Modeling,Simulation and Implementation using MATLAB & Simulink

Dhirendra Singh
Application Engineer, MathWorks
dsingh@mathworks.com
## Agenda – Day 1

### Day 1

<table>
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<tr>
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  • Multi-Body Dynamics Simulation using SimMechanics |
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  • Implement Control on Low cost hardware - Arduino  
  • Demo of Magnetic Levitation System |
| 1:00 pm - 2:00 pm | Lunch Break                                                            |
Key Industries

- **Aerospace and Defense**
- Automotive
- Biotech and Pharmaceutical
- Communications
- **Education**
- Electronics and Semiconductors
- Energy Production
- Financial Services
- Industrial Automation and Machinery
July 2014 News

IEEE Spectrum used 12 different metrics to compare programming language popularity and use.

Data sources include Google CareerBuilder, and Github.
Supporting Innovation
MATLAB Central

- Open exchange for the MATLAB and Simulink user community
- 800,000 visits per month
  - 50% increase over previous year

File Exchange
- Free file upload/download, including MATLAB code, Simulink models, and documents
- File ratings and comments
- Over 9,000 contributed files, 400 submissions per month, 25,500 downloads per day

Newsgroup and Web Forum
- Technical discussions about MATLAB and Simulink
- 200 posts per day

Blogs
- Read posts from key MathWorks developers who design and build the products

Based on Feb-March 2009 data
Classroom Resources at mathworks.in

Robotics and Mechatronics

Classroom Resources
Use MATLAB and Simulink to teach key areas in robotics and mechatronics, such as:
- Kinematics and dynamics
- Motor control and computer vision
- Multi-domain simulation and optimization
- Electromechanical systems

Group by Department

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<tr>
<th>Title</th>
<th>Summary</th>
<th>Resource Type</th>
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<tr>
<td>Simulink models and demo hardware for control design (from B &amp; R Automation)</td>
<td>Simulink models for Airball and Reaction Wheel Pendulum systems</td>
<td>Downloadable code or models</td>
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<td>MATLAB and Simulink interface to a Robotino® mobile robot system</td>
<td>MATLAB and Simulink libraries to control a Robotino robot over a USB or TCP/IP interface</td>
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<td>Control Hardware/Software solutions for teaching mechatronics</td>
<td>Integrated hardware/software solutions (based on Simulink) and course material for mechatronics</td>
<td>Course materials</td>
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<td>Teaching Mechatronics Using MATLAB and Simulink</td>
<td>Webinar on using Simulink to model, analyze, and visualize mechatronic systems</td>
<td>Video</td>
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Teacher Activities

- **Before a course**
  - Define learning objectives
  - Find or write material
  - Decide about teaching forms
  - Decide about examination

- **During a course**
  - Lectures
  - Practical sessions
  - Question hours
  - Communication with students

Am I addressing all the challenges?
Calculus -

After explaining to a student through various lessons and examples that:

$$\lim_{x \to 8} \frac{1}{x-8} = \infty$$

I tried to check if she really understood that, so I gave her a different example. This was the result:

$$\lim_{x \to 5} \frac{1}{x-5} = \infty$$

FAIL
Problem 1:
Find Horizontal Asymptotes and Absolute Maxima and Minima for below function

\[
F(x) = \frac{5x^2 + 8x - 3}{3x^2 + 2}
\]
Where is Symbolic Computing Used in Academia?

