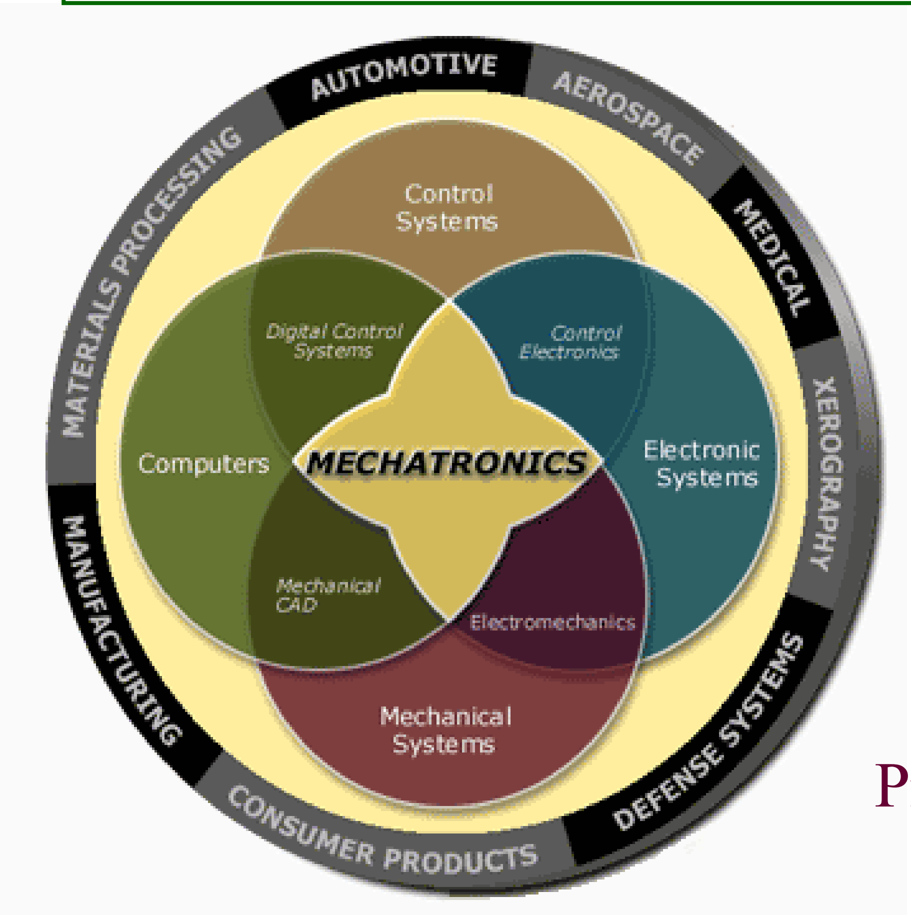
Mechatronics

The Practice of Multidisciplinary Systems Engineering



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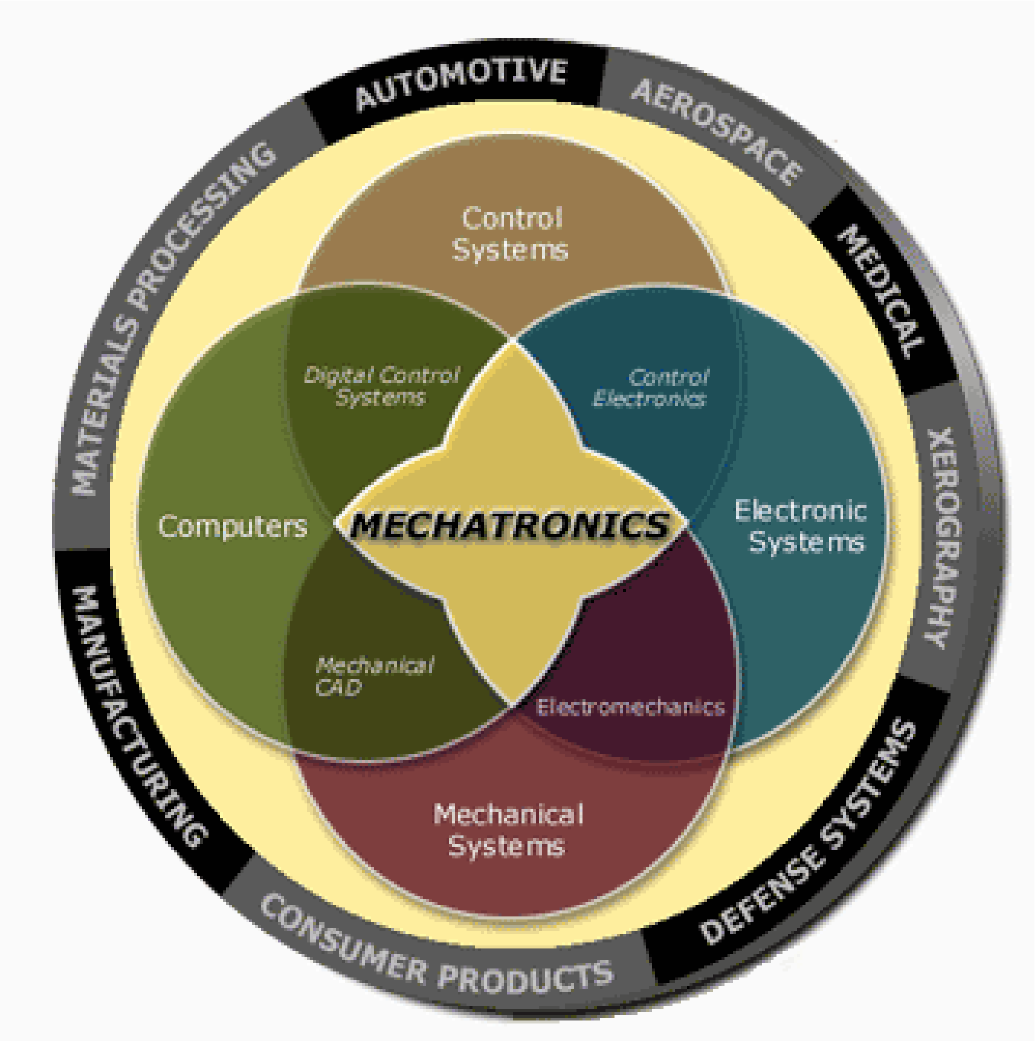
Presentation Topics

- Mechatronics
  - The What, Why, and How of Mechatronics
- Mechatronic System Design
  - Integration and Assessment Early in the Design Process
- Mechatronic System Design Case Study
  - Design → Prototype → Deploy

What is Mechatronics?

