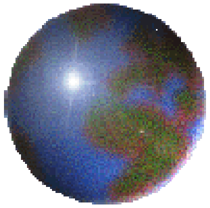


Two-Stage Adaptive Feed-forward Predictive Control:

with Applications to Algal Growth Systems

Michael Buehner
Ph.D. Preliminary Exam
June 26th, 2008
11:00 am

Biofuels From Microalgae

- Use CO_2, sun energy, nutrients to produce microalgae biomass
- Create storage lipids for biofuel production via "stressing"
- DOE's Aquadic Species Program
  - NREL (1978-1996)
- Solix Biofuels

Issues with Current Technology

- What are the desired operating conditions?
- What are the theoretical limits and how do we achieve them?
- What is a cost effective solution?
- What microalgae strain should be used?
- What method should be used for growing and stressing the microalgae?

Topics

- Adaptive Feed-forward (FF) Predictive Control
- Algal Growth System (AGS) Modeling
  - Understand and improve process
  - Address control objectives
- AGS Control
  - Reduce cost
  - Improve performance

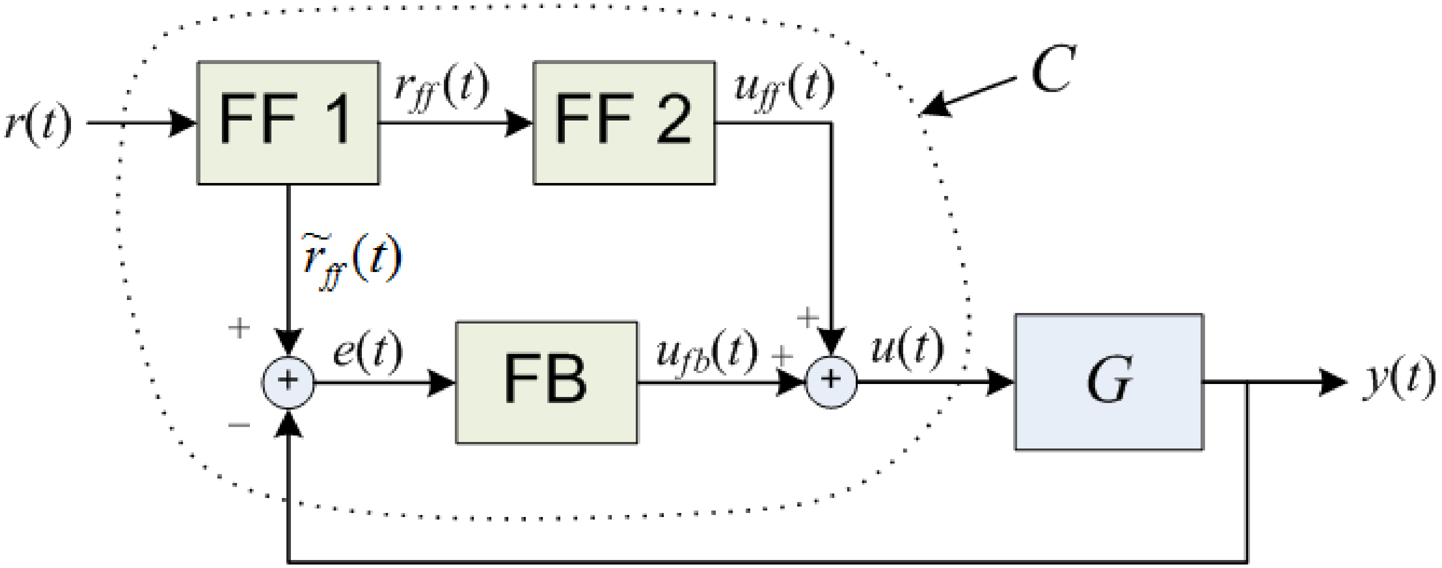
Adaptive FF Predictive Control

- Motivation
- Architecture
- LTI Methods
- Examples
- Future Work

Neuralmuscular Actuation Systems

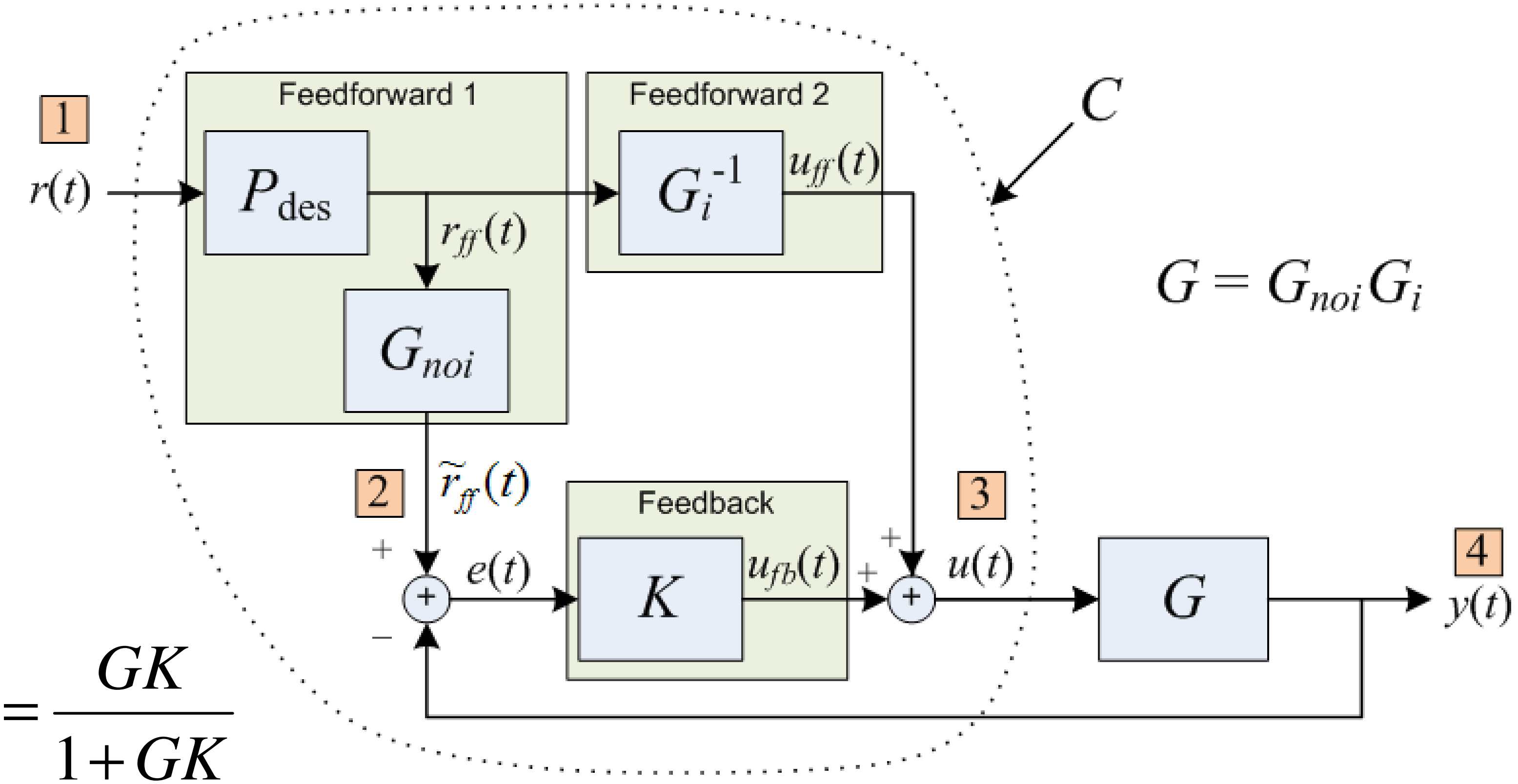
- Calculate desired path (FF calculation)
- Balistic response (FF Control)
- Dynamic corrections to ballistic response (FB control on small error signals)

Architecture



- $G = G_{noi} G_i$
- Desired Closed Loop: $G_{noi} P_{des}$
- FF 1: DC Gain = 1
- FF 1 and FF 2: Open-loop Stable

