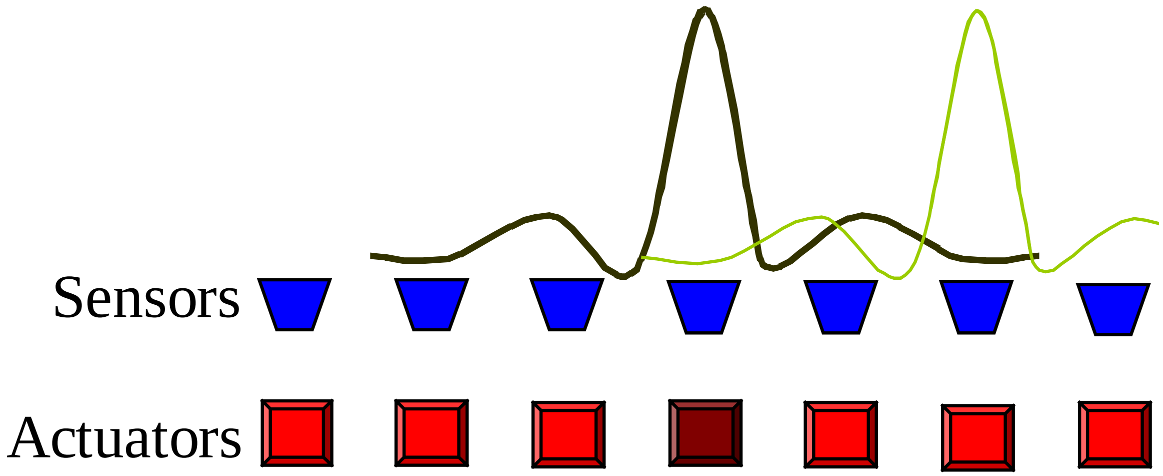
Lecture 15 - Distributed Control

- Spatially distributed systems
- Motivation
- Paper machine application
- Feedback control with regularization
- Optical network application
- Few words on good stuff that was left out

Distributed Array Control

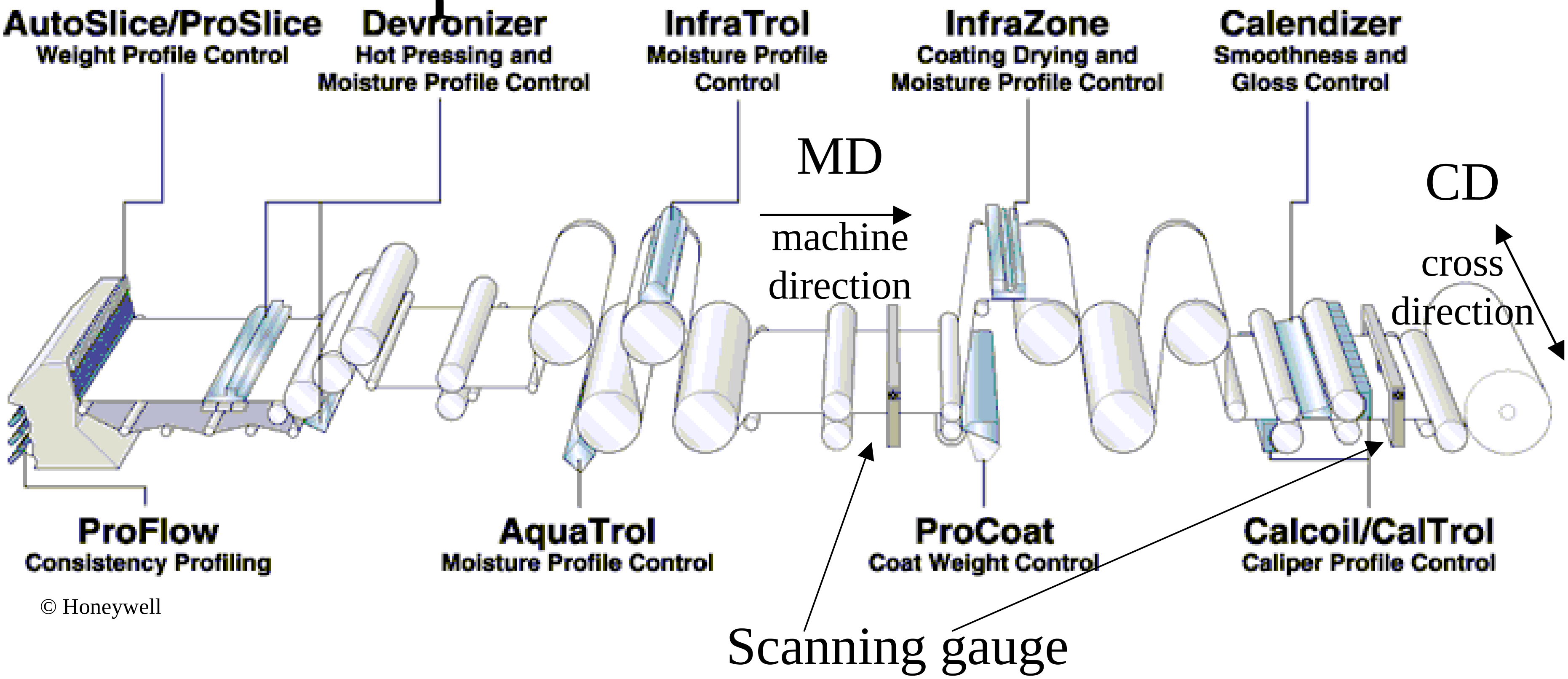
- Sensors and actuators are organized in large arrays distributed in space.
- Controlling spatial distributions of physical variables
- Problem simplification: the process and the arrays are uniform in spatial coordinate
- Problems:
  - modeling
  - identification
  - control