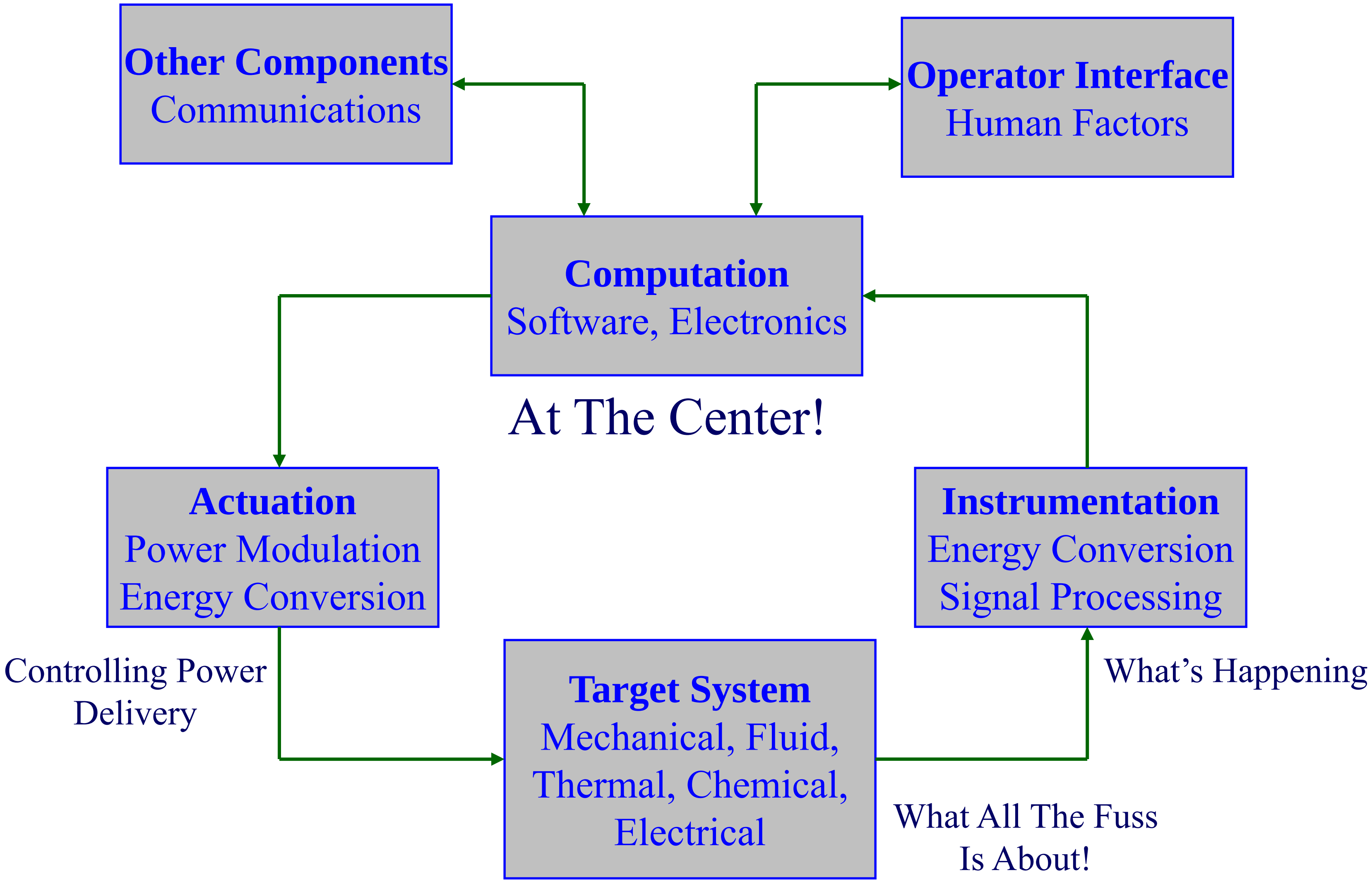


Relevant Question

How can a company stay successful in an industry where electronics, computers, and control systems are integral parts of an overall system and performance, reliability, low cost, and robustness are absolutely essential ?

Mechatronic System Elements

The 4 Central Components are energetically isolated



The WHY of Mechatronics

- Companies must:
  - have the ability to increase the competitiveness of their products through the use of technology
  - be able to respond rapidly and effectively to changes in the market place
- Mechatronic strategies:
  - support and enable the development of new products and markets
  - enhance existing products
  - respond to the introduction of new product lines by a competitor

- The adoption by a company of a mechatronic approach to product development and manufacturing provides the company with a strategic and commercial advantage:
  - through the development of new and novel products
  - through the enhancement of existing products
  - by gaining access to new markets
  - or by some combination of these factors

The HOW of Mechatronics

- The achievement of a successful mechatronics design environment essentially depends on the ability of the design team to communicate, collaborate, and integrate.
- Indeed, a major role of the mechatronics engineer is often that of acting to bridge the communications gaps that can exist between more specialized colleagues in order to ensure that the objectives of collaboration and integration are achieved.

The Design Challenge

The cost-effective incorporation of electronics, computers, and control elements in a system to achieve high performance, robustness, and reliability requires a new approach to design.

The modern engineer must draw on the synergy of

Mechatronics

Mechatronic Design

- Requires *System* Perspective
- *System* Interactions Are Important
- Requires *System* Modeling
- Control *Systems* Go Unstable
- The Realm of Mechatronics
  - High Speed, High Precision, High Efficiency
  - Highly Robust
  - Micro-Miniature

Mechatronic Design Concepts

- Direct-Drive Mechanisms
- Simple Mechanics
- System Complexity
- Accuracy and Speed from Controls
- Efficiency and Reliability from Electronics
- Functionality from Computers

Think System !

Is Mechatronics New?

- Mechatronics is simply the application of the latest, cost-effective technology in the areas of computers, electronics, controls, and mechanical systems to the design process to create more functional and adaptable products.
- **Just Good Design Practice!**
  - Many Forward-Thinking Designers and Engineers have been doing this for years!

Benefits To Industry

Starting at design and continuing through manufacture, mechatronic designs optimize the available mix of technologies to produce quality precision products and systems in a timely manner with features the customer wants.

- Shorter Development Cycles
- Lower Costs
- Increased Quality
- Increased Reliability
- Increased Performance
- Increased Benefits To Customers

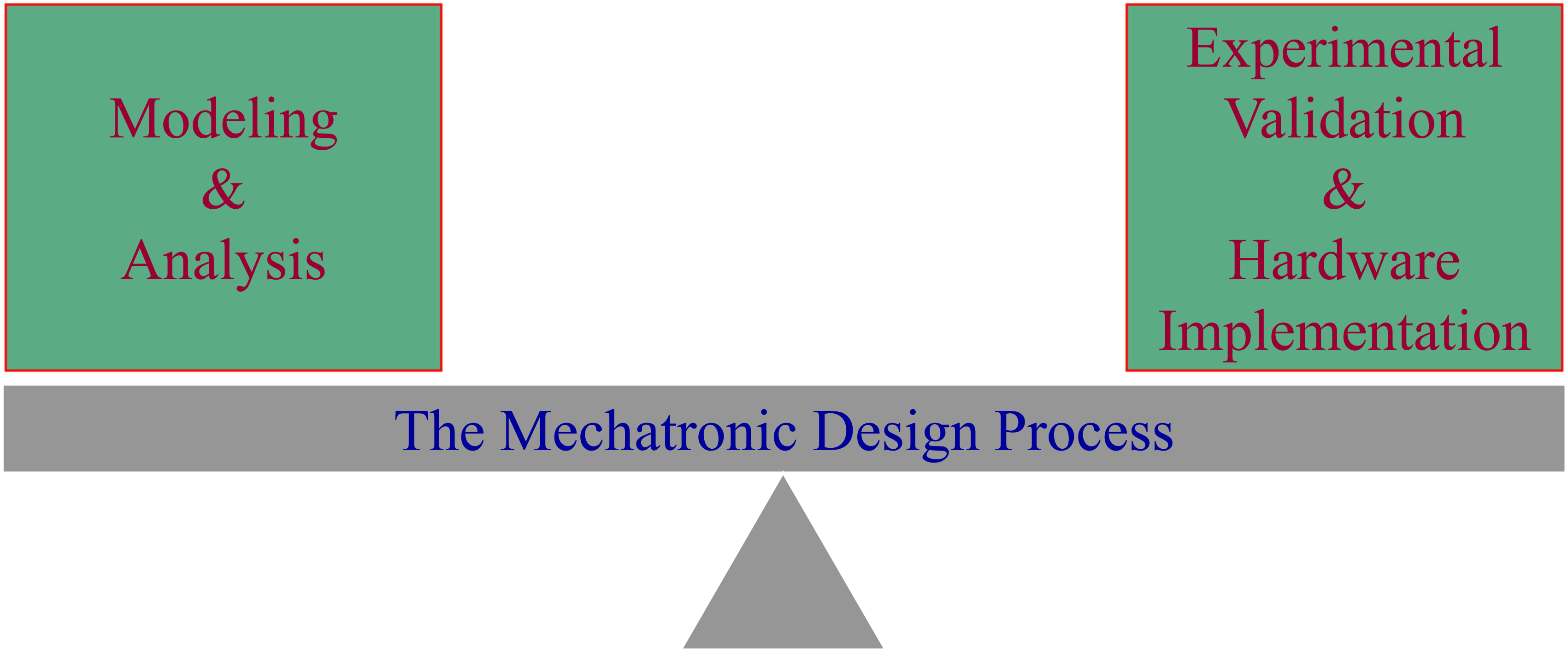
There Is Something New Here!

Mechatronics encompasses the knowledge base and the technologies required for the flexible generation of controlled motion.

Mechatronics demands horizontal integration among the various disciplines as well as vertical integration between design and manufacturing.

Mechatronics is a significant design trend – an evolutionary development – a mixture of technologies and techniques that together help in designing better products.