Anyone applying engineering, scientific, and mathematical principles to find analytical solutions to technical problems

- **Mathematics departments**
  - Foundation courses: Calculus, Differential equations, Linear algebra, …
  - Advanced courses: Number theory, Advanced algebra, …

- **Engineering departments**
  - Mechanical: System dynamics, Heat transfer, Fluid dynamics, …
  - Electrical: Circuit analysis, Signals and systems, …
  - Civil: Solid mechanics, Structural analysis, …

- **Physics and science departments**
  - Physics: Mechanics, Optics, Electromagnetics
  - Life sciences: Bioinformatics, Computational Biology, Systems Biology
Symbolic Math Toolbox Libraries

- **Calculus**
  - Differentiation
  - Integrals (definite, indefinite)
  - Jacobian
  - Taylor series
  - Limits

- **Solving Equations**
  - Algebraic Equations
  - Ordinary Differential Equations

- **Integral and Z-Transforms**
  - Fourier transform
  - Laplace transform
  - Z-transforms

- **Simplification**
  - Expansion of polynomials
  - Substitution

- **Linear Algebra**
  - Operations
  - Eigenvalues

- **Special Functions**
  - Bernoulli, Bessel, Beta, …
  - Fresnel sine/cosine integral, Gamma

- **Variable Precision Arithmetic**

- **Plotting**
  - 2-D
  - 3-D contour, surface, mesh
  - Movies
Symbolic Math Toolbox Use in Curriculum “Exploring Mathematics with MuPad” Course

• Course developed by Dr. Catherine Wilkins (University of Oxford)

• 56 page reference document on getting started with MuPAD notebook interface
Problem II:
You have been launched as a human cannonball from ground level at an initial velocity \( v_i \) of 50 m/s at an angle theta.

- How high do you go before falling back down?
- How long were you in the air?

\[
\text{Position } Y = \frac{v^2 \sin(2\theta)}{-g}
\]
Experimenting with Live Signals

- Acquire live signals from sensors, oscilloscopes and instruments
- Perform analysis and experiments on live data

Live Acquisition of Your Own Voice
Perform Discrete Fourier Transform
MATLAB Connects to Your Hardware Devices

Instrument Control Toolbox
Instruments and RS-232 serial devices

Data Acquisition Toolbox
Plug-in data acquisition devices and sound cards

Image Acquisition Toolbox
Image capture devices

Vehicle Network Toolbox
Vector & Kvaser CAN bus interface devices

MATLAB
Interfaces for communicating with everything
Learning Beyond Classroom

- Design interactive examples to explore what-if scenarios
- Share examples as GUI executable with students

```matlab
>> rlcdemo
```
Deploying Applications with MATLAB®

1. MATLAB Application
2. MATLAB® Compiler™
3. MATLAB Compiler Runtime (MCR)

MATLAB Desktop

End-User Machine

.exefile
Deploying Applications with MATLAB

Give MATLAB code to students and other faculties who do not have MATLAB

- Use MATLAB Compiler to create stand-alone executable and shared libraries
- Use Compiler add-ons to create software components
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Making Classroom Notes Living Documents

- Example: Stability Analysis of Second Order Systems

\[ m\ddot{x} + b\dot{x} + kx = W \]

Mass-Spring-Damper System
Design and Analysis with Simulink

- Introduce blocks, (libraries), how to make a model
- Hybrid systems - continuous and discrete components
- Time-driven simulation of system model
- Intuitive representation of a system
Teaching Multi-Domain Systems using Simscape™

\[
\begin{align*}
\begin{cases}
\ddot{x}(t) + \frac{b}{m} \dot{x}(t) + \frac{k}{m} x(t) = F(t) \\
\dot{x}(t) = \frac{1}{m} \left[ F(t) - b \dot{x}(t) - kx(t) \right] \\
X(s) &= \frac{1}{s(s^2 + \frac{b}{m}s + \frac{k}{m})} F(s)
\end{cases}
\end{align*}
\]
Let Students Explore More

“It's not that I'm very smart; I am only passionately curious and it's just that I stay with problems longer.”

