Data-Driven Methods for Engineers (MECH0107)

- Coursework 1 -

Dr Lama Hamadeh

Office 429 |Roberts Building

Mechanical Engineering Department

(l.hamadeh@ucl.ac.uk)

Dr Llewellyn Morse

Office 503D |Roberts Building

Mechanical Engineering Department

(l.morse@ucl.ac.uk)

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Coursework Brief and General Instructions

Module code	MECH0107
Module name	Data-Driven Methods for Engineers
Module lead	Dr Lama Hamadeh
Academic year	2025/26
Term	Term 2
Individual/group assessment	Individual
Page count limit	8 Pages
% contribution to module	40

Submission Date

Please see the submission portal on Moodle for the due date for this assessment.

Page Count Penalty

Page count applied only to the submitted report, not the code. Work that exceeds the word/page count by more than 10% will be reduced by 10 percentage points. This must not take the mark below the Pass Mark. Any material in addition to the 10% excess may not be taken into account in grading.

Eligibility for Delayed Assessment Permit (DAP)

This assessment is eligible for Delayed Assessment Permit.

Use of Generative AI

1. This assignment is classified as Category 2 where AI tools can be used in an assistive role.
2. You are **not permitted** to use AI tools for code writing or to generate any idea related to your coursework.
3. You can use these tools to receive feedback on or proofread your code.
4. You can use these tools to explain error messages generated by your code.
5. You can use these tools to check your written English's grammar and/or spelling.

6. If you use any of these tools, you need to state the tool name, the output, and how you used it within your submission.

7. Please be aware that failure to follow these instructions may result in academic misconduct proceedings and a reduction of marks for this assessment.

Submission

1. Submission requirements:

   (a) **Report:** Submit a single `.pdf` file. The report must not exceed 8 pages. Please refer to the end of this brief for details on the report's required contents. You should **NOT** include code snippets in your report to illustrate implementation details, as this would make the report unnecessarily long. Instead, ensure that your code and accompanying comments are sufficiently clear and self-explanatory.

   (b) **Code:** Submit all relevant code files that you have used. Please name your code files in a simple-to-follow manner. Your code files should be commented on, and the comments should be clear.

   (c) You should put everything **(codes AND your written report)** into a zip folder, then submit the zip folder to the submission point on Moodle. Please do not submit .rar file – only .zip is allowed.

2. Anonymity requirements:

   - Do not include your name, student number, or any identifiable information in any part of your submission. This includes your report, and your code files.

3. The marking rubric is available on Moodle.

4. The dataset that you will be working on can be found in Moodle.

Module's Intended Learning Outcomes

1. **Identify** the foundational concepts of artificial intelligence, machine learning, and data-driven modeling and their applications in science and engineering systems.

2. **Develop** and refine various supervised and unsupervised algorithms and appreciate their underlying mathematical backgrounds.

3. **Recognise** the value of data, **know** how to ask and answer data-driven questions, and **examine** the reliability and robustness of data-driven models.

4. **Extract** features and patterns from data and discover new knowledge from it.

5. **Identify** the need to use neural networks and deep learning algorithms in some applications, **compare** their efficiency with machine learning algorithms, and **interpret** their predictions.

Coursework 1

Spring Pendulum: The Theory of Hybrid Systems

1. Introduction.

In the study of dynamical systems, a hybrid system combines multiple modes of motion or physical principles into a single framework. A classic example is the elastic pendulum (also called a spring pendulum or swinging spring), where a mass is attached to a spring and its motion blends the characteristics of both a simple pendulum and a spring–mass oscillator, as illustrated in Fig.(1). The spring–mass part of the system follows Hooke's law ($\mathbf{F} = -k\mathbf{x}$, where k is the spring constant), where the restoring force is always directed toward the equilibrium position and is proportional to the displacement. The pendulum component, on the other hand, is governed by gravity, which provides a restoring force that pulls the mass back toward its vertical equilibrium. When these two dynamics interact, the resulting motion can vary significantly depending on the system's energy: at certain energy levels it demonstrates chaotic behavior and strong sensitivity to initial conditions, while at very low or very high energies the motion tends to be more regular. This complexity arises because the coupling of spring and pendulum dynamics introduces an additional degree of freedom, making the elastic pendulum a rich example of nonlinear hybrid dynamics.

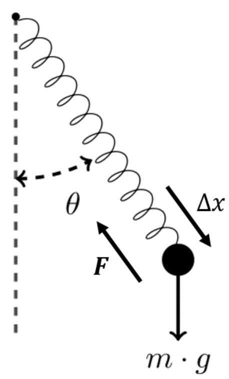

Figure 1: Spring Pendulum: a spring-mass system oscillates in two types of oscillations: a pendulum motion in the $x - y$ plane and a simple harmonic oscillator along the z axis.

2. Problem.

Consider a hybrid mass–spring–pendulum system in which the mass is intentionally released from an off-center position, inducing oscillations both vertically (along the z-axis) and horizontally (within the x–y plane). The system's motion arises from the interaction between two primary restoring mechanisms: the gravitational force, which drives pendulum-like swinging in the horizontal plane, and the elastic spring force, which governs vertical oscillations along the suspension axis.