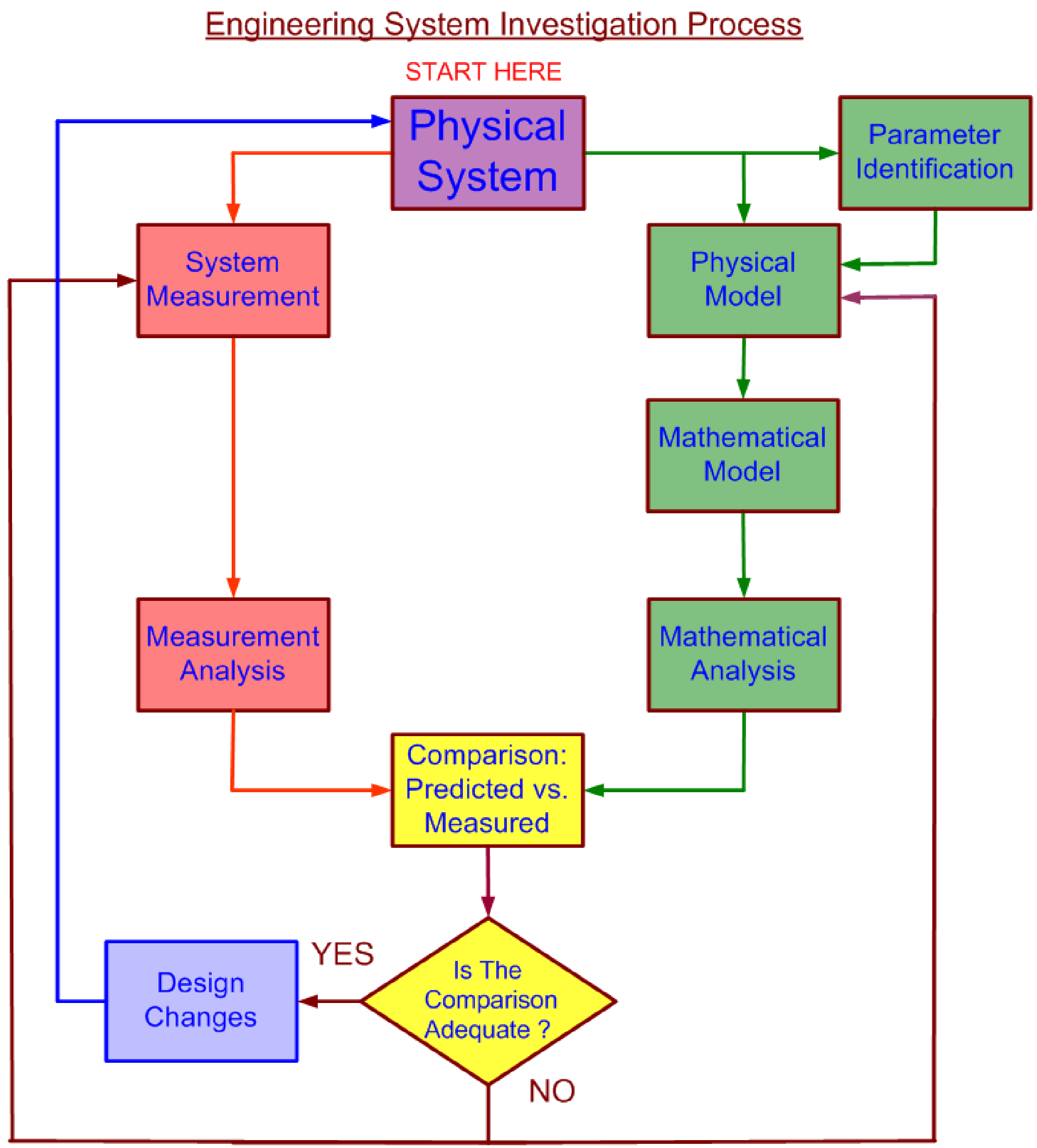
Balance: The Key to Success



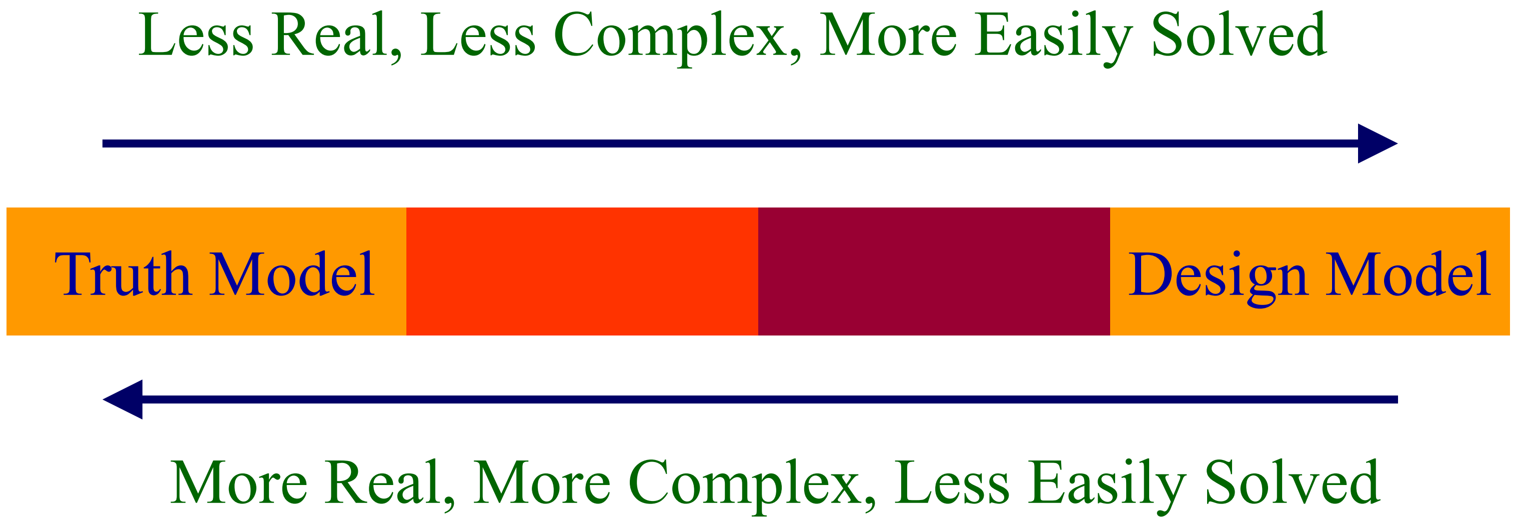
Computer Simulation Without Experimental Verification Is At Best Questionable, And At Worst Useless!

Engineering System Investigation Process

The cornerstone of modern engineering practice !



Modeling: Physical and Mathematical

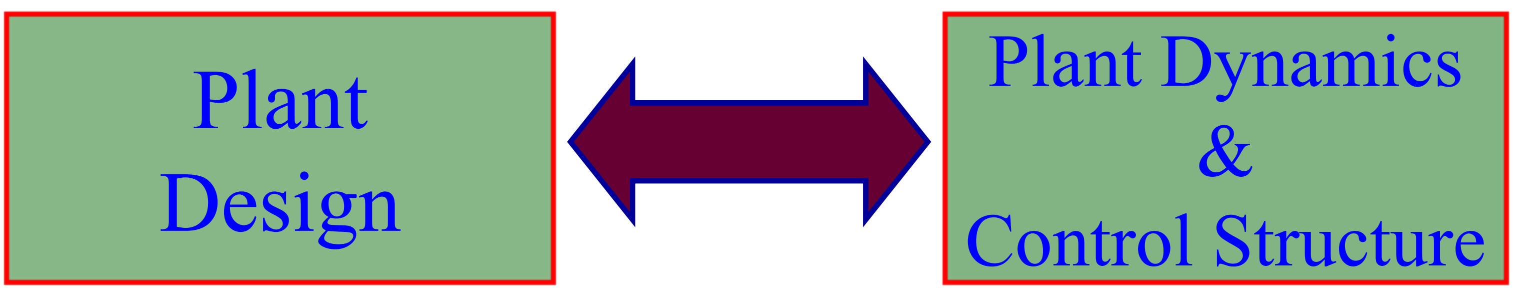


Hierarchy Of Models

Always Ask: Why Am I Modeling?

Design + Control Integration

- Traditionally, plant design and control system design have been separate activities. Control system design normally has not been initiated until after the plant design is well underway.
- *Serious Limitations to this approach!* Dynamics and Control Issues need to be considered early in the plant design.



What Skills Are Currently Lacking?