LTI Method 1



$$G = G_{noi} G_i$$

$$T_{42} = \frac{GK}{1+GK}$$

$$T_{43} = \frac{G}{1+GK}$$

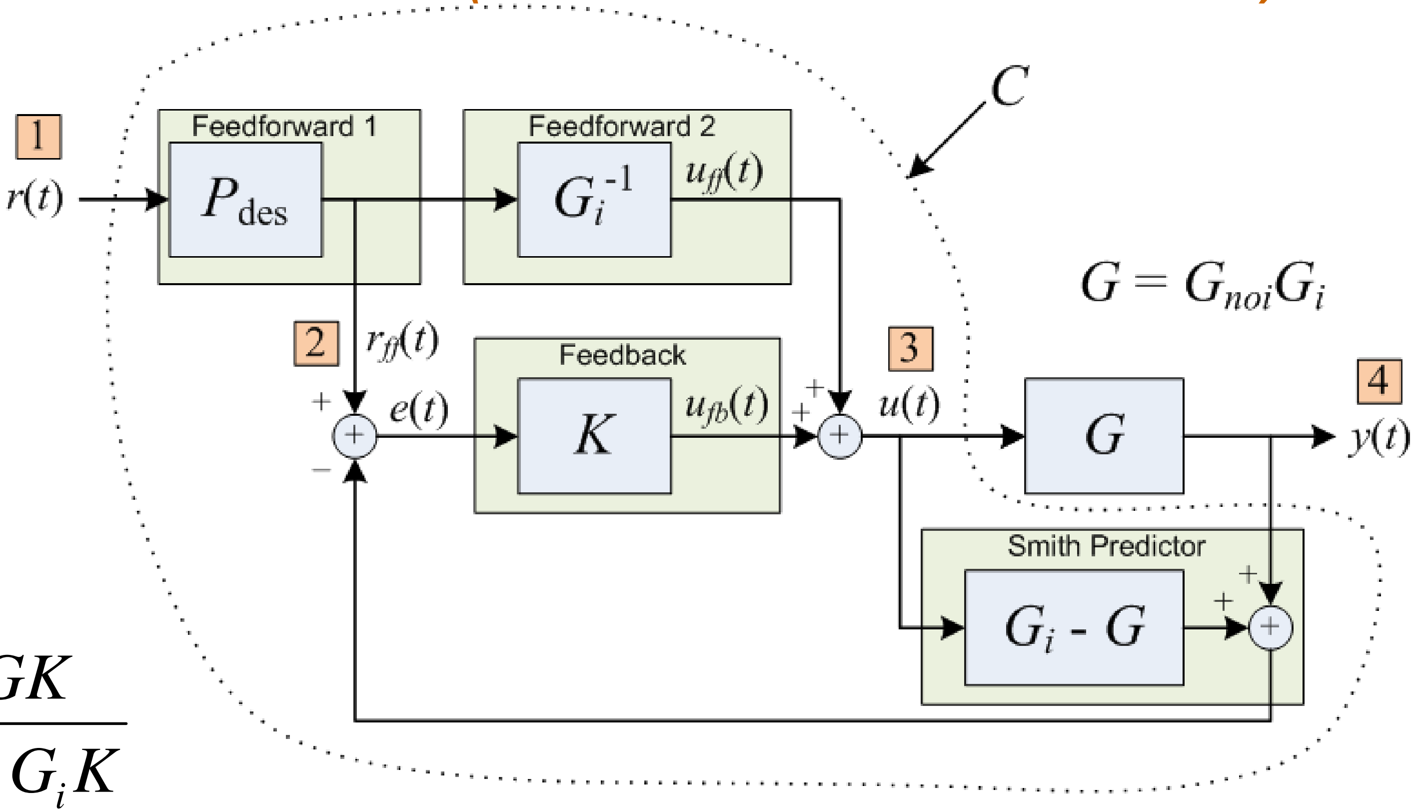
$$T_{41} = T_{42} G_{noi} P_{des} + T_{43} G_i^{-1} P_{des}$$

LTI Method 1 Cont.

$$T_{42} = \frac{GK}{1+GK} \qquad T_{43} = \frac{G}{1+GK}$$

$$\begin{aligned}
T_{41} &= T_{42} G_{noi} P_{des} + T_{43} G_i^{-1} P_{des} \\
&= \frac{GK}{1+GK} G_{noi} P_{des} + \frac{(G_{noi} G_i)}{1+GK} G_i^{-1} P_{des} \\
&= \frac{GK}{1+GK} G_{noi} P_{des} + \frac{1}{1+GK} G_{noi} P_{des} \\
&= \frac{1+GK}{1+GK} G_{noi} P_{des} \\
&= G_{noi} P_{des}
\end{aligned}$$

LTI Method 2 (Smith Predictor)



$$G = G_{noi} G_i$$

$$T_{42} = \frac{GK}{1 + G_i K}$$

$$T_{43} = \frac{G}{1 + G_i K}$$

$$T_{41} = T_{42} P_{des} + T_{43} G_i^{-1} P_{des}$$

LTI Method 2 Cont.

$$T_{42} = \frac{GK}{1+G_iK} \qquad T_{43} = \frac{G}{1+G_iK}$$

$$\begin{aligned}
T_{41} &= T_{42}P_{des} + T_{43}G_i^{-1}P_{des} \\
&= \frac{(G_{noi}G_i)K}{1+G_iK}P_{des} + \frac{G_{noi}G_i}{1+G_iK}G_i^{-1}P_{des} \\
&= \frac{G_iK}{1+G_iK}G_{noi}P_{des} + \frac{1}{1+G_iK}G_{noi}P_{des} \\
&= \frac{1+G_iK}{1+G_iK}G_{noi}P_{des} \\
&= G_{noi}P_{des}
\end{aligned}$$