-- Albert Einstein, Theoretical Physicist

• Interactive tools allows students to explore more and stay with problem longer.
Simulink
Run on target hardware

Run Simulink models on low-cost target hardware

- With a click, your model runs on target hardware
- Supported target hardware:
  - new – R2013a: Raspberry Pi®
  - new – R2013a: Gumstix® Overo®
  - R2012b: PandaBoard
  - R2012a: Arduino®, LEGO® MINDSTORMS® NXT and BeagleBoard
Demo
How it Works

Wheels

Motor

Gyro Sensor
Modeling the Segway Dynamics

Motion Equations of Two-Wheeled Inverted Pendulum

\[ T_1 = \frac{1}{2} m (y_t^2 + z_t^2) + \frac{1}{2} m (y_r^2 + z_r^2) + \frac{1}{2} J_\psi \dot{\psi}^2 + \frac{1}{2} J_\phi \dot{\phi}^2 + \frac{1}{2} J_a (\dot{\theta}_a - \psi)^2 + \frac{1}{2} J_m (\dot{\theta}_m - \phi)^2 \]

\[ T_2 = \frac{1}{2} m (y_t^2 + z_t^2) + \frac{1}{2} m (y_r^2 + z_r^2) + \frac{1}{2} J_\psi \dot{\psi}^2 + \frac{1}{2} J_\phi \dot{\phi}^2 + \frac{1}{2} J_a (\dot{\theta}_a - \psi)^2 + \frac{1}{2} J_m (\dot{\theta}_m - \phi)^2 \]

\[ U = mgz_t + mgz_r + Mg \theta_m \]

\[ L = T_1 + T_2 - U \]

Lagrange equations are the following

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\theta}} \right) - \frac{\partial L}{\partial \theta} = F_\theta \]

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\phi}} \right) - \frac{\partial L}{\partial \phi} = F_\phi \]

\[ \frac{d}{dt} \left( \frac{\partial L}{\partial \dot{\psi}} \right) - \frac{\partial L}{\partial \psi} = F_\psi \]
Different modeling approaches

- **Data Driven**
  - Physical Modeling (Schematic)
  - Simulink (Block diagram)

- **Physical Modeling**
  - LTI System
  - Controller
  - Motor Inertia
  - Shaft
  - Friction
  - Housing
  - Resistor
  - Inductor
  - Electromechanical Connector

- **Integration**
  - DSP
  - FPGA
  - ASIC
  - Embedded Software
  - Digital Electronics
  - C, C++

- **Verification and Validation (V&V)**

- **Modeling**
  - Algorithm Development
  - Implementation

- **Modeling and Simulation**
  - Simulink (Block diagram)
Modeling the Controller

Know your plant/system - Linearization

Design the controller with linear plant model

Test controller with non-linear plant in closed-loop

Design state-logic and supervisory logic

Test the controller in real time

PID

Virtual Displacement

Time effect: 0
Testing the Controller
What our tools offer?

- **Simulink solution**
  - Real-Time Toolbox for LEGO Platform enables you to execute Simulink® and Stateflow® models on a LEGO MINDSTORMS hardware platform for rapid control prototyping
  - hardware-in-the-loop (HIL) simulation, and other real-time applications
  - library of I/O device drivers for LEGO MINDSTORMS sensors and actuators, a real-time kernel, and an interface for real-time monitoring, parameter tuning, and data logging.
LEGO MINDSTORMS NXT Block Library
Installing Target Library

Get from the MATLAB Toolstrip: Add-Ons → Get Hardware Support Packages

Get from the MATLAB Command Line: `>> targetinstaller`
Additional Resources

www.mathworks.com/academia

http://www.mathworks.com/hardware-support

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Machine Learning is Everywhere

- Image Recognition
- Speech Recognition
- Stock Prediction
- Medical Diagnosis
- Data Analytics
- Robotics
- and more…
Machine Learning

Machine learning uses **data** and produces a **program** to perform a **task**

**Task:** Human Activity Detection

**Standard Approach**
- Hand Written Program
- Formula or Equation
  
  \[
  Y_{activity} = \beta_1 X_{acc} + \beta_2 Y_{acc} + \beta_3 Z_{acc} + \ldots
  \]

**Machine Learning Approach**
- **model**: Inputs → Outputs
  
  \[
  model = \langle \text{Machine Learning Algorithm} \rangle (sensor\_data, activity)
  \]
Example: Human Activity Learning Using Mobile Phone Data