Distributed Control Motivation

- Sensors and actuators are becoming cheaper
  - electronics almost free
- Integration density increases
- MEMS sensors and actuators
- Control of spatially distributed systems increasingly common
- Applications:
  - paper machines
  - fiberoptic networks
  - adaptive and active optics
  - semiconductor processes
  - flow control
  - image processing

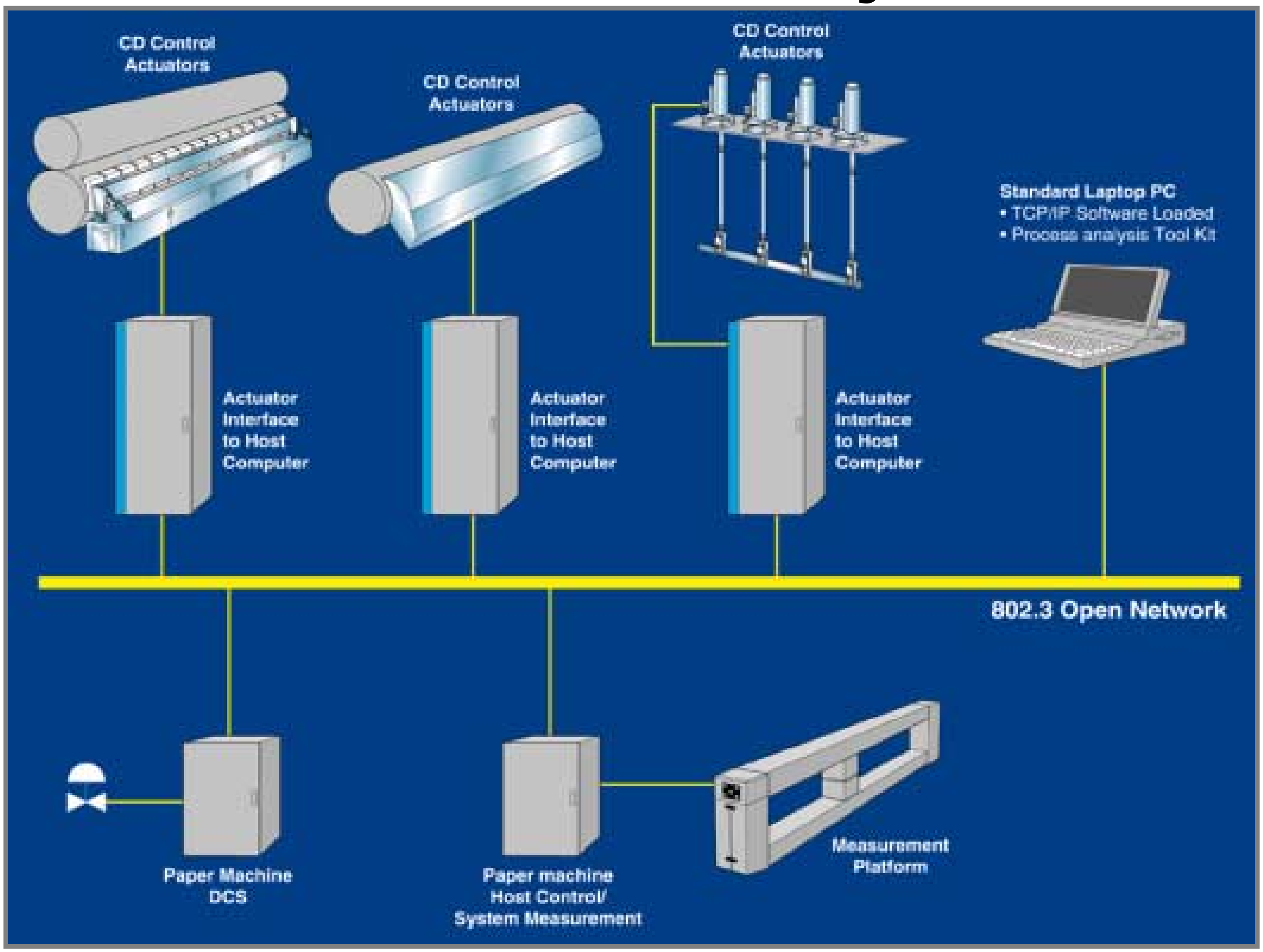
Paper Machine Process



- Control objective: flat profiles in the cross-direction
- The same control technology for different actuator types: flow uniformity control, thermal control of deformations, and others