LTI Example Using Standard FB

Plant

$$G(s) = \frac{s+5}{s+1} e^{-s\tau_d}$$

$$\tau_d = 1$$

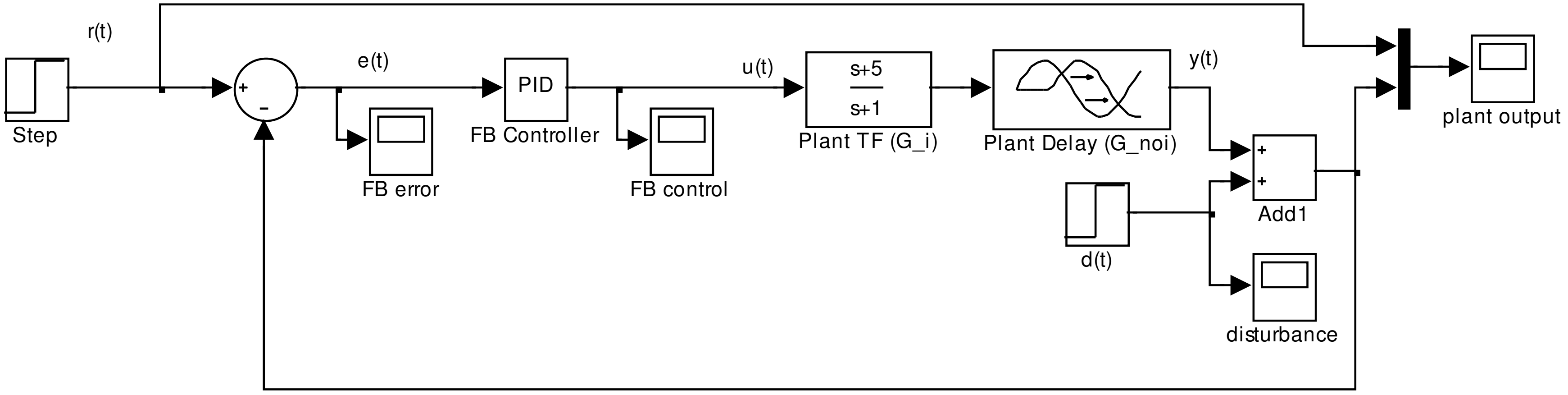
PI Controller

$$K_p = 0.1111$$

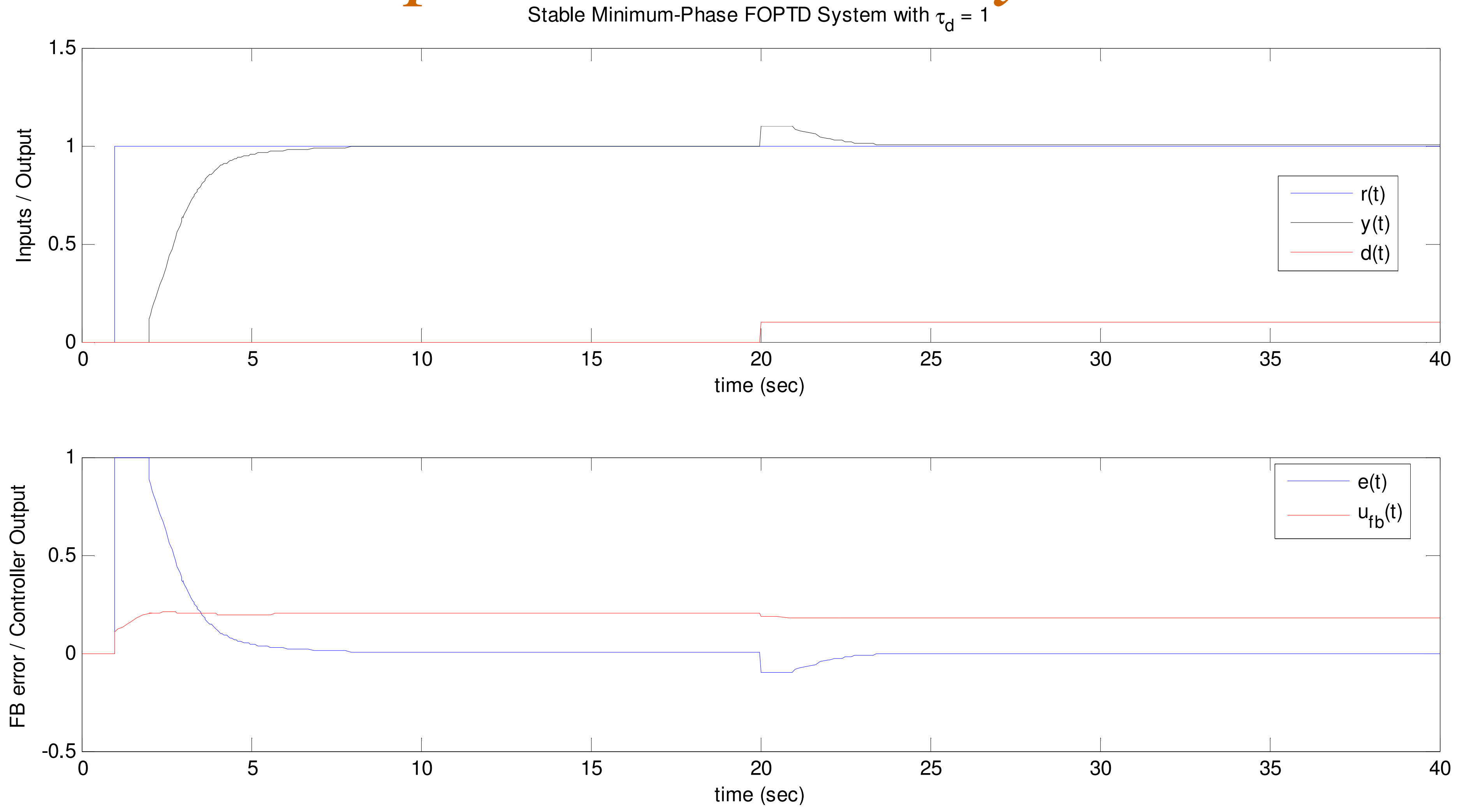
$$K_i = 0.1005$$

Disturbance

$$d(t) = 0.1\ u(t\text{-}20)$$



LTI Example with FB Only Plots



LTI Example Using Method 1

Plant

$$G(s) = \frac{s+5}{s+1} e^{-s\tau_d}$$

$$\tau_d = 1$$

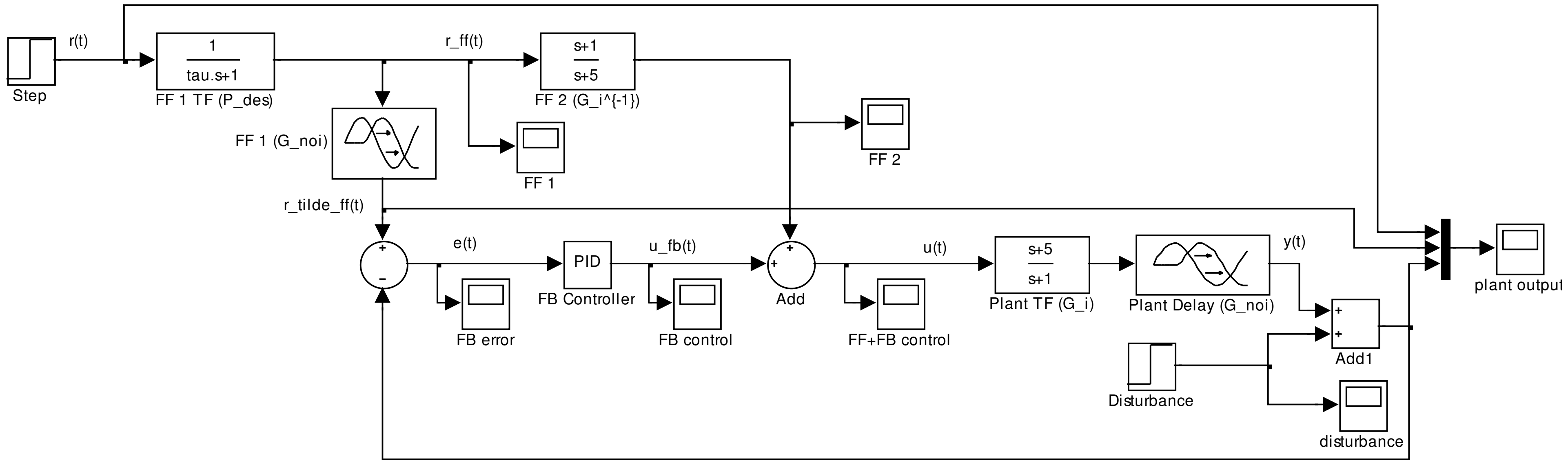
Feed-forward Terms

$$G_{noi}(s) = e^{-s\tau_d}$$

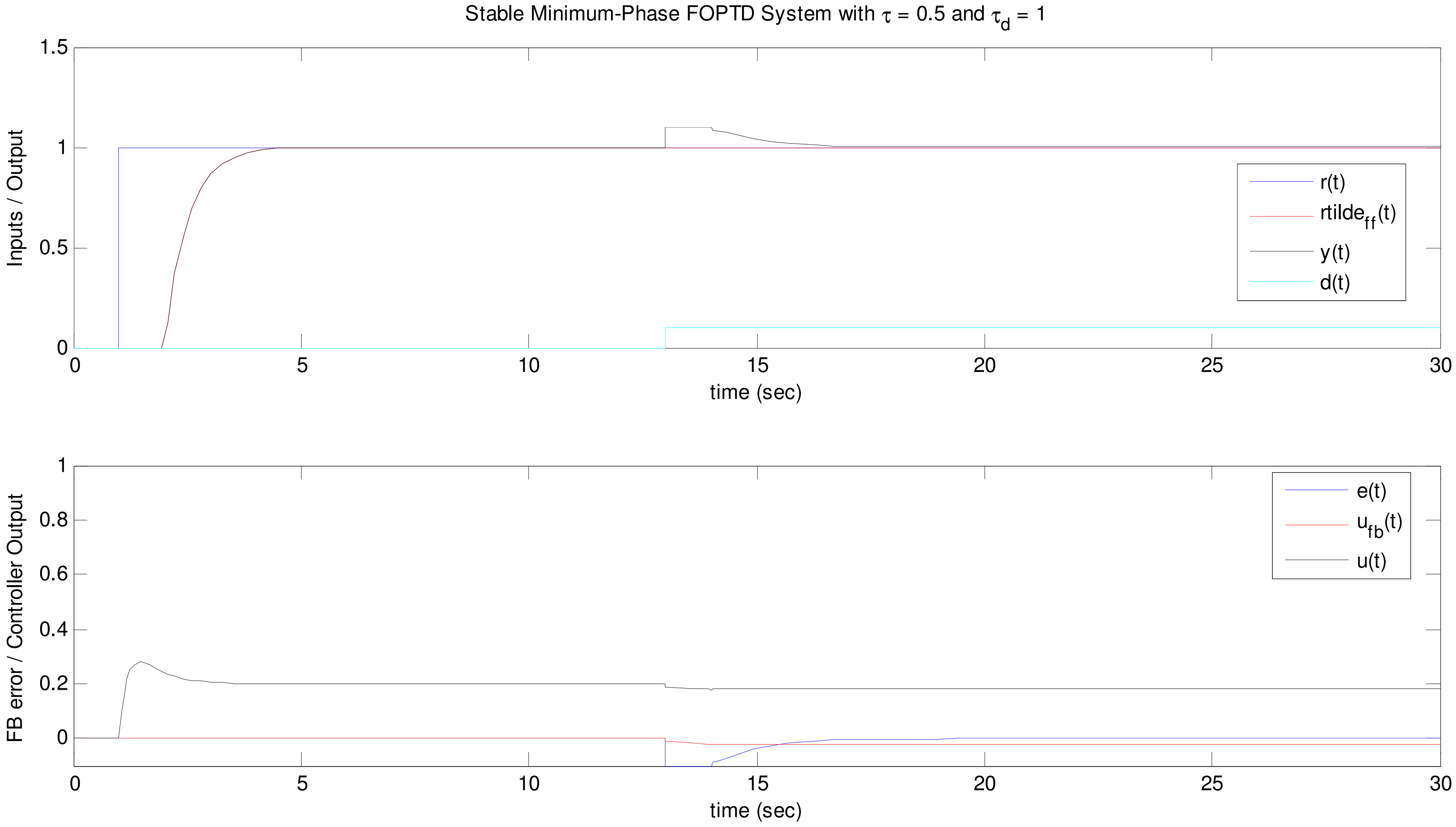
$$G_i(s) = \frac{s+5}{s+1}$$

$$P_{des}(s) = \frac{1}{\tau s + 1}$$

$$\tau \geq 0$$



Method 1 Plots



LTI Example Using Method 2

Plant

$$G(s) = \frac{s+5}{s+1} e^{-s\tau_d}$$

$$\tau_d = 1$$

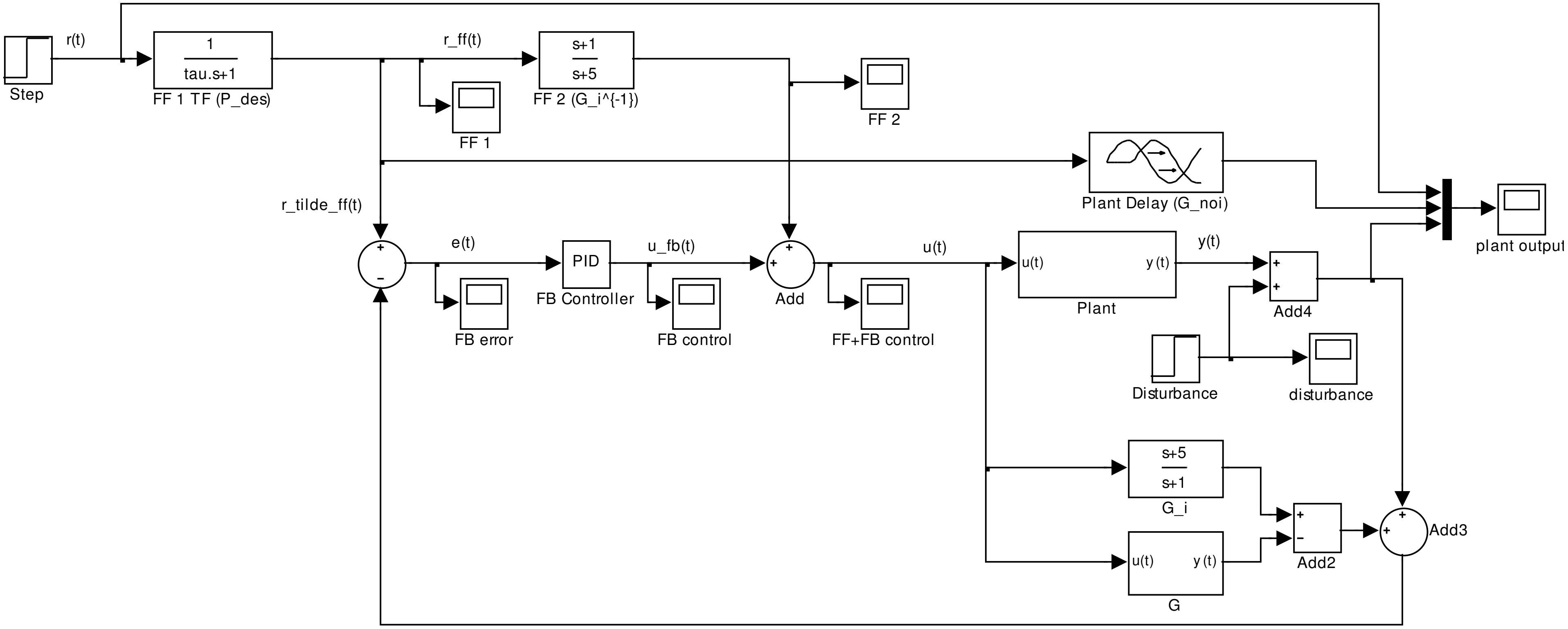
Feed-forward Terms