This coupling between gravitational and elastic restoring forces produces a complex, yet structured, nonlinear motion—richer than that of a simple harmonic oscillator. The resulting trajectory often exhibits frequency modulation, phase coupling, and energy exchange between vertical and horizontal modes, making it a useful case study for analyzing multi-degree-of-freedom oscillatory systems.

To capture the full behavior of the system, three high-speed cameras are strategically positioned at different orientations, providing multi-perspective recordings of the motion, as illustrated in Fig. (2). The recorded video data are then processed and converted into MATLAB datasets in `.mat` format. The three dataset files are named `cam1.mat`, `cam2.mat`, and `cam3.mat`, each corresponding to one of the three camera views. You can access and download the three datasets from Moodle.

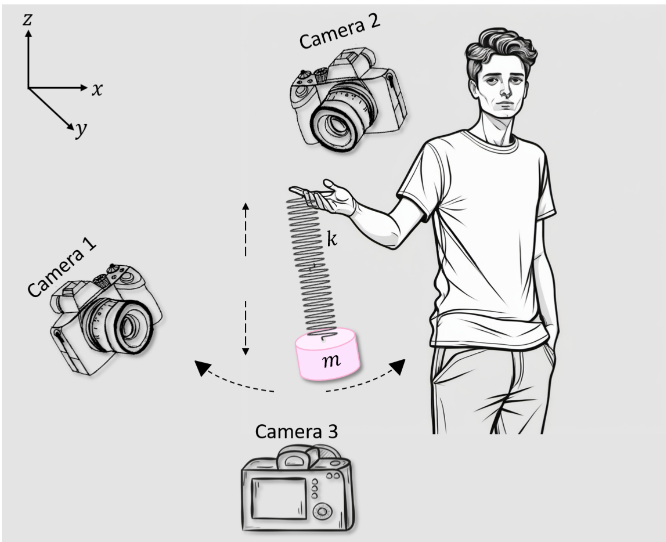

Figure 2: The motion data of this hybrid system is captured by three cameras from different angles.

3. Coursework.

After downloading the provided datasets, you are required to conduct a comprehensive analysis of the system's nonlinear dynamics and underlying physics using either MATLAB or Python. Your investigation should address the following tasks:

1. **Motion Tracking**. Apply robust image processing techniques to extract position data of the oscillating mass from each camera. Justify your choice of technique based on accuracy, computational cost, and robustness to noise.

2. **Time–Frequency Analysis**. Perform a time–frequency analysis on the displacement data obtained from a single camera dataset.
   (a) Examine how the dominant frequency components evolve over time.
   (b) Discuss whether the observed variations provide sufficient insight into mode coupling and system dynamics, or whether additional data-driven methods are required.

3. **Dimensionality Reduction**. Using the tracked position data, construct a reduced-order model of the system by applying an appropriate dimensionality reduction method such as SVD or PCA.
   (a) Justify your choice of technique in the context of the physical behavior of the system and the interpretability, efficiency, and computational suitability of the chosen method.
   (b) Identify and interpret the dominant modes of motion and their associated physical meaning (e.g., pendulum-like vs. spring-like behavior).
   (c) Discuss whether the observed coupling could be described as linear modal coupling or if evidence of nonlinear mode interaction (e.g., energy transfer between modes) is present.

4. **Physical Interpretation**. Analyze and interpret your results by linking them to the underlying physics of the hybrid oscillator.
   (a) Derive a simplified analytical model (e.g., small-angle approximation) and compare its solution with your experimental data.
   (b) Critically discuss any discrepancies and propose possible physical or experimental reasons (e.g., damping, geometric nonlinearity, or camera calibration errors).
   (c) Suggest how the experimental setup could be improved to obtain more accurate or insightful results.

4. Report Writing.

The submitted report must be a single PDF file and must not exceed 8 pages in total (excluding references, appendices, cover page, and table of contents if included). Your report should be written in a clear, concise, and professional style, using appropriate figures, tables, and references where necessary. All figures should include legends, axis labels, and brief captions that describe the content.
The report should include the following sections:

1. **Introduction and Problem Statement.** Provide a brief overview of the hybrid mass–spring–pendulum system and summarize the physical principles governing its motion. Clearly describe the problem represented in the provided datasets and explain the objectives of your analysis. Outline your planned workflow, including data pre-processing, modeling, and interpretation steps, so that the reader understands your overall approach to solving the problem.

2. **Methodology.** Provide a detailed explanation of the methods used to analyse the system, together with the underlying mathematical background. This should include:

   - The image processing steps used to extract the position or trajectory of the mass from each camera view.
   - The dimensionality reduction methods employed (e.g., PCA, SVD) and the justification for choosing them.
   - Any additional analysis performed, such as time–frequency analysis.

3. **Results.** Present the main findings of your analysis using clear and well-labeled plots, figures, and tables. Highlight key patterns or behaviors observed in the system.

4. **Discussion.** Interpret the physical meaning of your results. Discuss how the identified modes or frequency components relate to the underlying physics of the hybrid oscillator (e.g., spring stiffness, pendulum motion, energy coupling). Evaluate the reliability of your results by considering sources of error such as noise, camera calibration, or numerical approximations.

5. **Conclusion.** Summarize the main outcomes of your work, highlighting what your analysis reveals about the system's dynamics. Reflect briefly on the effectiveness of your chosen methods and suggest possible improvements or alternative techniques that could enhance accuracy or insight in future studies.

End of Coursework