Headbox with Slice Lip CD Actuators

Profile Control System



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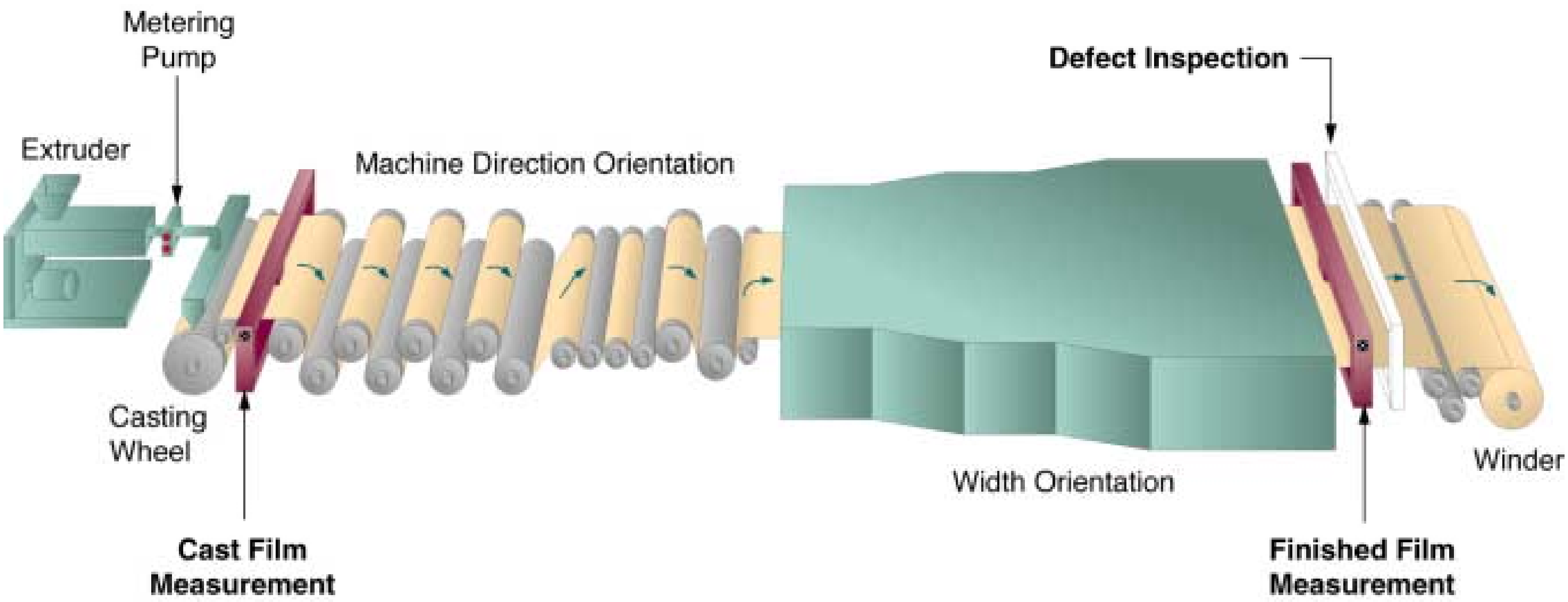
Biaxial Plastic Line Control



