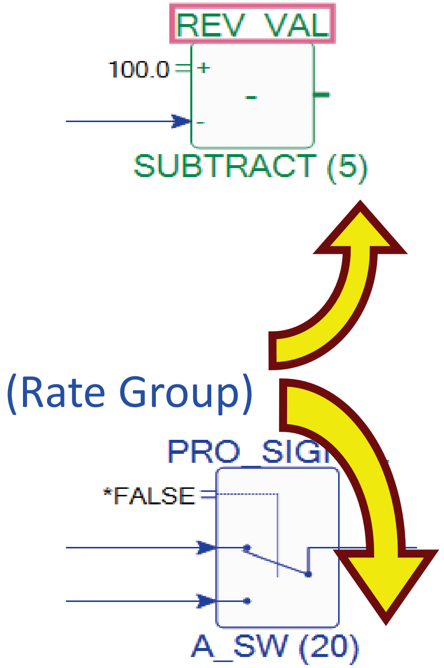
Control Code Execution – Deterministic

TECHNICAL BASICS & BACKGROUND: SYNCHRONOUS, RATE GROUP ENSURES DETERMINISTIC BEHAVIOR

- Master Scheduler
  - **Based on 5 ms hardware real time clock tick (MFT)**
- All time-critical tasks are assigned to rate groups
- 4-6 Rate Groups
  - **5 ms, 10 ms, 20 ms, 40 ms, 80 ms, 160 ms**
  - **"Free Run" group executes non-critical tasks as CPU load allows**
- Data Synchronization between Rate Groups
  - **Copy of all referenced blocks is made at the time Rate Group is scheduled to run**

Control Code Execution – Deterministic

TECHNICAL BASICS & BACKGROUND: SYNCHRONOUS, RATE GROUP ARCHITECTURE



- **Guaranteed "Sample Rate" For The function Block**
  - Millisecond Units
  - No Faster / No Slower
- **Each Rate Group:**
  - Looks At Inputs
  - Processes Them
  - Updates Outputs
- **Rate Groups can be:**
  - 5 mSec
  - 10 mSec
  - 20 mSec
  - 40 mSec
  - 80 mSec
  - 160 mSec