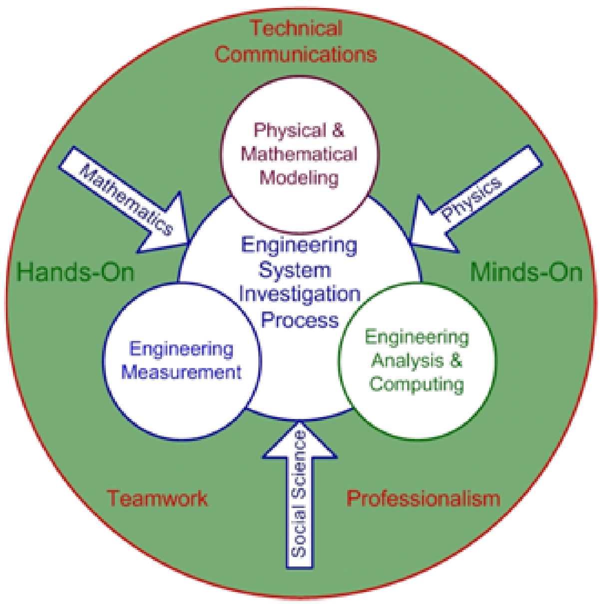
- Control Design and Implementation is still the domain of the specialist.
- Controls and Electronics are still viewed as afterthought add-ons.
- Very few practicing engineers perform any kind of physical and mathematical modeling.
- Mathematics is a subject that is not viewed as enhancing one’s engineering skills but as an obstacle to avoid.
- Very few engineers have the balance between analysis and hardware essential for success in Mechatronics.

What is the best way to train the 21st century engineer ?