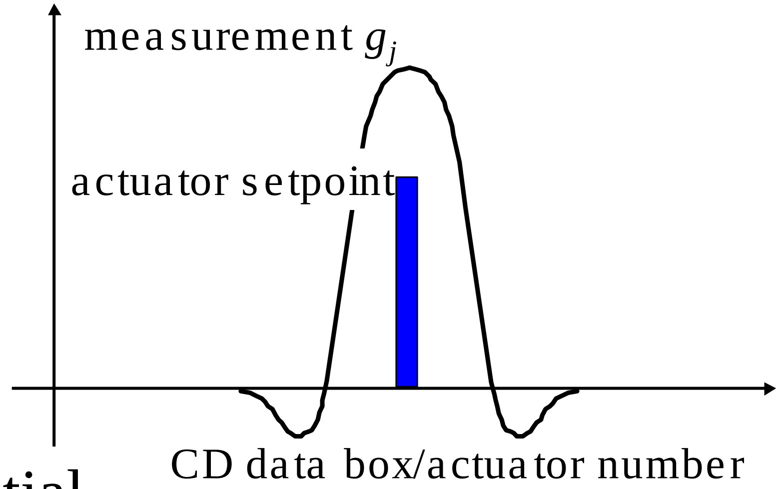
Model Structure

- Process-independent model structure

$$\Delta Y = G\Delta U$$

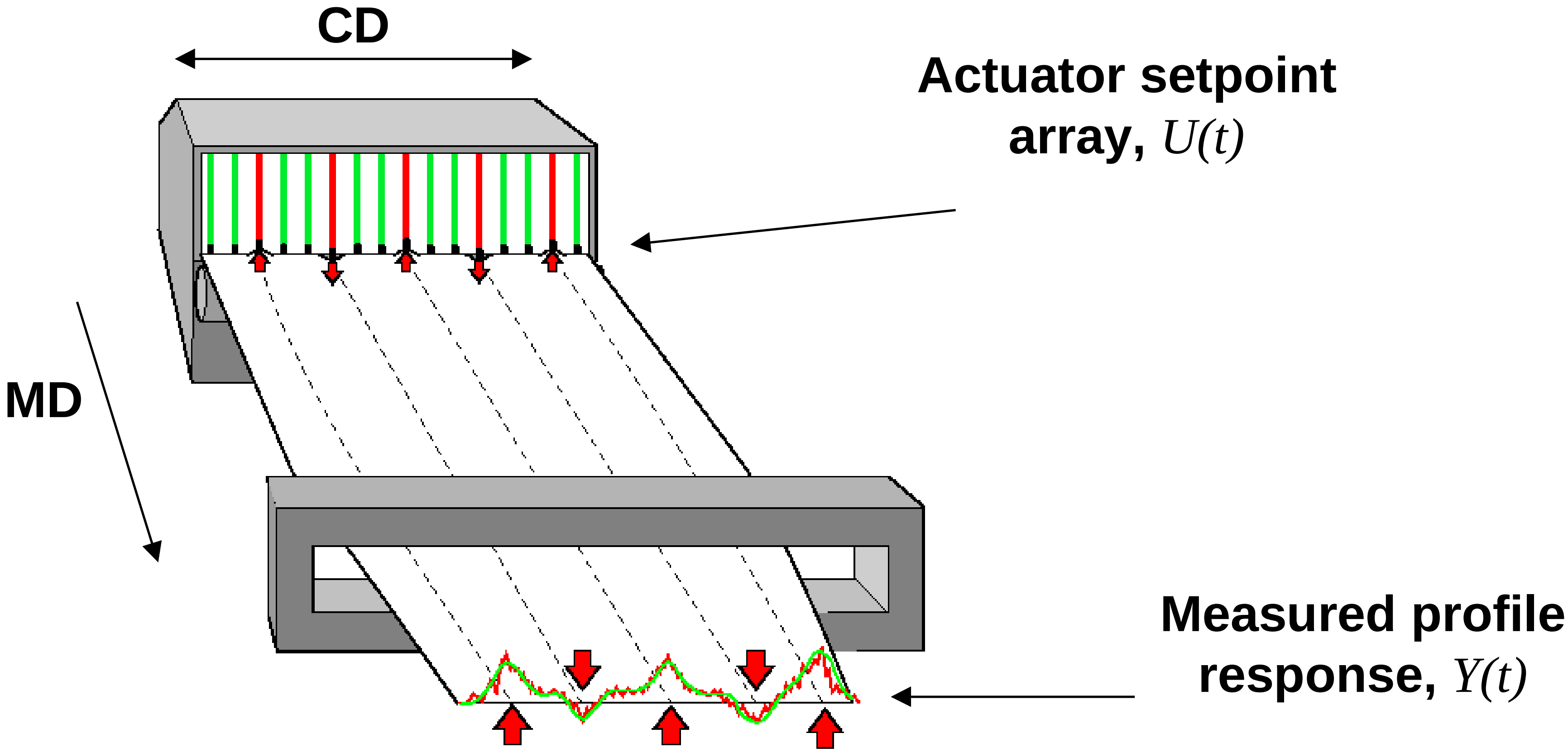
$$Y \in \Re^m, U \in \Re^n, G \in \Re^{m,n}$$

- G - spatial response matrix with columns g_j
- Known parametric form of the spatial response (noncausal FIR)
- Green Function of the distributed system