Data:
- 3-axial Accelerometer data
- 3-axial Gyroscope data
# Challenges in Machine Learning

## Hard to get started

<table>
<thead>
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<th>Challenge</th>
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<td>Access, explore and analyze data</td>
<td><strong>Data diversity</strong></td>
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<tr>
<td></td>
<td>Numeric, Images, Signals, Text – not always tabular</td>
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Machine Learning Workflow

**Train:** Iterate till you find the best model

- **LOAD DATA**
- **PREPROCESS DATA:**
  - FILTERS
  - PCA
  - SUMMARY STATISTICS
  - CLUSTER ANALYSIS
- **SUPERVISED LEARNING:**
  - CLASSIFICATION
  - REGRESSION
- **MODEL**

**Predict:** Integrate trained models into applications

- **NEW DATA**
- **PREDICTION**
Agenda

- Machine Learning
  - What is Machine Learning and why do we need it?
  - Common challenges in Machine Learning

- Example 1: Human activity learning using mobile phone data
  - Learning from sensor data

- Example 2: Real-time car identification using images
  - Learning from images

- Summary & Key Takeaways
Example 1: Human Activity Learning Using Mobile Phone Data

Objective: Train a classifier to classify human activity from sensor data

Data:

<table>
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<tr>
<th>Predictors</th>
<th>3-axial Accelerometer and Gyroscope data</th>
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<tbody>
<tr>
<td>Response</td>
<td>Activity:</td>
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</table>

Approach:

- Extract features from raw sensor signals
- Train and compare classifiers
- Test results on new sensor data
Machine Learning Workflow for Example 1

Train: Iterate till you find the best model

Predict: Integrate trained models into applications
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- Summary & Key Takeaways
Example 2: Real-time Car Identification Using Images

Objective: Train a classifier to identify car type from a webcam video

Data:

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Several images of cars:</th>
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</thead>
<tbody>
<tr>
<td>Response</td>
<td>NIGEL, LIGHTNING, SANDDUNE, MATER</td>
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Approach:
- Extract features using Bag-of-words
- Train and compare classifiers
- Classify streaming video from a webcam
Machine Learning Workflow for Example 2

**Train:** Iterate till you find the best model

**Predict:** Integrate trained models into applications
Agenda

- **Machine Learning**
  - What is Machine Learning and why do we need it?
  - Common challenges in Machine Learning

- **Example 1: Human activity learning using mobile phone data**
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### MATLAB Strengths for Machine Learning

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<td>Lack of domain tools</td>
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<td>Time consuming</td>
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<td>Assess model performance</td>
<td><strong>Avoid pitfalls</strong></td>
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<td>Over Fitting, Speed-Accuracy-Complexity</td>
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Key Takeaways

- Consider Machine Learning when:
  - Hand written rules and equations are too complex
    - *Face recognition, speech recognition, recognizing patterns*
  - Rules of a task are constantly changing
    - *Fraud detection from transactions, anomaly in sensor data*
  - Nature of the data changes and the program needs to adapt
    - *Automated trading, energy demand forecasting, predicting shopping trends*

- MATLAB for Machine Learning

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What wakes you up in the morning?

Professors
- Attract, engage, and retain students?
- Equip them to succeed in industry?
- Educate students with theory, modelling, hands-on practice, and a systems perspective?

Researchers
- Able to analyse all the data?
- Discovering at the right pace?
- Spending your time effectively?
- Accessing the right tools to collaborate in a multi-disciplinary environment
- Leveraging the computer power?

Students
- Going to find a job?
- Able to bring innovation?
- Be competitive in a global economy?
Student Algorithms in Action
Student Competitions - IIT Bombay Racing team

- The only Indian car ever to finish endurance at Formula Student UK.

- EVo 3.0 was among only 9 Electric Cars (out of 32) to finish the endurance run at FS UK'14

- A professional outlook towards the project, healthy relationship with the industry and a good testing time for the car, helped us rise to a respectable performance at Formula Student this season
BAJA SAE India
Vibrational analysis of dynamic mechanical system using Simulink and Simscape

How do we model 2 DOF mechanical system?