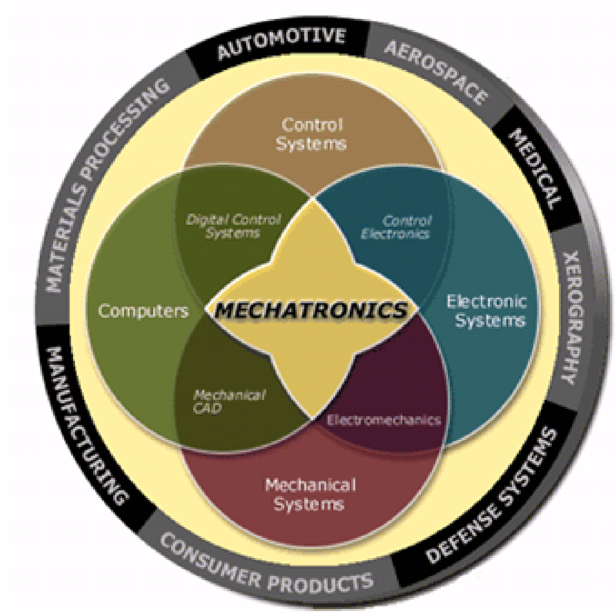
Industrial Interaction

Rensselaer SHAPES **Philosophy**

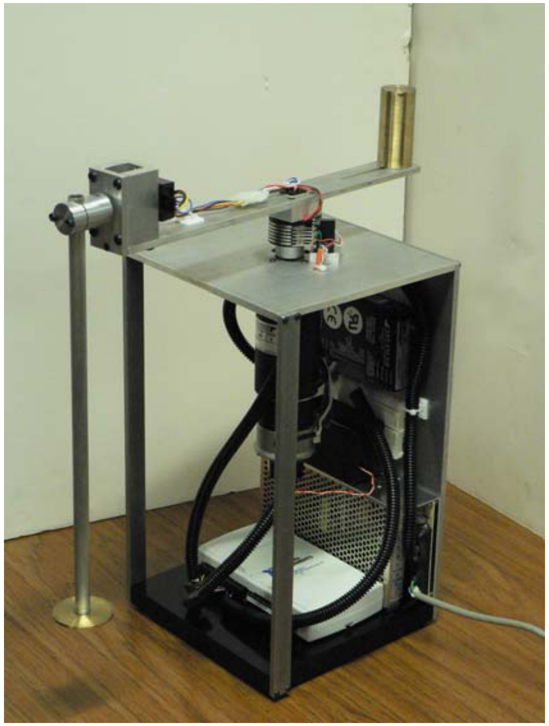
Engineering Curriculum



Freshman Year To Senior Year

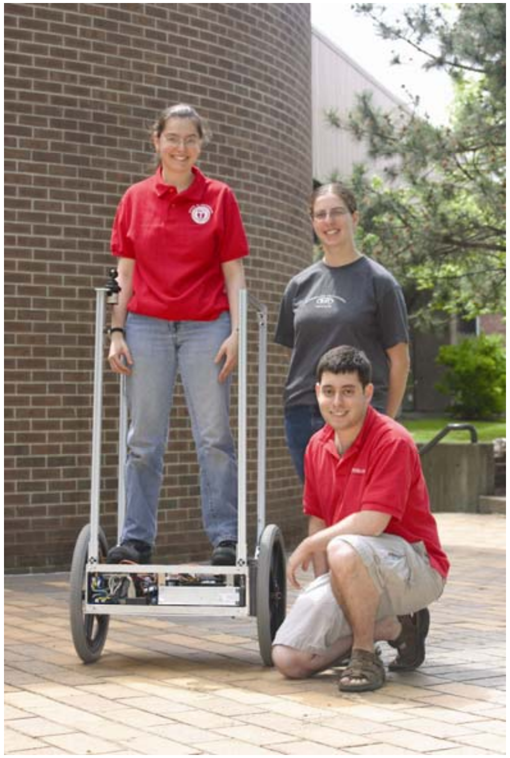


Mechatronic Teaching Systems

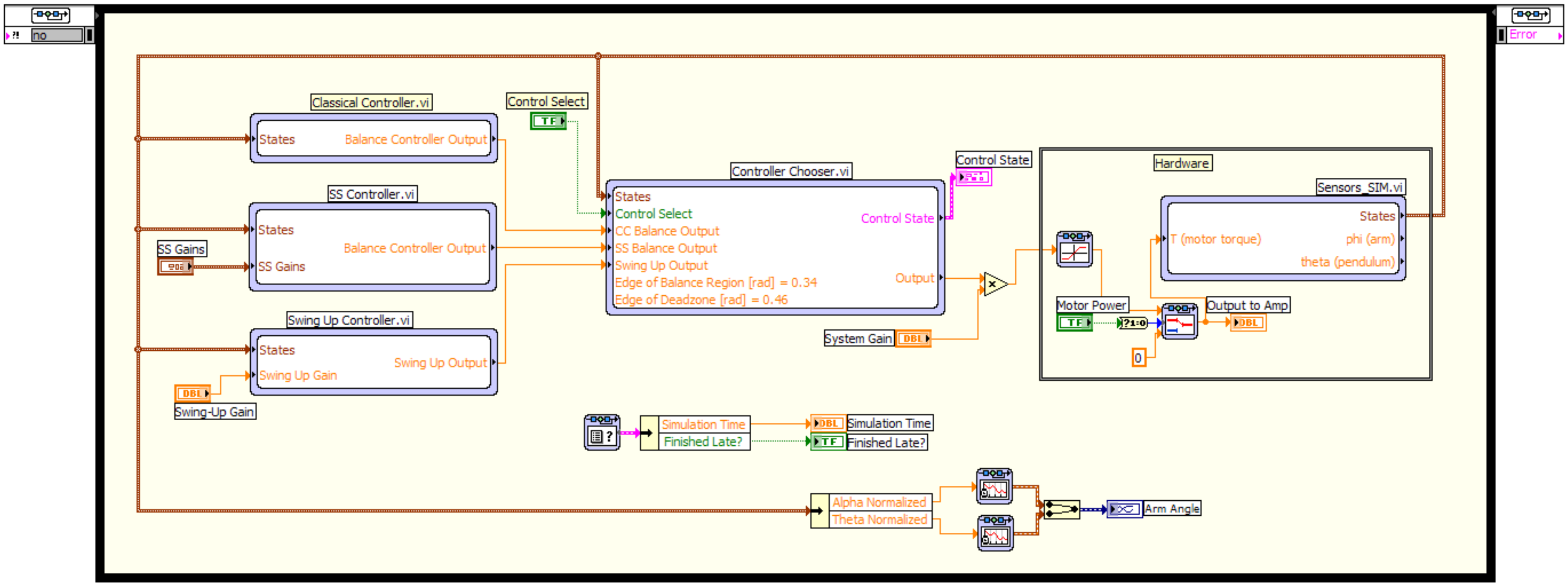


Rotary Inverted Pendulum System

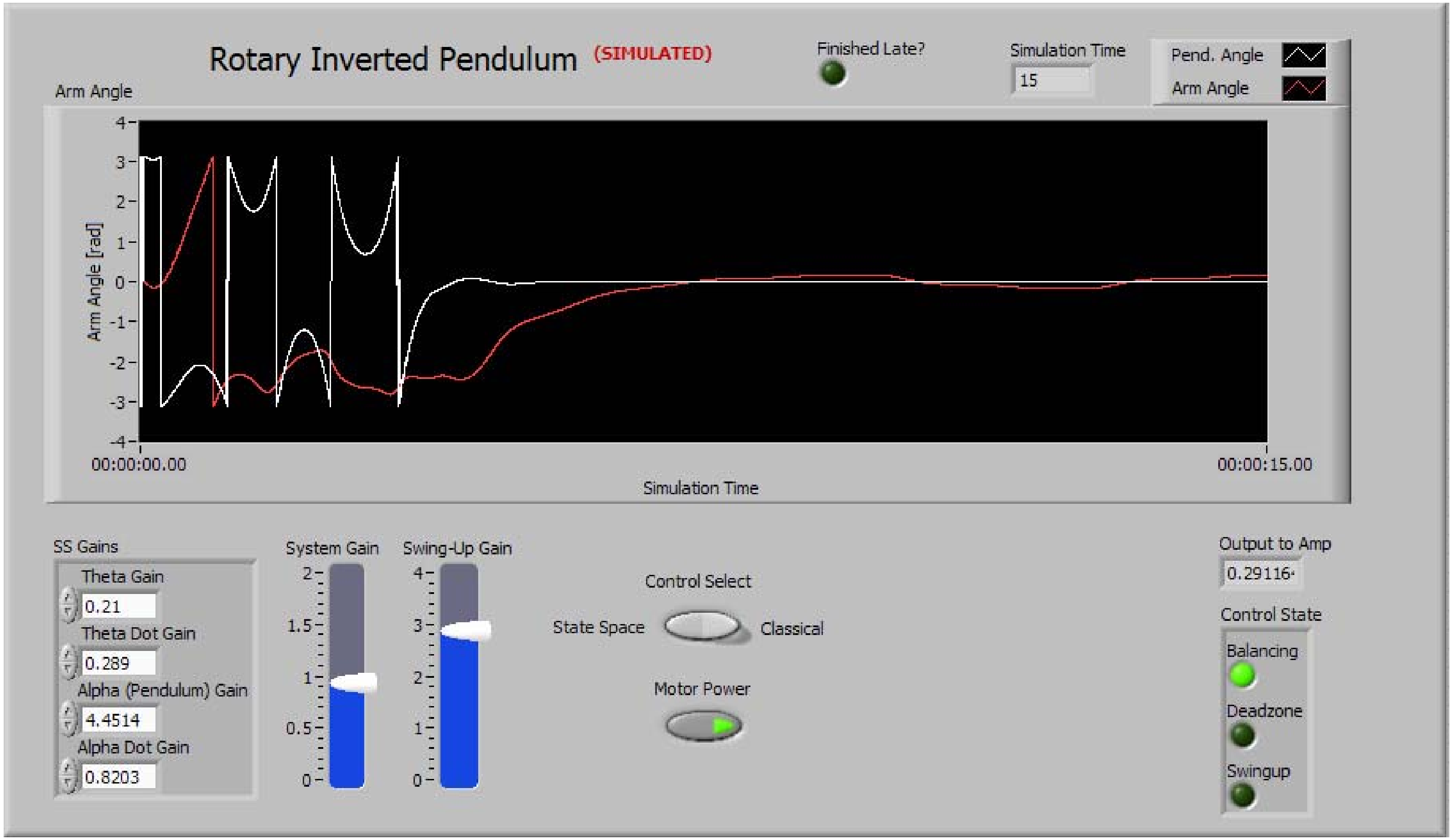
Balancing Human Transporter



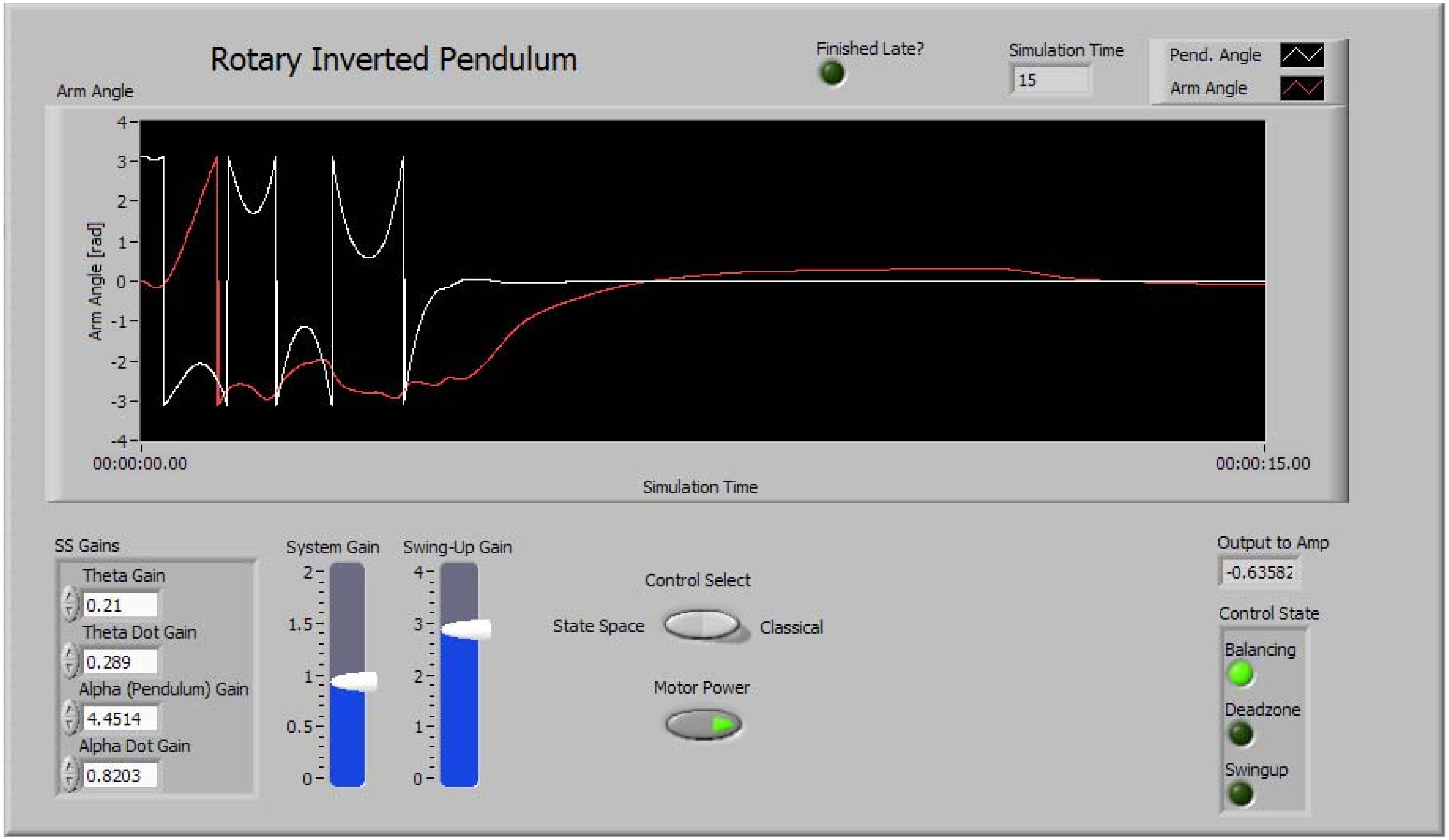
LabVIEW Rotary Inverted Pendulum Block Diagram