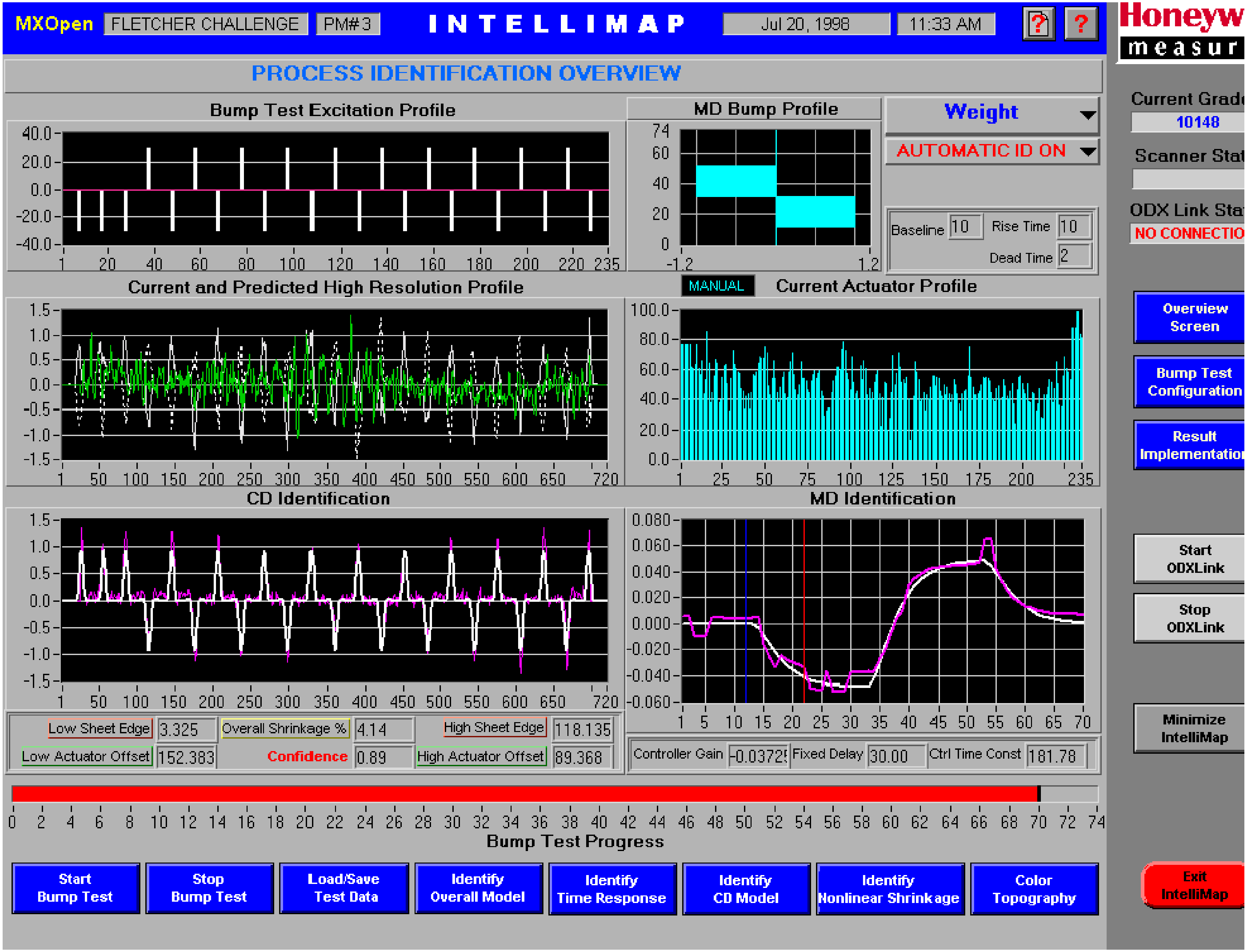


$$g_{j,k} = g\varphi(x_k - c_j)$$

Process Model Identification



- Extract noncausal FIR model
- Fit parameterized response shape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CD Identification
MD Identification
Low Sheet Edge 3.325
Overall Shrinkage % 4.14
High Sheet Edge 118.135
Low Actuator Offset 152.383
Confidence 0.89
High Actuator Offset 89.368
Controller Gain -0.0372
Fixed Delay 30.00
Ctrl Time Const 181.78
Bump Test Progress
Start Bump Test
Stop Bump Test
Load/Save Test Data
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Overview Screen
Bump Test Configuration
Result Implementation
Start ODXLink
Stop ODXLink
Minimize IntelliMap
Exit IntelliMap

Simple I control

- Compare to Lecture 4, Slide 5

I control

- Step to step update:

$$Y(t) = G \cdot U(t) + D(t)$$

$$U(t) = U(t-1) - k\left[Y(t-1) - Y_d\right]$$

- Closed-loop dynamics

$$Y = \left((z-1)I + kG\right)^{-1}\left[kGY_d + (z-1)D\right]$$

- Steady state: $z = 1$

$$Y = Y_d, \qquad U = G^{-1}(Y_d - D)$$

Simple I control

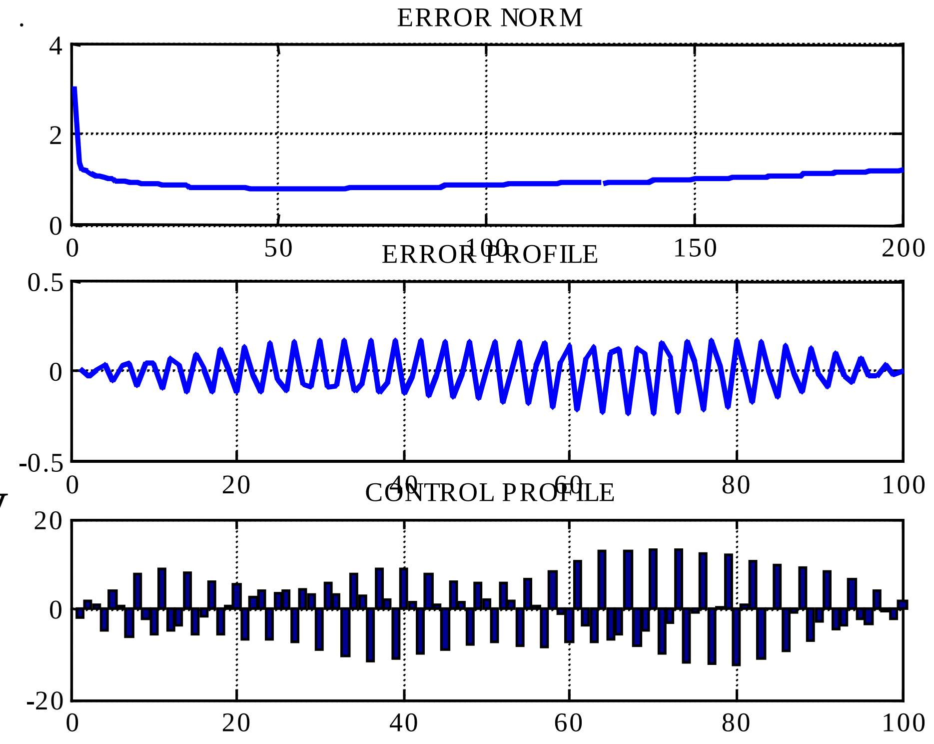
Issues with simple I control

- G not square positive definite
  - use G^{T} as a spatial pre-filter

$$Y_G(t) = G^T G \cdot U(t) + D_G(t)$$

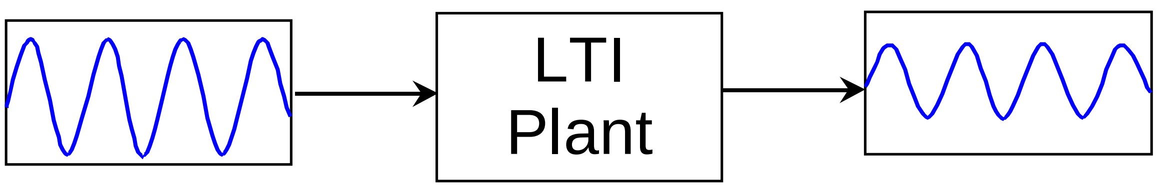
$$Y_G = G^T Y, \quad D_G = G^T D$$

- For ill-conditioned G get very large control, picketing
  - use regularized inverse
- Slowly growing instability
  - control not robust
  - regularization helps again



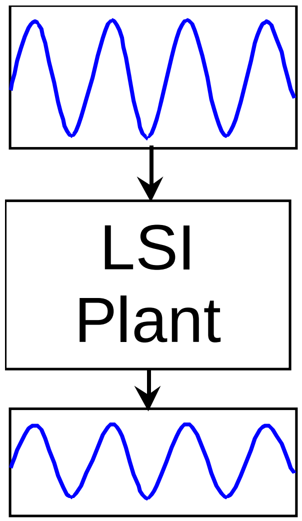
Frequency Domain - Time

- LTI system is a convenient engineering model
- LTI system as an input/output operator
- Causal
- Can be diagonalized by harmonic functions
- For each frequency, the response is defined by amplitude and phase



Frequency Domain - Space

- Linear Spatially Invariant (LSI) system
- LSI system is a convenient engineering model
- LSI system as an input/output operator
- Noncausal
- Can be diagonalized by harmonic functions
- Diagonalization = modal analysis; spatial modes are harmonic functions



Control with Regularization

- Add integrator leakage term

$$\Delta U(t) = -K\left(Y(t-1) - Y_d\right) - SU(t-1)$$

- Feedback operator *K*
  - spatial loopshaping
    - $KG \approx 1$ at low spatial frequencies
    - $KG \approx 0$ at high spatial frequencies
- Smoothing operator *S*
  - regularization
    - $S \approx 0$ at low spatial frequencies
    - $S \approx s_0$ at high spatial frequencies - regularization

Spatial Frequency Analysis

- Matrix $G \;\rightarrow$ convolution operator g (noncausal FIR) $\rightarrow$ spatial frequency domain (Fourier) $g(v)$
- Similarly: $K \rightarrow k(v)$ and $S \rightarrow s(v)$
- Each spatial frequency - mode - evolves independently

$$y(\nu) = \frac{g(\nu)k(\nu)}{z-1+s(\nu)+g(\nu)k(\nu)} y_d + \frac{z-1+s(\nu)}{z-1+g(\nu)k(\nu)} d$$