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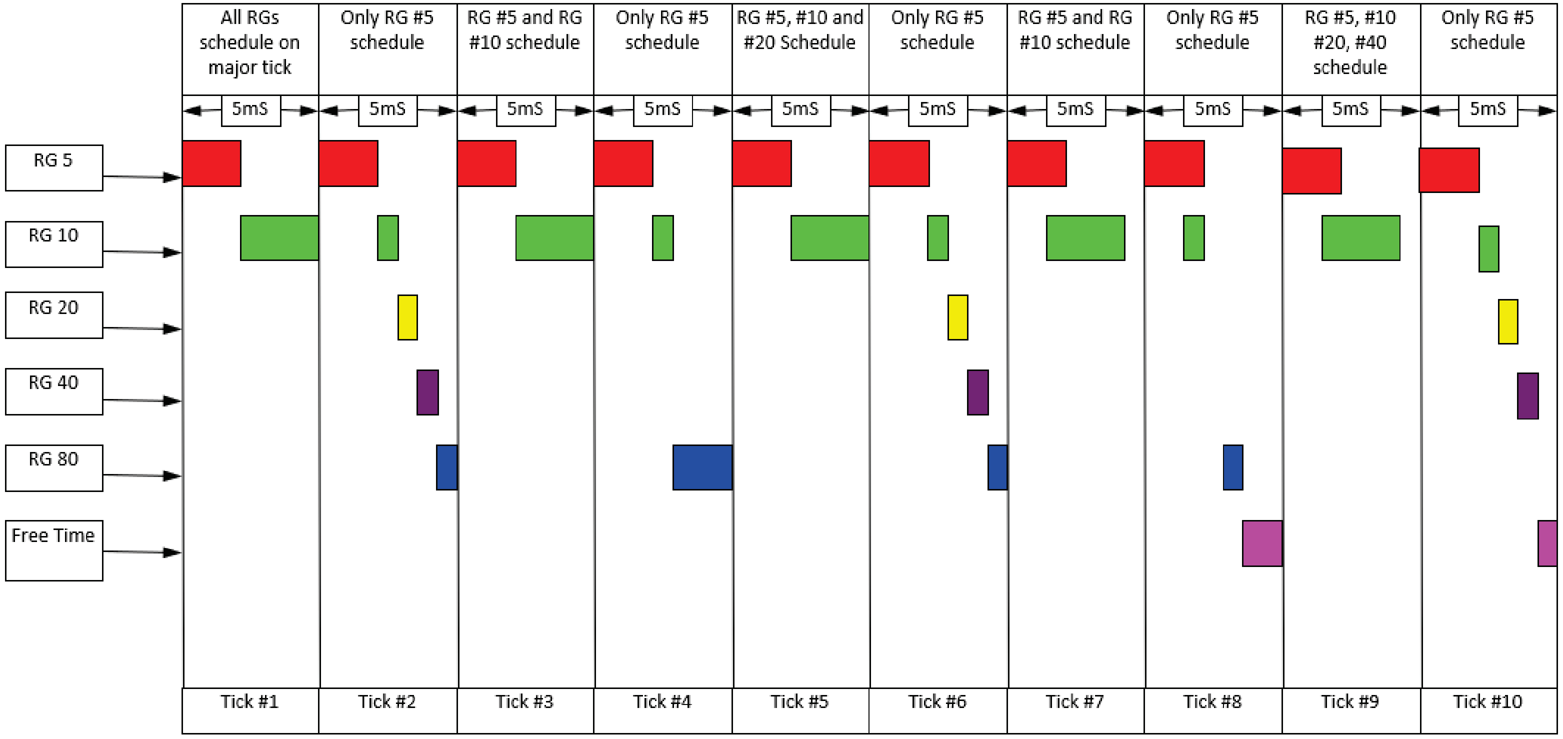
TECHNICAL BASICS & BACKGROUND: SYNCHRONOUS, RATE GROUP ARCHITECTURE



Rate group execution order is from left to right.

The CPU will not process a block until all the inputs to that block have been processed or come from a different rate group.

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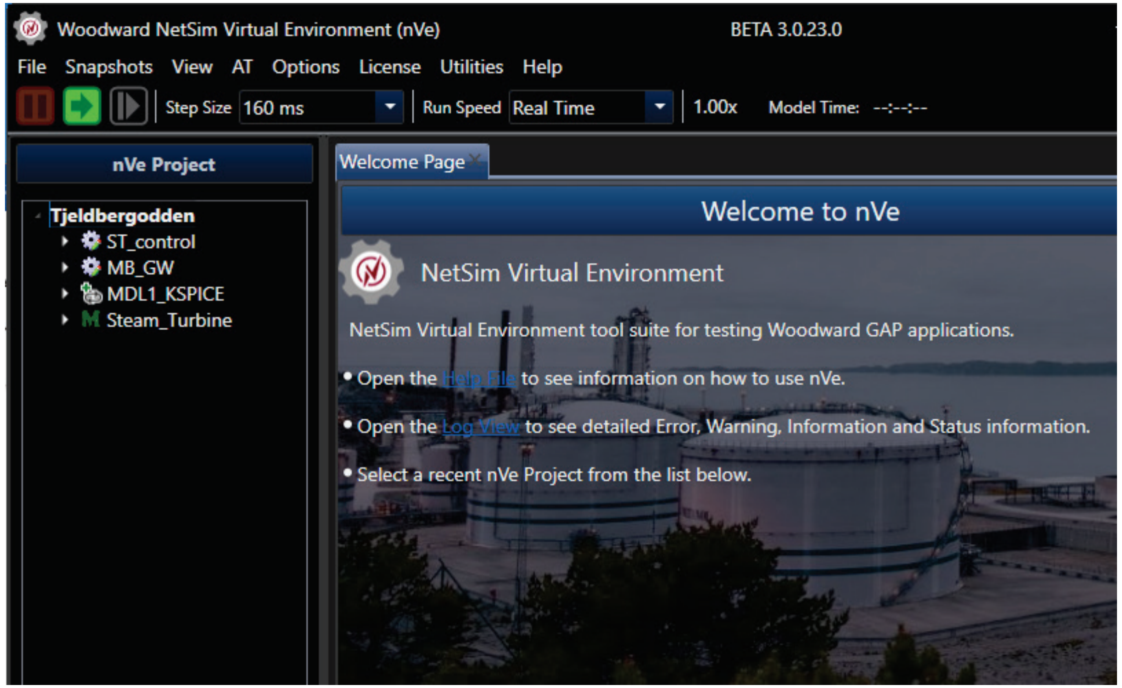
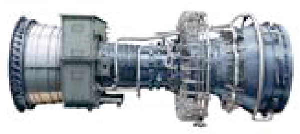
Control Code Execution – Deterministic Simulations