$$G_{noi}(s) = e^{-s\tau_d}$$

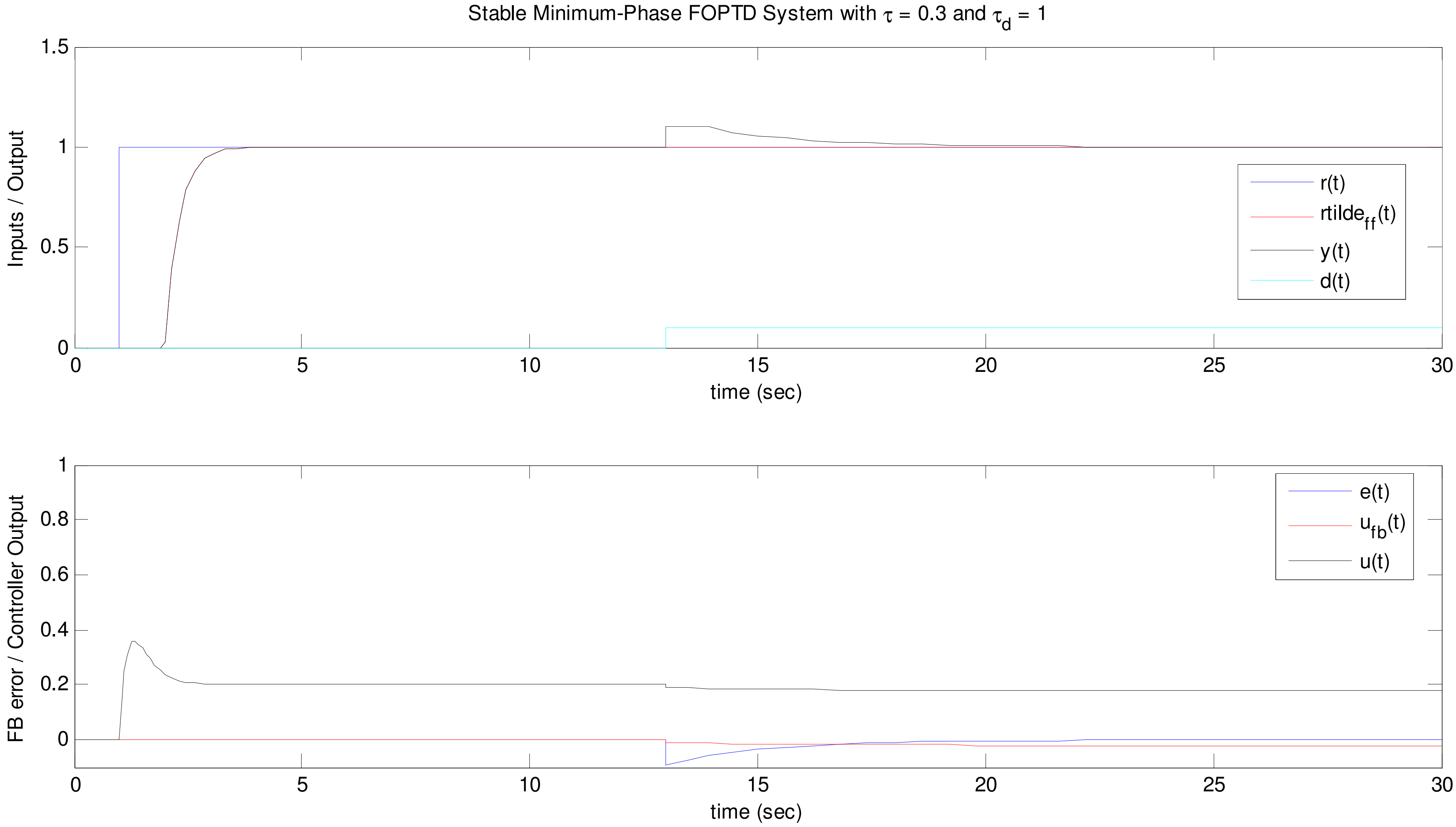
$$G_i(s) = \frac{s+5}{s+1}$$

$$P_{des}(s) = \frac{1}{\tau s + 1}$$

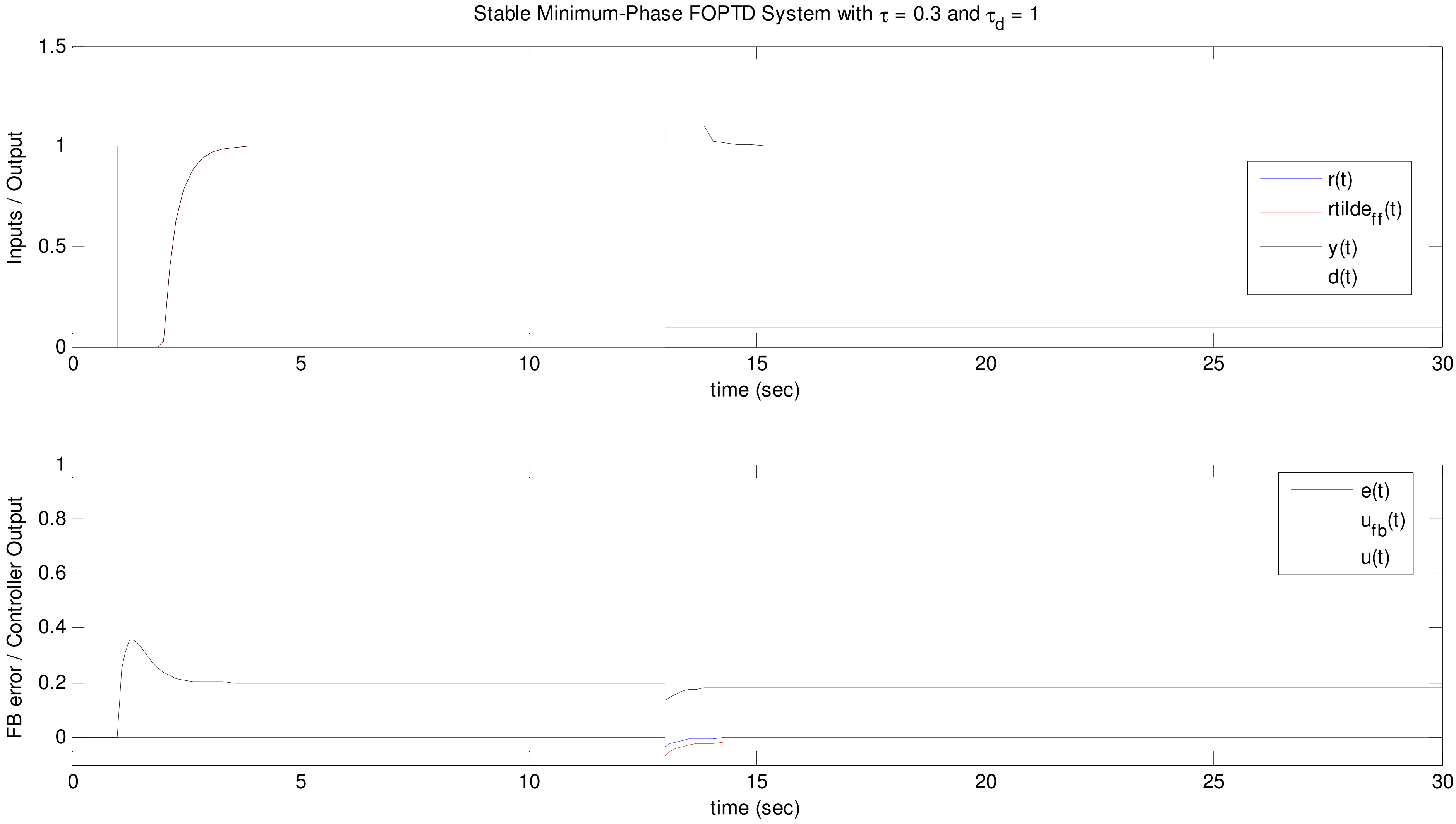
$$\tau \geq 0$$



Method 2 Plots


Stable Minimum-Phase FOPTD System with $\tau = 0.3$ and $\tau_d = 1$

Method 2 Plots ($K_p = 2, K_i = 1$)



Stable Minimum-Phase FOPTD System with $\tau = 0.3$ and $\tau_d = 1$

Future Work – LTI Methods

- Optimized designs
  - Closed-loop $G_{noi}P_{des}$
  - Feedback controller K
- Robustness analysis and design
  - Smith predictor
  - Model uncertainty

Future Work – NLTV Methods

- Nonlinear Time-varying (NLTV) Methods
  - Nonlinear models
  - Reinforcement learning
  - Echo state networks
- G_i^{-1} : well studied
- P_{des} : research required