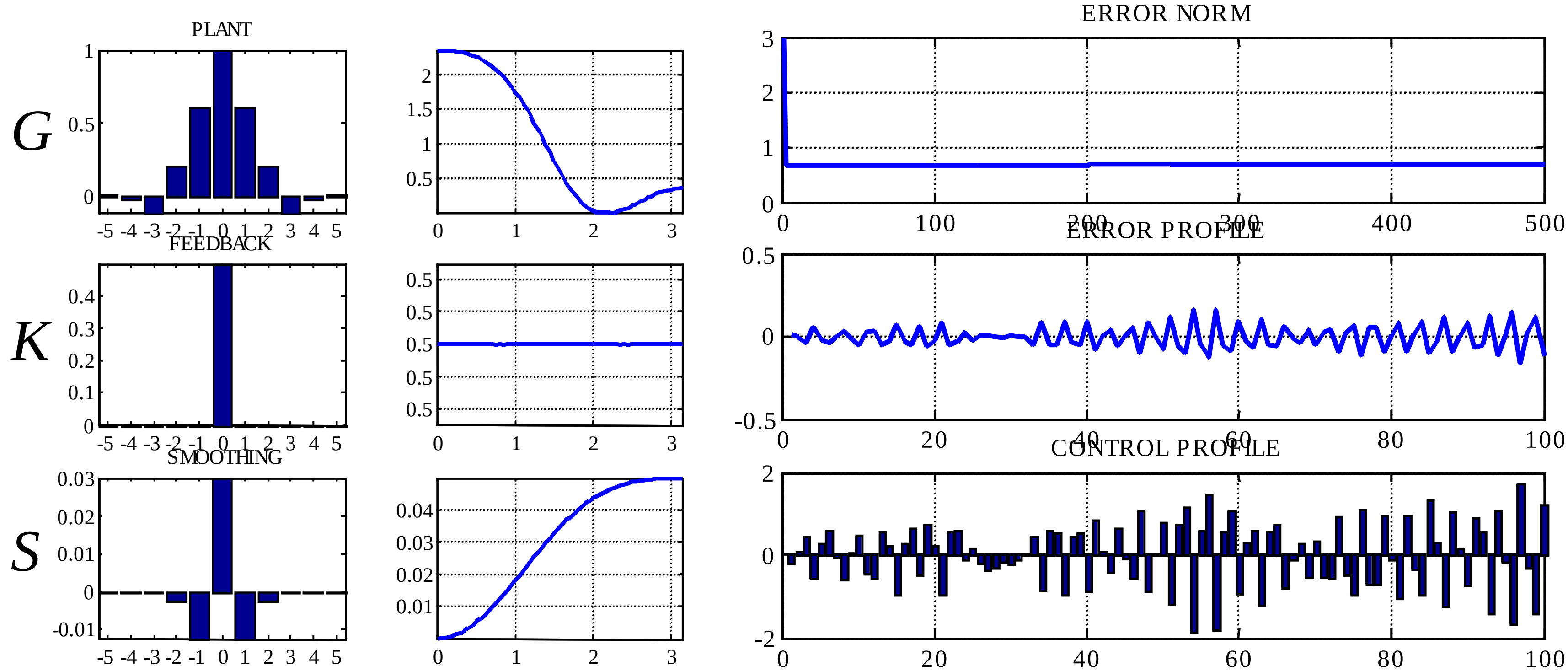
- Steady state

$$y(\nu) = \frac{g(\nu)k(\nu)}{s(\nu)+g(\nu)k(\nu)} y_d + \frac{s(\nu)}{s(\nu)+g(\nu)k(\nu)} d$$

$$u(\nu) = \frac{k(\nu)}{s(\nu)+g(\nu)k(\nu)} \left(y_d(\nu) - d(\nu)\right)$$

Sample Controller Design

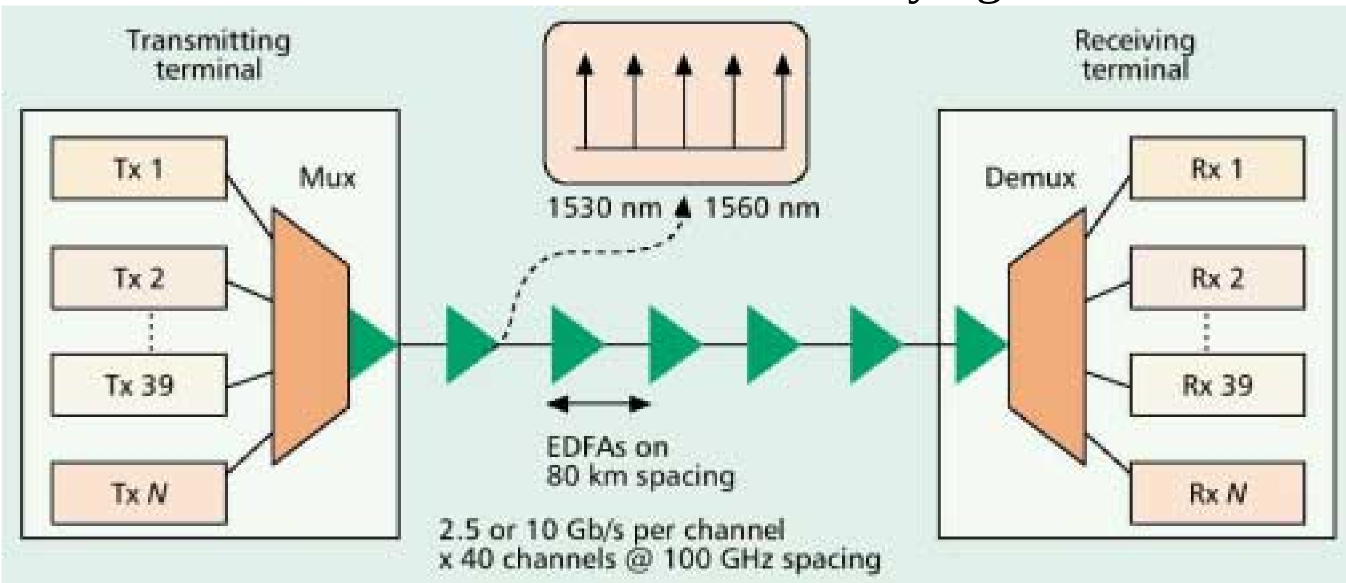
- Spatial domain loopshaping is easy - it is noncausal
- Example controller with regularization