TECHNICAL BASICS & BACKGROUND: nVe Simulation advantages



- Deterministic control simulation allows tuning and troubleshooting prior or after commissioning
- Including GE Aviation LM CLM SAC/DLE models allows high fidelity dynamical behavior
- API's allows interfacing with end-user process simulations (Matlab/Simulink, Dynsim, K-Spice, Mimic, etc)

Package Model



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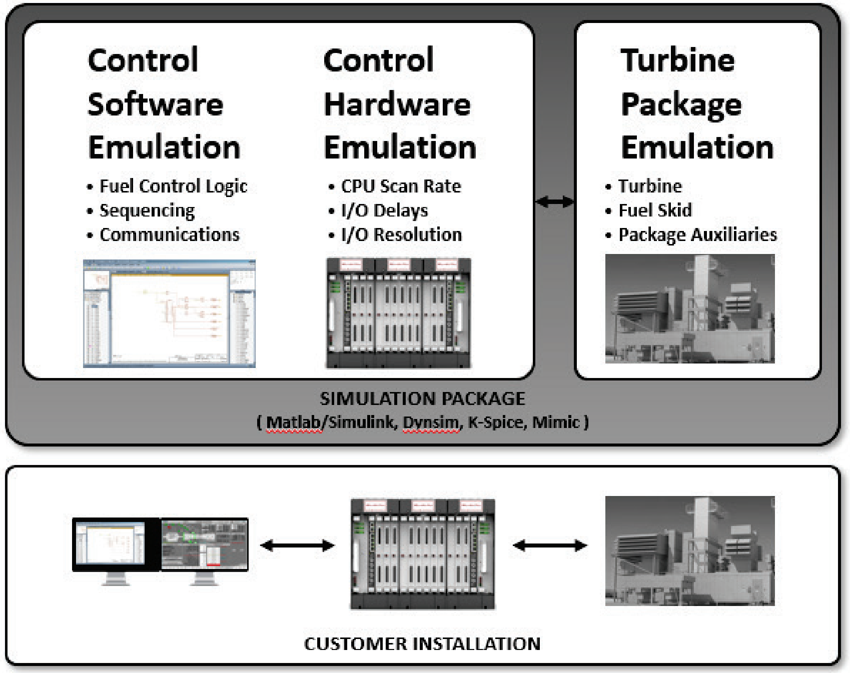
Control Code Execution – Deterministic Simulations

TECHNICAL BASICS & BACKGROUND: nVe Simulation advantages



- **Import & use OEM's GT Models**
- Software before installing on a control
- Utilized during FAT
- Reduces Commissioning Time
- Reduces Commissioning Risk
- Test future software updates
- Perform scenario specific site operational cases
- Use as an operator training tool

Control Specifications – Q & A

Impact of control system IO(input/output) versus operational gas turbine cost

Thanks for attending.

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