AGS Modeling

- Motivation
- Types of Models
- Prior Work
- Overall Model
- Future Work

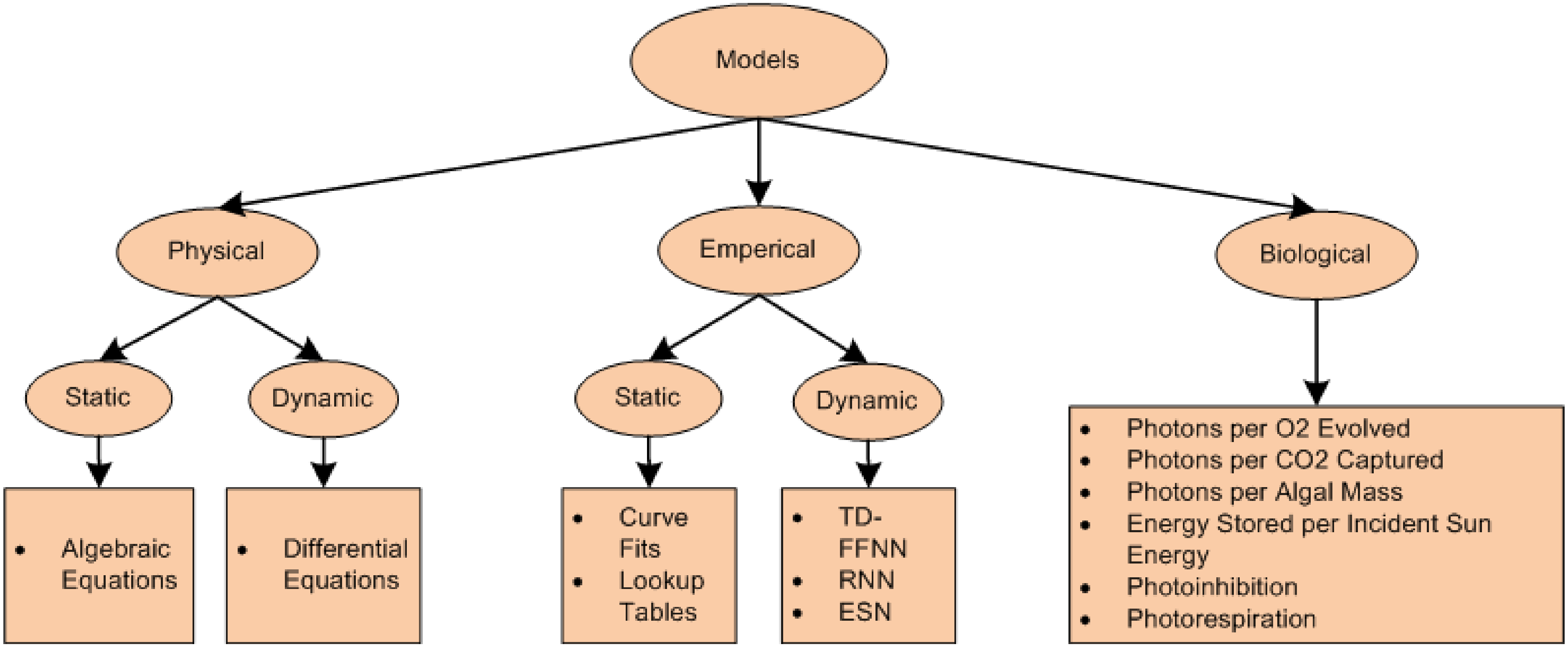
Motivation

- Understand Process
- Feedback Controller Synthesis
- FF Control

Prior Work

- Reactors
  - Open Ponds
  - Airlift Reactors
  - Flat Panel Reactors
- Modeling Techniques
  - Curve Fits
  - 1st and 2nd order LTI Systems
  - Monod Kinetics

Types of Models



Models

Physical

- Static
  - Algebraic Equations
- Dynamic
  - Differential Equations

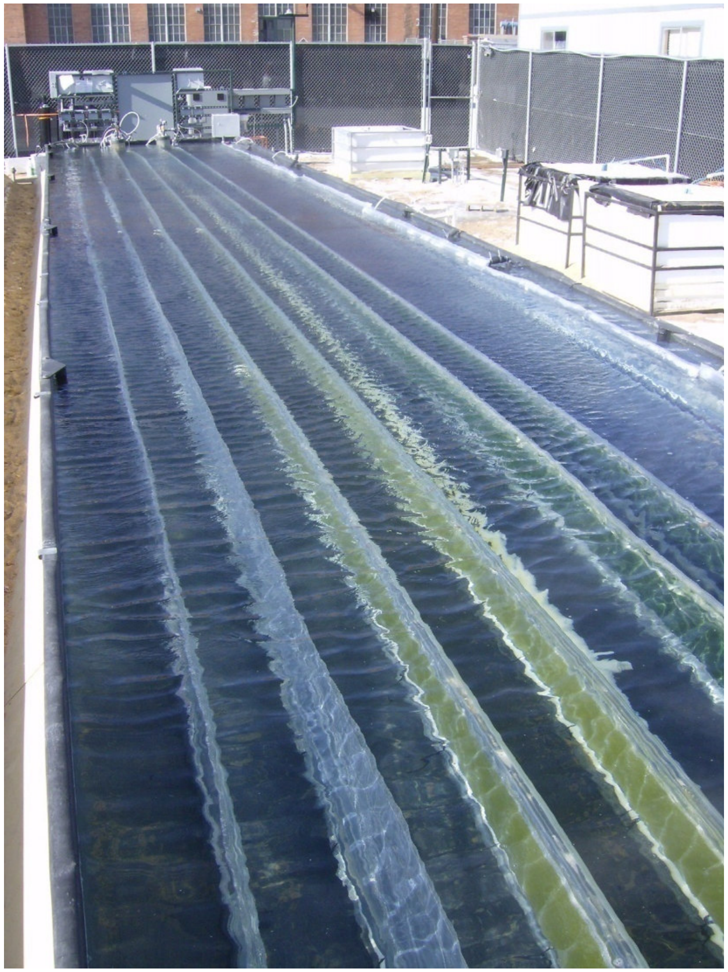
Emperical

- Static
  - Curve Fits
  - Lookup Tables
- Dynamic
  - TD-FFNN
  - RNN
  - ESN

Biological

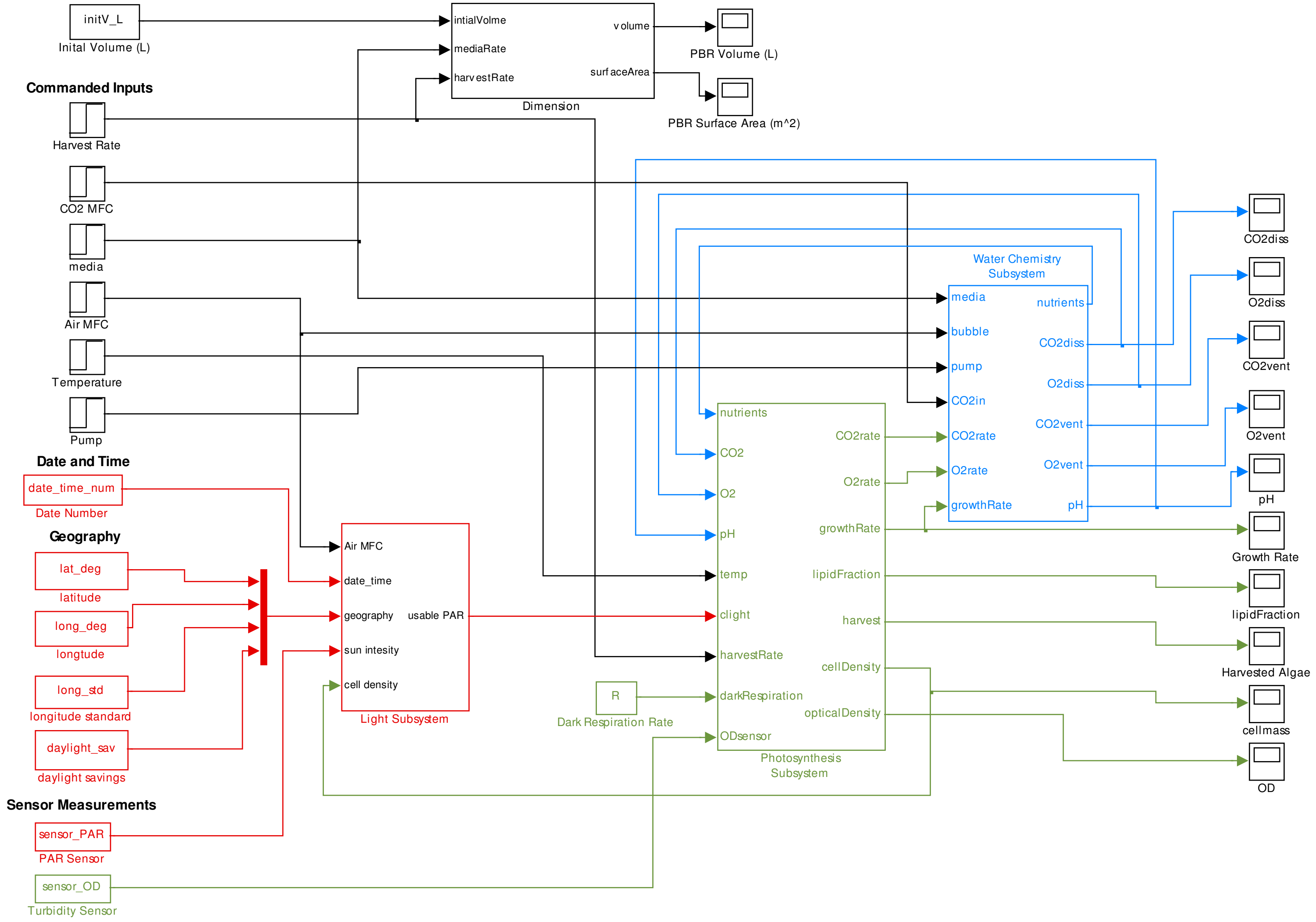
- Photons per O2 Evolved
- Photons per CO2 Captured
- Photons per Algal Mass
- Energy Stored per Incident Sun Energy
- Photoinhibition
- Photorespiration