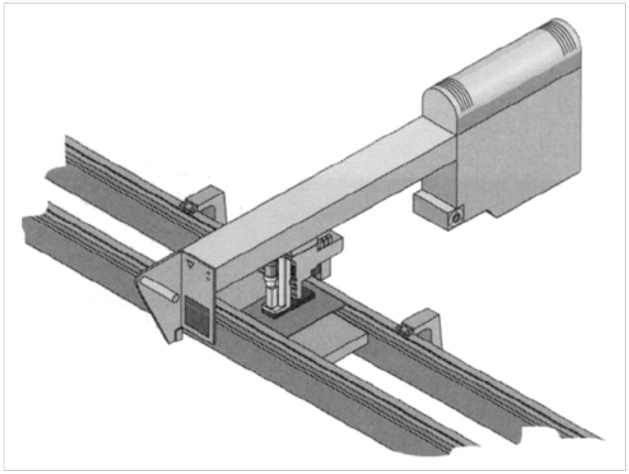
Rotary IP Simulation Results

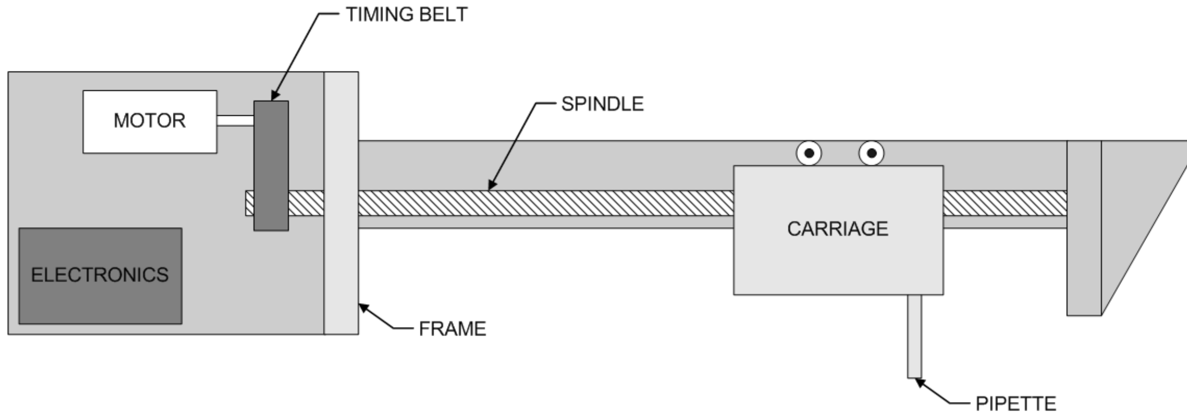


Rotary IP Controlled System Response

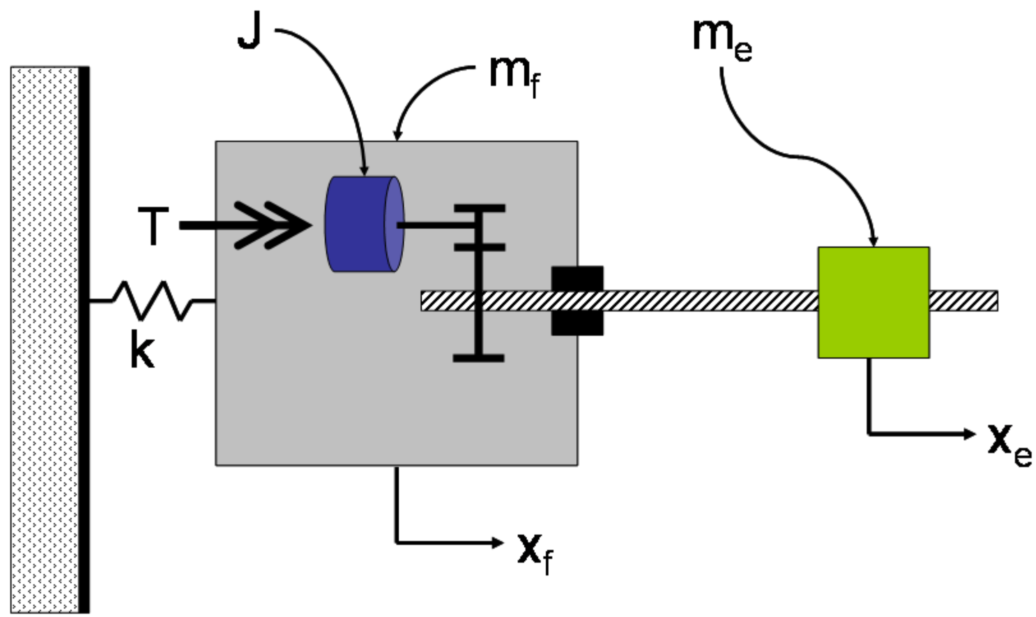


Mechatronic System Design
Integration and Assessment Early in the Design Process





Fast Component Mounter Placement Module

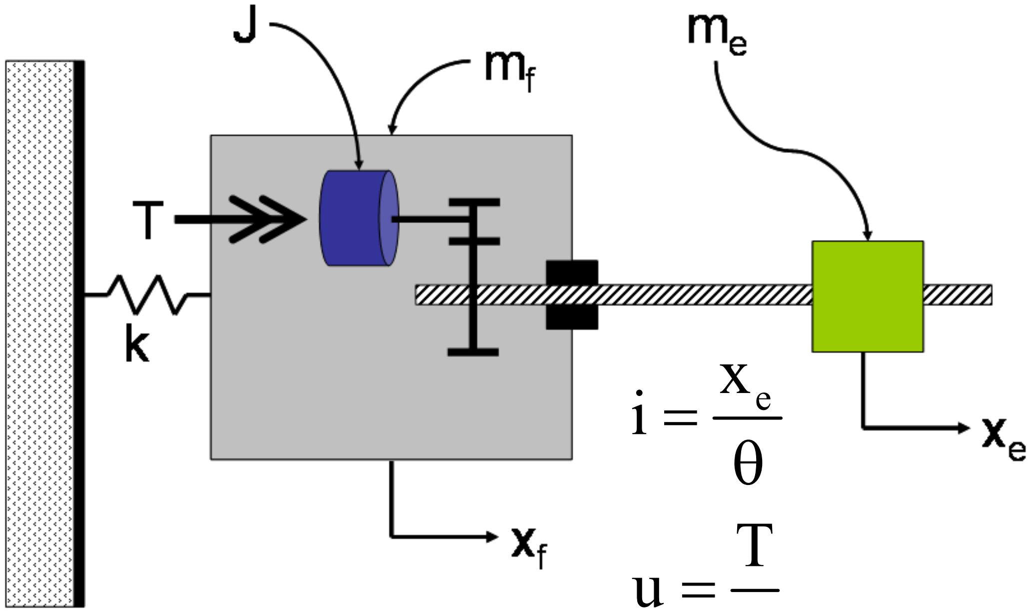


- Conceptual Integrated Design of Controlled Electro-Mechanical Motion Systems
  - Goal: Identify the performance-limiting factors of the design proposal(s) and choose satisfactory specifications for these factors.
  - Factors which dominantly determine system performance:
    - Task specification: motion distance, motion time, required positional accuracy after motion time
    - Path Generator: smoothness of the path
    - Controller: proportional and differential gains
    - Plant: total mass to be moved, lowest eigenfrequency, location of the position and velocity sensors

– The dominant plant factors motivate the use of simple 4^{th}-order models which take only the rigid-body mode and the lowest mode of vibration into account. These models have the following characteristics:
  - Simple and of low order
  - Have a small number of parameters
  - Completely describe the performance-limiting factor
  - Are a good basis to provide reliable estimates of the dominant dynamic behavior and the attainable closed-loop bandwidth

– A Mechatronic Approach to Design allows for the assessment of the influence of these design factors on the system performance.

- Classes of Electromechanical Motion Systems
  - Flexible Mechanism, Flexible Frame
  - Flexible Actuator Suspension, Flexible Guidance
- Example of a Flexible Actuator Suspension
  - Type AR when actuator position is measured
  - Type RA when end-effector position is measured



$$i = \frac{x_e}{\theta}$$

$$u = \frac{T}{i}$$

$$m = \frac{J}{i^2} + m_e = \text{moving mass}$$

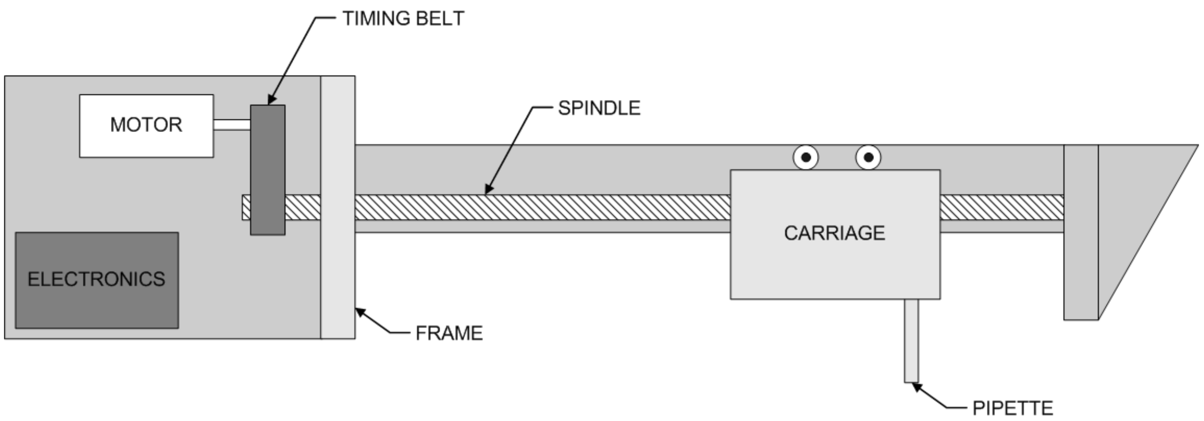
$$\omega_r = \sqrt{\frac{\left(J + i^2 m_e\right)k}{J\left(m_e + m_f\right) + i^2 m_e m_f}}$$