For more depth and references, see: Gorinevsky, Boyd, Stein, ACC 2003

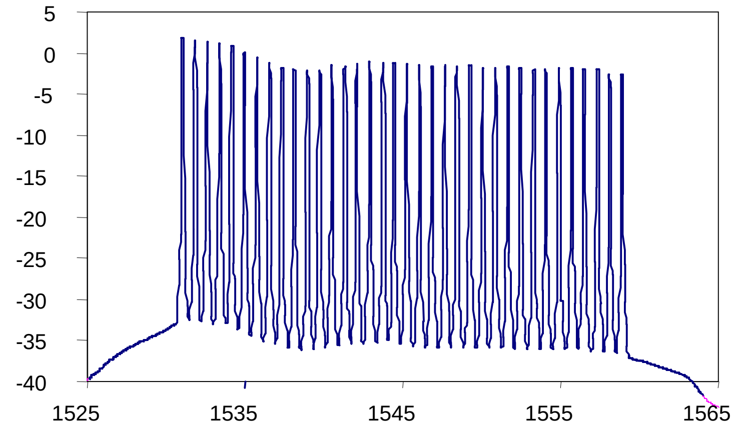
WDM network equalization

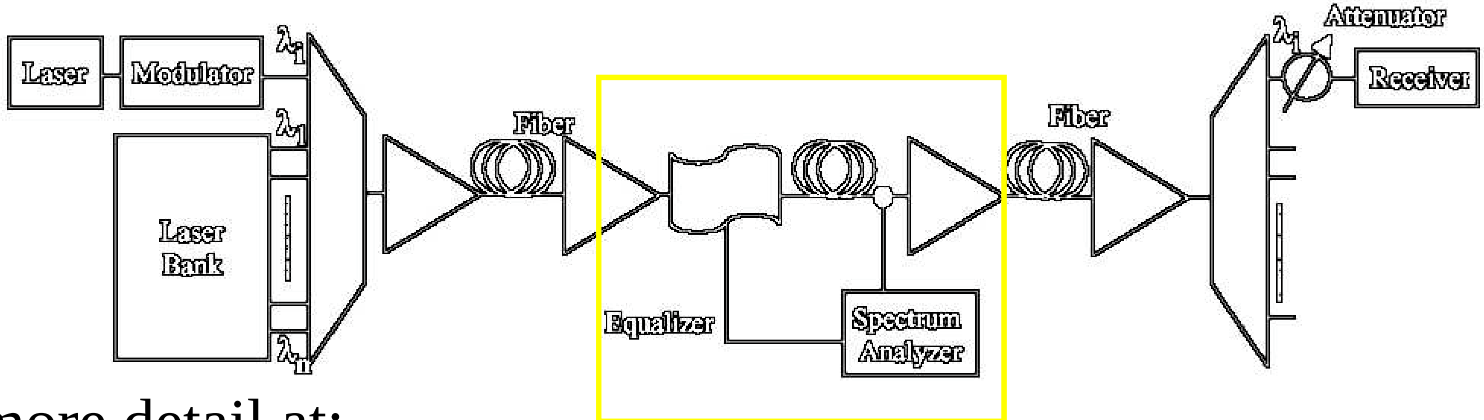
- WDM (Wave Division Multiplexing) networks
  - multiple (say 40) independent laser signals with closely space wavelength packed (multiplexed) into a single fiber
  - each wavelength is independently modulated
  - in the end the signals are unpacked (de-mux) and demodulated
  - increases bandwidth 40 times without laying new fiber



WDM network equalization

- Analog optical amplifiers (EDFA) amplify all channels
- Attenuation and amplification distort carrier intensity profile
- The profile can be flattened through active control





See more detail at:

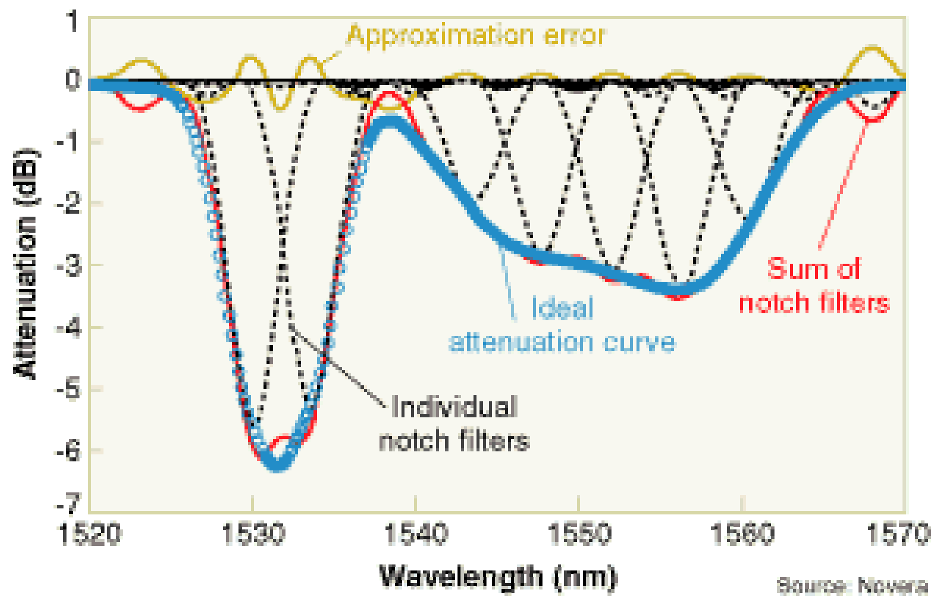
www126.nortelnetworks.com/news/papers_pdf/electronicast_1030011.pdf

WDM network equalization

- Logarithmic (dB) attenuation for a sequence of notch filters

$$A = A_1 \cdot \ldots \cdot A_N$$

$$\log A = \sum_{k=1}^{N} \log A_k$$



$$a(\lambda) = \sum_{k=1}^{N} w_k \varphi(\lambda - \lambda_0 - ck)$$

Attenuation gain - control handle

Notch filter shape

WDM

Good stuff that was left out

- Estimation and Kalman filtering
  - navigation systems
  - data fusion and inferential sensing in fault tolerant systems
- Adaptive control
  - adaptive feedforward, noise cancellation, LMS
  - industrial processes
  - thermostats
  - bio-med applications, anesthesia control
  - flight control
- System-level logic
- Integrated system/vehicle control