AGS Testbed at Solix Biofuels



- Testbed AGS with 3 PBRs
- Each PBR contains 2 panels

Overall Model



Light Subsystem

- Physical / Algebraic Model
- Photosynthetically Active Radiation (PAR)
  - 43% of incident light energy
- Number of Available PAR photons
- $\mathrm{PAR}_{\mathrm{algae}} = f_1(\mathrm{PAR}_{\mathrm{sensor}},\ \text{sun position, mixing})$

Growth Model Overview

- Microalgal growth is function of incident light photons
    - Exponential for sparse cultures
    - Linear for more dense cultures
- Microalgae will respirate in the dark (i.e., loss of biomass)
- Harvesting

Growth Model Overview Cont’d

- Measures of Growth
  - Biomass produced
  - CO_2 consumed
  - O_2 produced
- Microalgae are 50% Carbon
  - 1.83 g CO_2 / g Microalgae
- 8 Moles Light / Mole O_2 Produced

Growth Model

$$\dot{m}_{\text{algae}} = K_{\text{PAR}} I_{\text{PAR}} \overline{m}_{\text{algae}} - R m_{\text{algae}} - u_D$$

$$\overline{m}_{\text{algae}} = \min(m_{\text{algae}}, m_{\text{dense}})$$

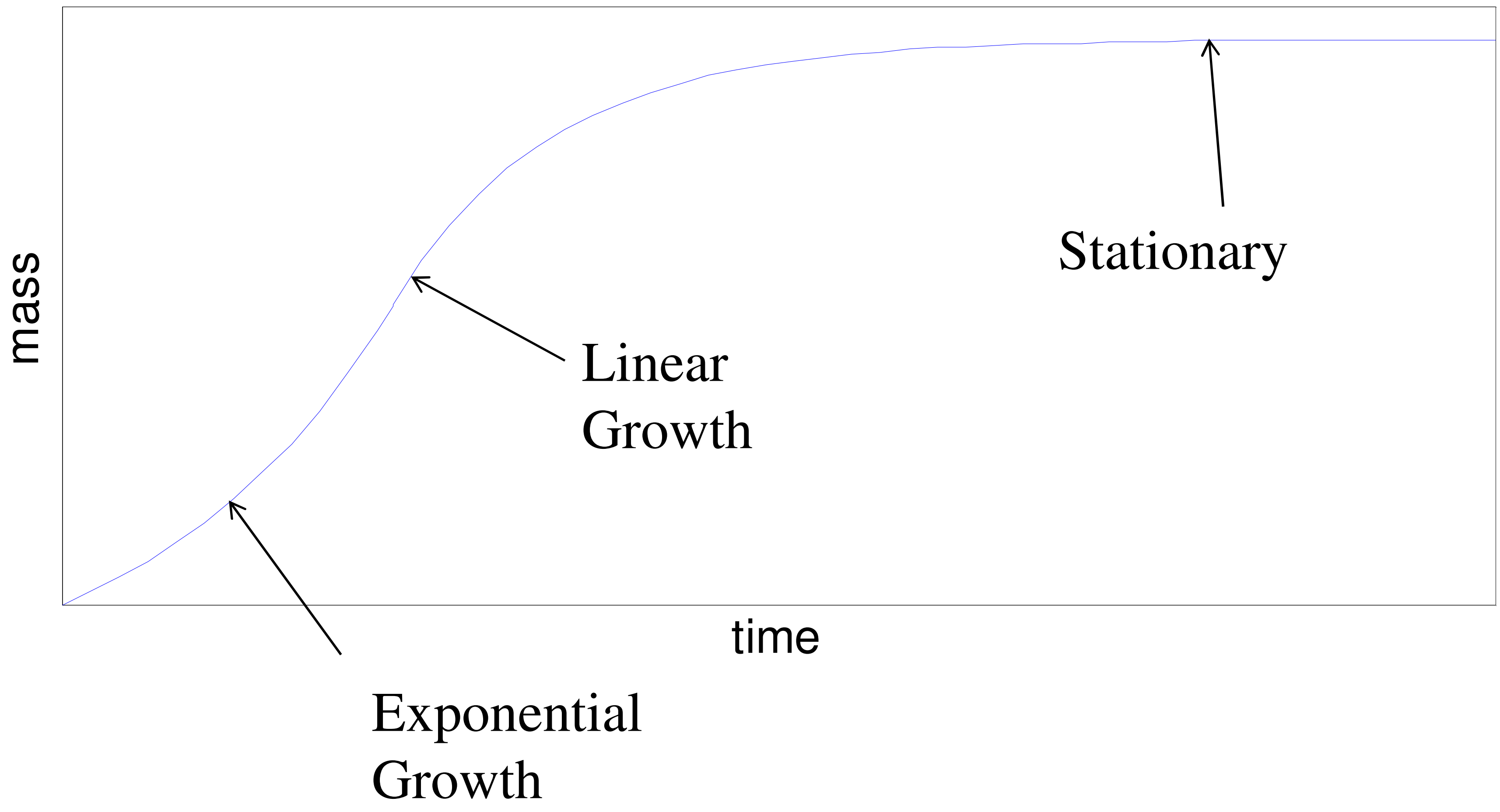
$$m_{\text{dense}} = f(m_{\text{algae}}, \text{mixing}, \text{geometry})$$

$$\dot{m}_{\text{CO}_2} = K_{\text{CO}_2} \dot{m}_{\text{algae}}$$

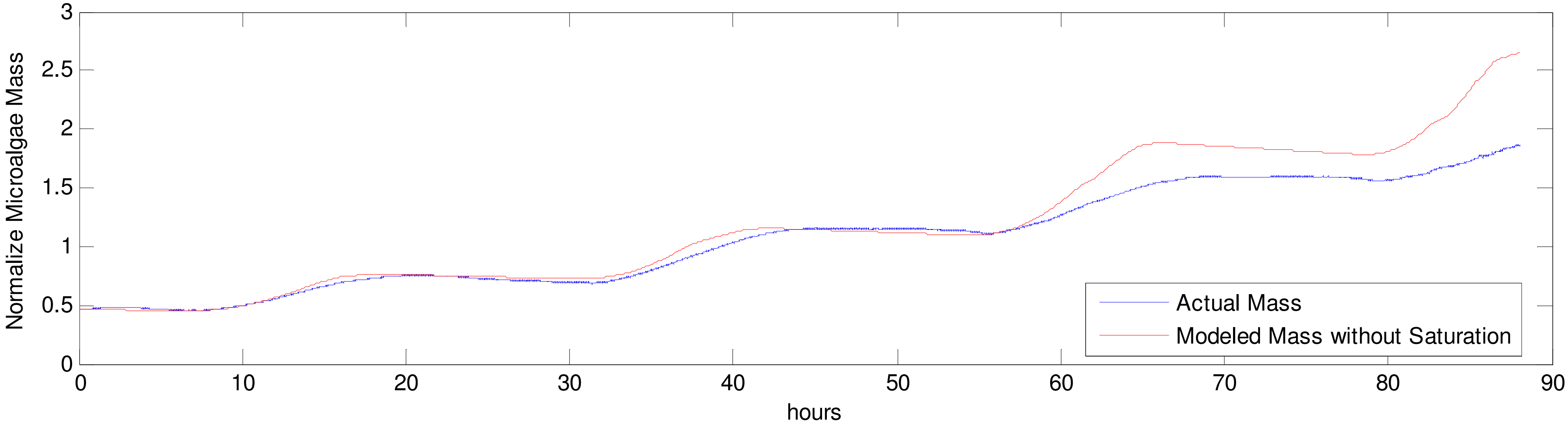
$$\dot{m}_{\text{O}_2} = K_{\text{O}_2} \dot{m}_{\text{algae}}$$

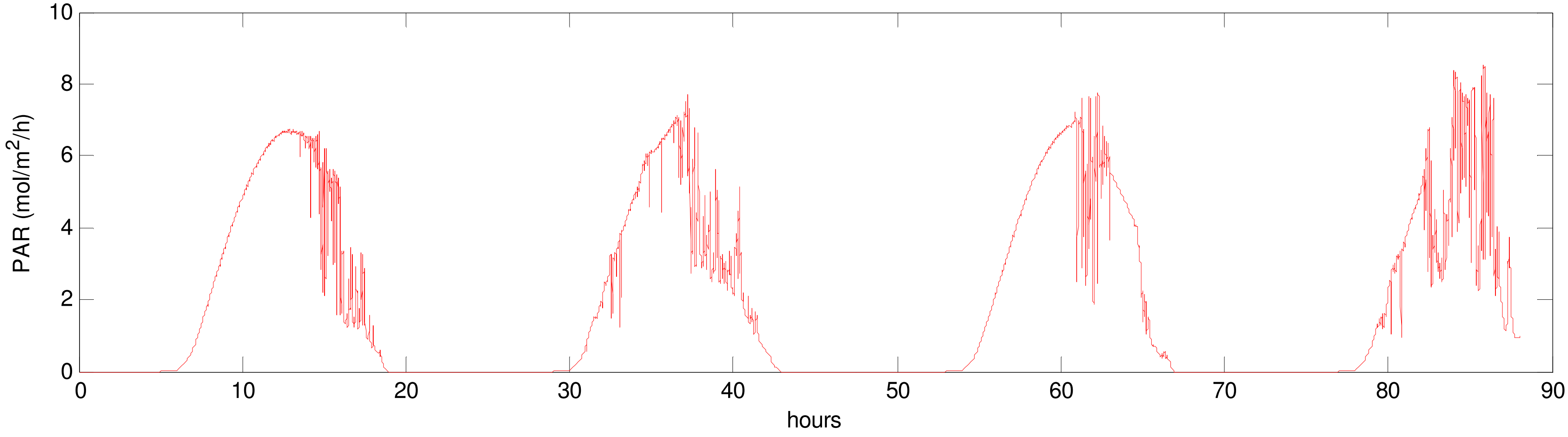
- $m_{\text{algae}} < m_{\text{dense}}$ - exponential growth ($K_{\text{PAR}} I_{\text{PAR}} - R$)
- $m_{\text{algae}} \geq m_{\text{dense}}$ - linear growth, exponetial Decay