DOF: Degrees-Of-Freedom

- Equation of motion

\[
\begin{align*}
    m_1 \ddot{x}_1 + c_1 \dot{x}_1 + k_1 x_1 + c_2 (\dot{x}_1 - \dot{x}_2) + k_2 (x_1 - x_2) &= f \\
    m_2 \ddot{x}_2 + c_2 (\dot{x}_2 - \dot{x}_1) + k_2 (x_2 - x_1) &= 0
\end{align*}
\]

<table>
<thead>
<tr>
<th>( m_1, m_2 )</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( c_1, c_2 )</td>
<td>Viscous damping coefficient [Ns/m]</td>
</tr>
<tr>
<td>( k_1, k_2 )</td>
<td>Spring stiffness [N/m]</td>
</tr>
<tr>
<td>( x_1, x_2 )</td>
<td>Position [m]</td>
</tr>
<tr>
<td>( f )</td>
<td>External force [N]</td>
</tr>
</tbody>
</table>

2 DOF system
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MATLAB Model

- Define ordinary differential equations using MATLAB and Toolboxes
- Time- and frequency- domain simulation
  - ODE solver in MATLAB
  - Control System Toolbox

```matlab
% Create System Matrices
N = [m1 0 : 0 m2];
C = [c1+c2 -c2 -c2 c2];
K = [k1+k2 -k2 -k2 k2];

Ap = [zeros(2) eye(2) ; -MKV -MVK];
Bp = [zeros(2,1) ; 1 0];
Cp = [1 0 0 0]; % Measured x1 only
Dp = 0;

%% Initial Time Response Simulation using ODE Solver

tspan = [0 5]; % Interval of integration
X0 = [1 :0.1 : 0 ; 0]; % Initial condition
options = odeset('MaxStep',1e-3);
[T,X] = ode45(@diff2dof,tspan,X0,options,Ap);
plot(T,X(:,1))
```
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Simulink Model

- Graphical modeling in block-diagram environment

\[ m_1 \frac{d^2 x_1}{dt^2} + c_1 \frac{dx_1}{dt} + k_1 x_1 + c_2 (\frac{dx_1}{dt} - \frac{dx_2}{dt}) + k_2 (x_1 - x_2) = f \]
\[ m_2 \frac{d^2 x_2}{dt^2} + c_2 (\frac{dx_2}{dt} - \frac{dx_1}{dt}) + k_2 (x_2 - x_1) = 0 \]
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Frequency-Domain Analysis in Simulink

- Bode plot for any input-output specified in Simulink model
There Has to Be a More Efficient Way of Modeling?

Assemble physical system by connecting physical components
Physical Network Approach

- Easier to read
- Easier to reuse
- Leverage MATLAB and Simulink
  - System-level simulation
  - System optimization
  - Control design
SimMechanics
2 DOF system (3D)
Content

- Importing CAD models
- Automatically Create SimMechanics Models using GetMechanics App
- Performing Co-Simulation with SimWise 4D
- Simulating Controls, FEA, Dynamics, Thermal, Sound and Vibration in one go.
Importing CAD models

Open the CAD model in Simwise 4D

SimWise converts the CAD model into SimMechanics convertible format (*.wm3)
Automatically Create SimMechanics Models using GetMechanics App

GetMechanics App can import SimWise *.wm3 file

To get GetMechanics App
Contact MathWorks
Performing Co-Simulation with SimWise 4D

Use MATLAB for Controls Modeling and Leverage MATLAB capabilities.

Perform Plant Simulation in SimWise 4D for Multibody Dynamics, FEA, Heat, Vibration, Buckling, Durability and Reliability.
Simulating Controls, FEA, Dynamics, Thermal, Sound and Vibration in one go.
Performing multi-body dynamic system using SimMechanics
Thank You

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