$$\omega_{ar} = \sqrt{\frac{k}{m_e + m_f}} \qquad \omega_{ar} = \sqrt{\frac{k}{m_f}}$$

$$y = i\theta \qquad y = x_e$$

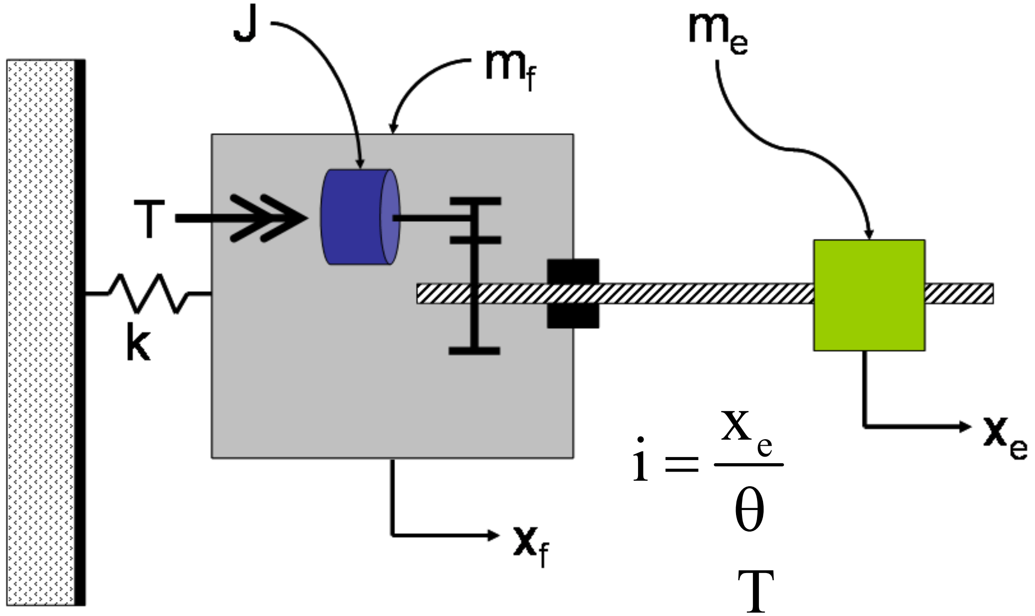
- Specifications for this Electromechanical Device

Fast Component Mounter Placement Module



  - Maximum error $e_0 = 100\ \mu m$
  - Motion time $t_m = 250$ ms
  - Motion distance $h_m = 0.15$ m
  - Settling time $t_s = 30$ ms
  - Maximum acceleration $a_{max} = 10\ m/s^2$
  - Maximum velocity $v_{max} = 1$ m/s
- Goal: Satisfy design requirements in a short design cycle using only plant knowledge available at the conceptual design stage

- Simple Model



$$i = \frac{x_e}{\theta}$$

$$u = \frac{T}{i}$$

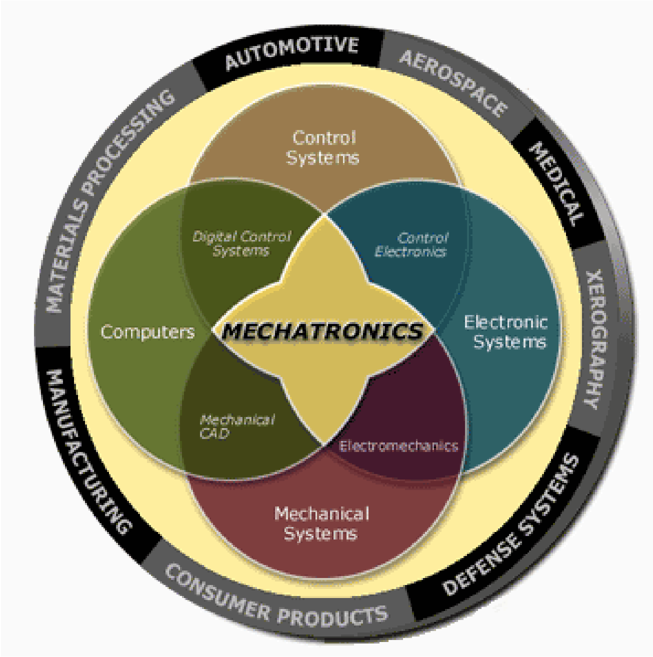
- Parameter Values
  - Motor mass (J/i^2) $m_m = 6.53$ kg
  - Frame stiffness $k = 4.3E6$ N/m
  - Frame mass $m_f = 16.5$ kg
  - End-effector mass $m_e = 2.3$ kg

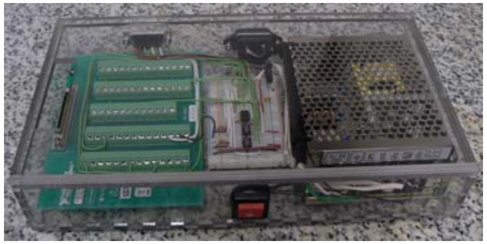
- Summary
  - The aim of conceptual design is to obtain a feasible design for the path generator, control system, and electromechanical plant with appropriate sensor locations in an integrated way.
  - Electromechanical motion systems are classified by four types using standard 4th-order plant transfer functions.
  - Dimensionless quantities are used to characterize closed-loop behavior (i.e., reference path generator, controller, and plant) and standard closed-loop transfer functions are defined.
  - Standard solutions are determined for these standard problems and an assessment method is developed.

- Conclusions
  - Using minimal plant knowledge, the assessment method provides the designer with relevant knowledge about the design process, early in the design process.
  - The assessment method can quickly provide insight into the design problem and feasible goals and required design efforts can be estimated at an early stage.
- Reference for this Section

  - E. Coelingh, T. deVries, and R. Koster, "Assessment of Mechatronic System Performance at an Early Design Stage," IEEE/ASME Transactions on Mechatronics, Vol. 7, No. 3, September 2002, pp. 269-279.

Mechatronics: Design → Prototype → Deploy
Balancing Robot & Human Transporter

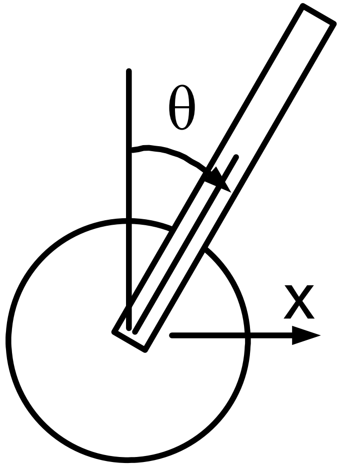




Nonlinear Equations of Motion:

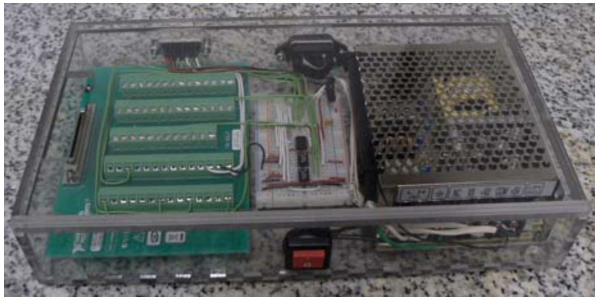
$$\left(\bar{I} + m\bar{r}^2\right)\ddot{\theta} - B\frac{\dot{x}}{\bar{r}} + m\ddot{x}\bar{r}\cos\theta - mg\bar{r}\sin\theta = -T_d + T_f$$

$$\left(m + m_w + \frac{\bar{I}_w}{r^2}\right)\ddot{x} + \left(m\bar{r}\cos\theta\right)\ddot{\theta} - m\bar{r}\dot{\theta}^2\sin\theta + \left(\frac{B}{r^2}\right)\dot{x} = \frac{1}{r}\left(T_d - T_f\right)$$