Growth Phases

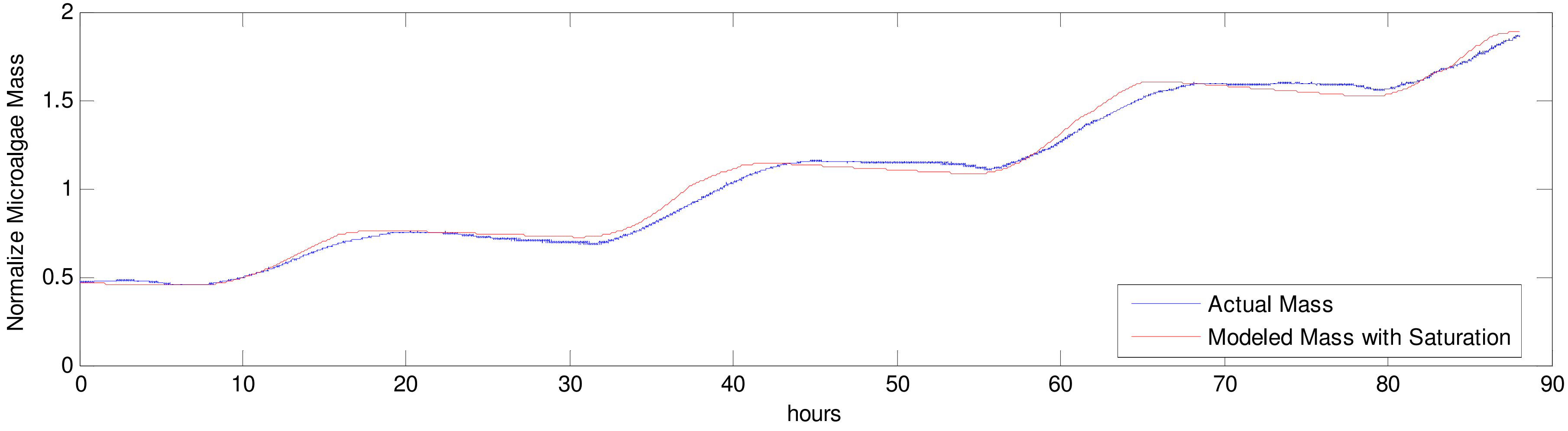


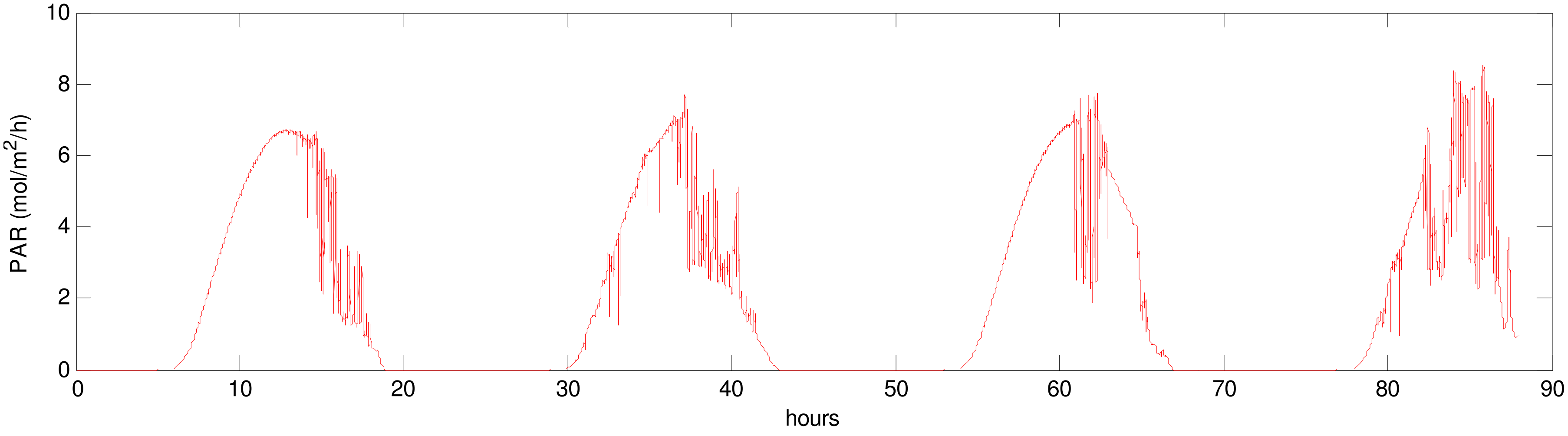
Growth Model Sim Without Saturation





Growth Model Sim With Saturation





Water Chemistry Model

- Dynamic physical and empirical model
- Mass balances
  - Input CO_2 and O_2
  - Dissolve CO_2 and O_2
  - Consumed CO_2 and O_2
  - Vented CO_2 and O_2
  - Nutrients input
  - Nutrients consumed

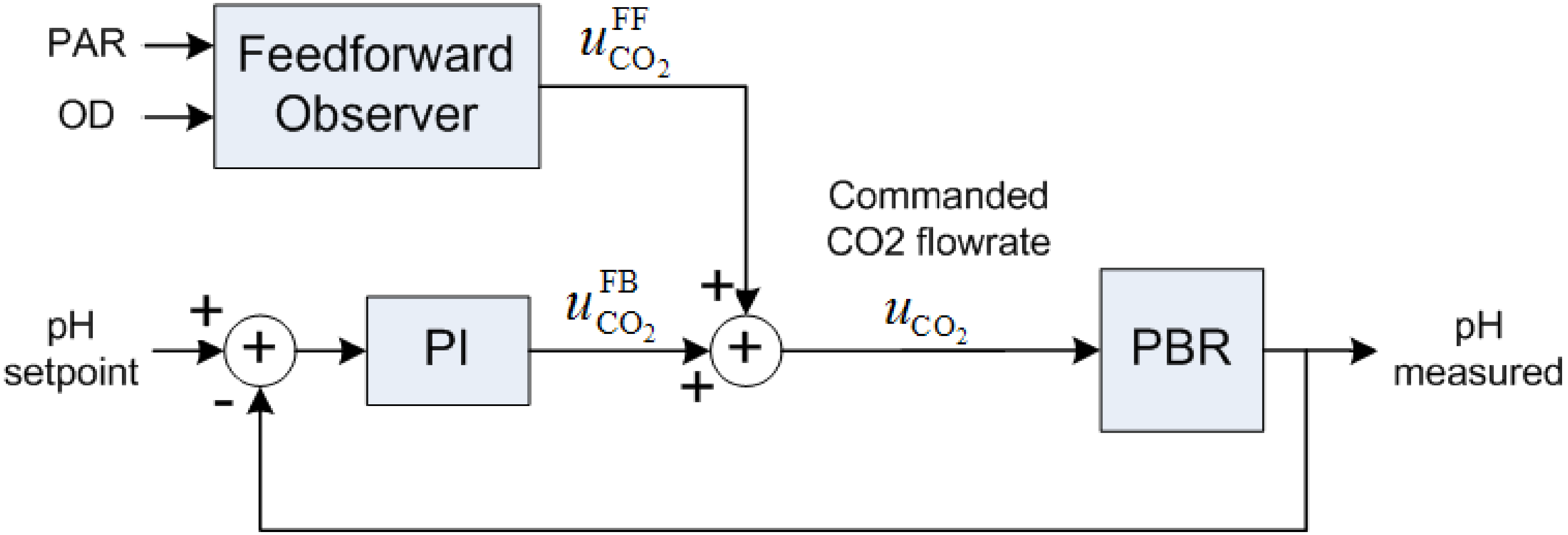
Future Work

- Define other interactions through experimentation
  - Mixing
  - Nutrient availability
- Use biological and physical based models when possible
- Lipid production model