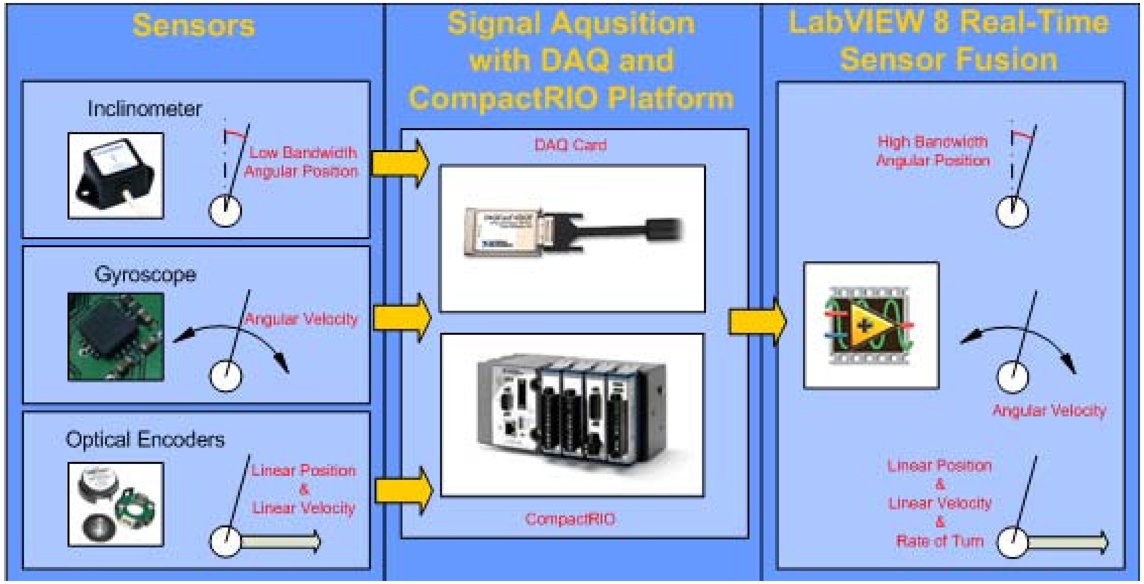


Simplifying Assumptions:

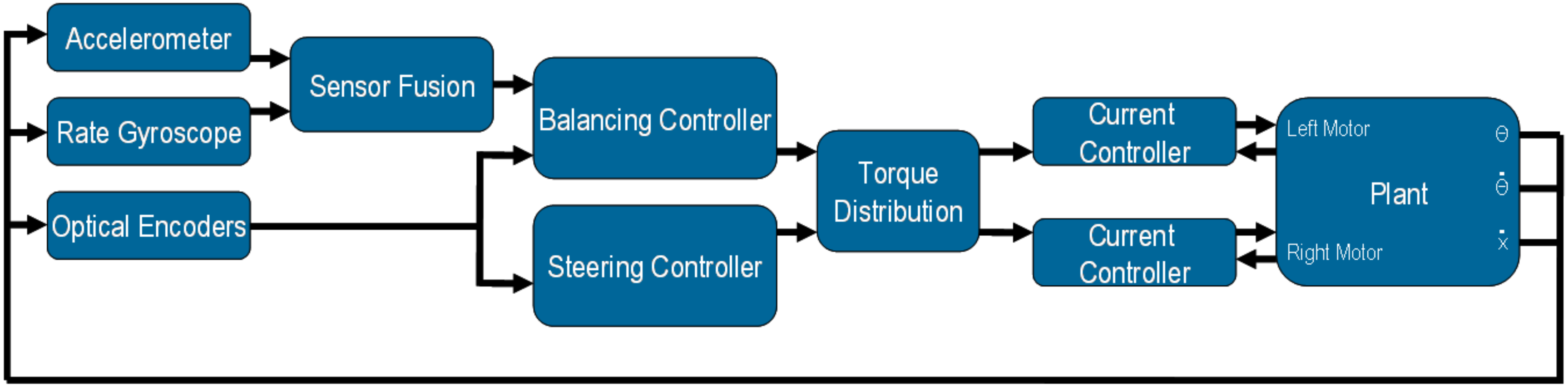
- Two degrees of freedom: x and θ
- Wheels roll without slipping
- Rotating structure is a rigid body
- Both wheel motors mounted to rotating body are identical
- Rate gyro and inclinometer give instantaneous response

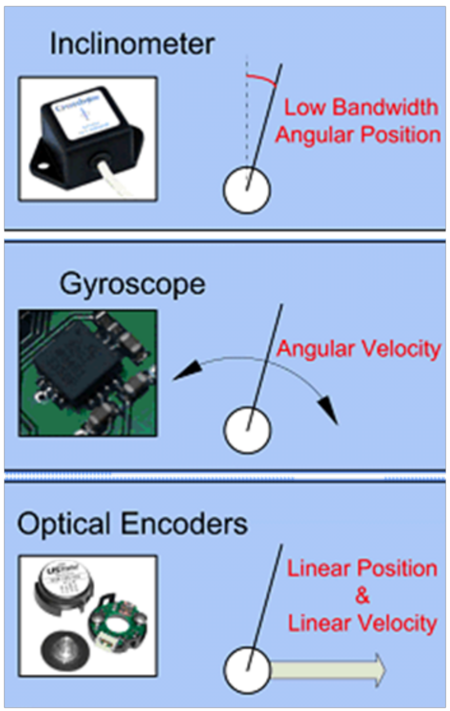


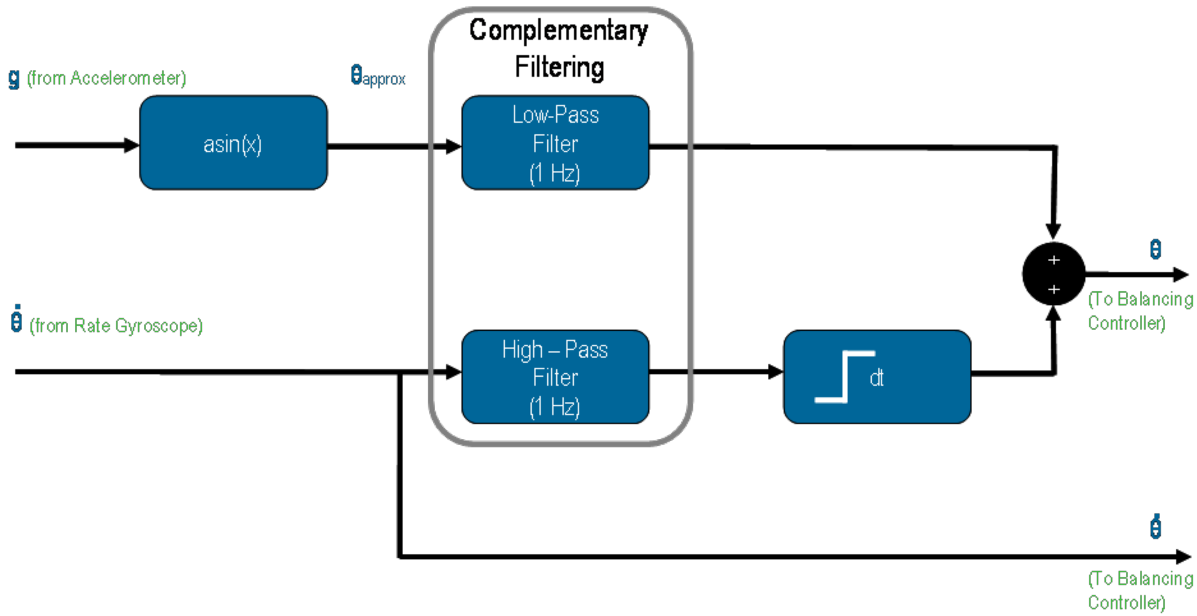
RPI Mechatronics Balancing Robot



RPI Mechatronics Human Transporter


Accelerometer
Rate Gyroscope
Optical Encoders
Sensor Fusion
Balancing Controller
Steering Controller
Torque Distribution
Current Controller
Current Controller
Left Motor
Plant
Right Motor
θ
$\dot{\theta}$
$\dot{x}$


Inclinometer
Low Bandwidth Angular Position
Gyroscope
Angular Velocity
Optical Encoders
Linear Position & Linear Velocity


g (from Accelerometer)
asin(x)
θ_{approx}
Complementary Filtering
Low-Pass Filter (1 Hz)
High – Pass Filter (1 Hz)
$\dot{\theta}$ (from Rate Gyroscope)
dt
+
+
θ
(To Balancing Controller)
$\dot{\theta}$
(To Balancing Controller)