AGS Control

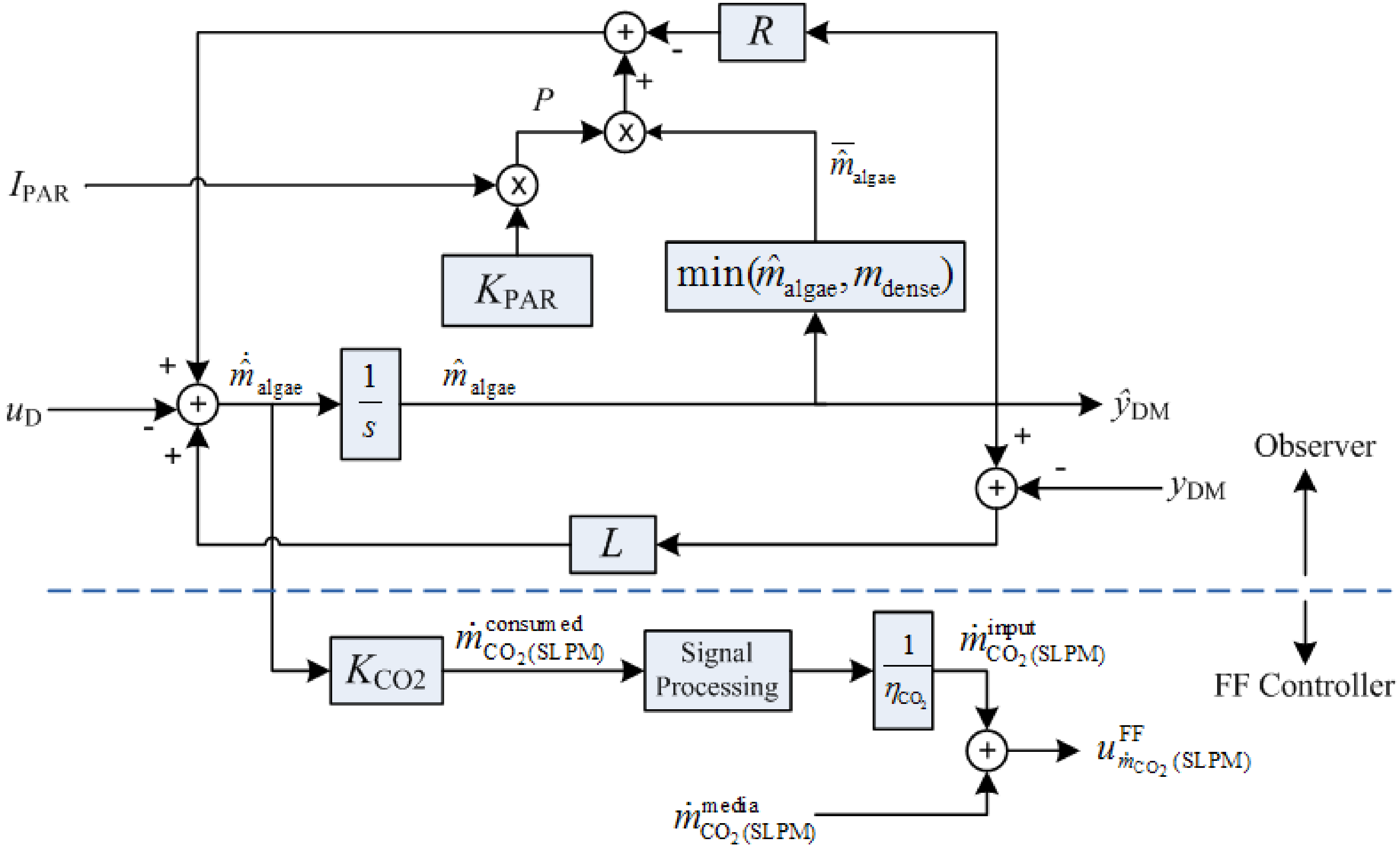
- Completed Work
  - FF + FB pH control
  - Observer-based FF controller
  - Example with FB only control
- Ongoing Research
  - Two-Stage FF Control
  - Lipid Production (w/ open Q’s)

pH Control

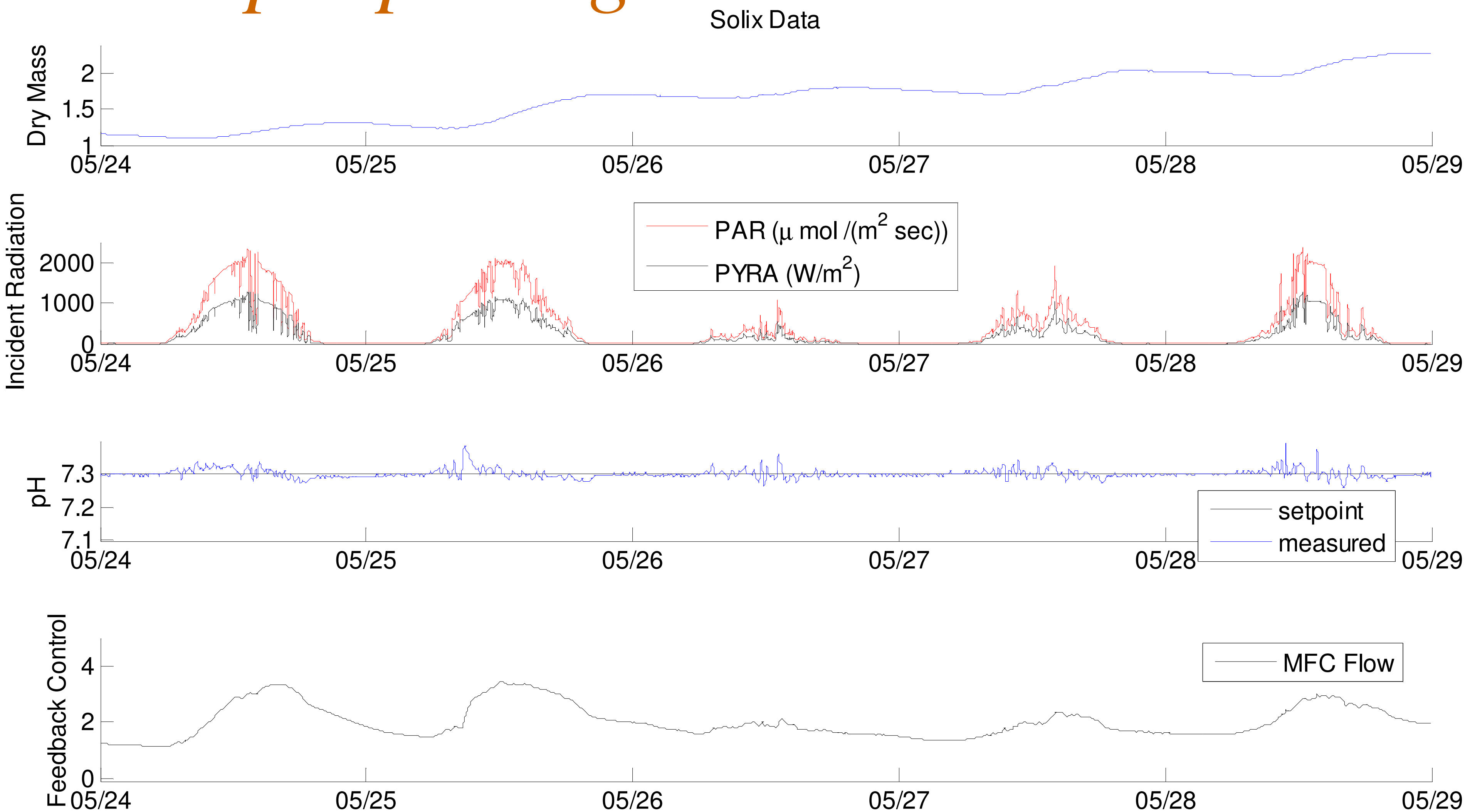


PAR
OD
Feedforward Observer
$u_{CO_2}^{FF}$
Commanded CO2 flowrate
+
$u_{CO_2}^{FB}$
+
pH setpoint
+
-
PI
u_{CO_2}
PBR
pH measured

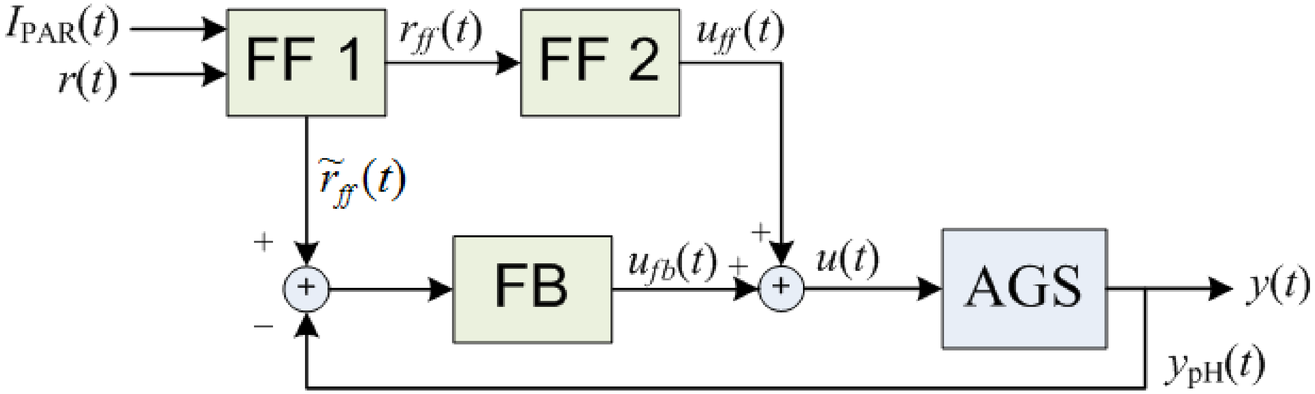
Observer-Based FF Control



Example pH regulation



Two-Stage FF AGS Control



$u_{fb}(t)$: CO_2 flow rate

$$u_{ff}(t) = \begin{bmatrix} CO_2 \text{ flow} \\ \text{nutrient rate} \\ \text{mixing} \end{bmatrix}$$

$r(t)$: target culture density
$r_{ff}(t)$: growth trajectory
$\tilde{r}_{ff}(t)$: pH trajectory for given growth

$$y(t) = \begin{bmatrix} \text{pH} \\ \text{density} \\ \text{dissolved } O_2 \\ \text{dissolved } CO_2 \end{bmatrix}$$

$$u(t) = \begin{bmatrix} u_{fb}(t) \\ 0 \\ 0 \end{bmatrix} + u_{ff}(t)$$

Lipid Production

- Microalgae respond to stress by creating lipids
  - Stress includes nutrient depletion, CO_2 limitation, and intense sun energy
- Biphasic approach
  - Grow to a target density
  - Deplete nutrients
- One-Shot Nutrient Limited Growth

Expected Contributions

- Two-Stage Adaptive FF Predictive Control
  - Theoretical framework
  - Robust performance analysis and design
- Flat Panel AGS Model
  - Physically based
- AGS Control
  - Improve Resource Utilization
- See Appendix for Other Work

Future Directions – FB Control

- Optimized Design
  - Design P_{des} and K
- Robust Performance Analysis and Design
  - Model Uncertainty
  - Smith Predictor

Future Directions – FF Control

- Nonlinear Adaptive and Predictive FF Control Methodologies
  - Techniques
  - Impact on Robustness
- NLTV Desired Closed-loop (P_{des}) Design
- NLTV G_i^{-1} Design

Future Directions – AGS

- Improve Growth Model
- Develop Lipid Model
- Improve Controller Performance
- Extend Proposed Architecture to AGS Control

Questions ?