A Platform for Data-Driven Nonlinear Dynamics and Mechatronics Education: A Student-Designed Spherical Magnetic Pendulum

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Abstract. The spherical magnetic pendulum is a classic experiment that is relatively straightforward to construct and allows for improved intuitive understanding of nonlinear systems, chaos, as well as understanding the tools that are used to explore such systems, such as basins of attraction. In this work, we consider the design of a prototype spherical magnetic pendulum that exhibits chaotic behavior. The eventual goal is to produce a public display that allows laypersons to interact with an instrumented apparatus and contribute to an experimentally generated map of the system's basins of attraction. Another goal of the project is to serve as an opportunity to introduce the participating students to mechatronic instrumentation techniques for dynamic systems. The collected trajectory data is aggregated, for use in coursework topics in data-driven nonlinear dynamics, including recursive neural networks and variants, physics-informed neural networks, and system identification.

Introduction

The spherical magnetic pendulum is a classic experiment, often seen as a common desktop toy, with a magnetic "bob" at the end of the pendulum and magnets on the base. It demonstrates the extreme sensitivity to initial conditions characteristic of chaotic nonlinear systems [1], [2]. Prior experimental efforts used simple data collection approaches to use this system as a teaching tool [3] but had relatively noisy trajectory tracking (results were admirable given the low cost of implementation). In this work, a capstone student team was assembled, and assigned budgetary and performance constraints to create a prototype, instrumented spherical pendulum towards creating a demonstration of chaotic behavior that would be suitable for interaction with the public. A second goal was to generate data for use in coursework for methods in data-driven nonlinear dynamics. The public display and coursework uses both require smooth, accurate trajectory measurement beyond that provided by prior work.

Results and Discussion

The design team had significant freedom in their approach and used local resources for laser cutting and 3D printing to produce a pendulum system appropriately sized for interaction with human users (Figure 1(a)). A hinge design translates motion to individual paddles isolated the two angular coordinates, and the motion of the paddles is tracked at 2 kHz by Avago ADNS-9800 High-Performance LaserStream Sensors, used in computer mice. The apparatus consists of a Raspberry Pi Model 400 computer connected to a monitor, running custom scripts programmed in Python, and connects to an Arduino Mega microcontroller responsible for communicating with the sensors. The mouse sensors combined with the paddles allow for tracking accuracy of better than 0.5 mm. To prevent long-term drift due to the trajectory integration approach, a periodic self-calibration system was implemented based on beam-break sensors attached to the paddles. Figure 1(b) gives a representative measured trajectory, from start by a human releasing the pendulum from an arbitrary initial condition to the pendulum finally stopping at one of the magnets. The data generated by the system is aggregated and will be made available publicly for use in coursework in data-driven nonlinear dynamics, for topics such as recursive neural networks, physics-informed neural networks, and system identification (examples of such coursework will be presented). The coursework will have been applied in a Machine Learning for Dynamic Systems and Control course in the Spring of 2023. Future efforts will involve students developing alternative designs and means for measurement and improving the real-time visualization of the pendulum motion towards a final public display piece.

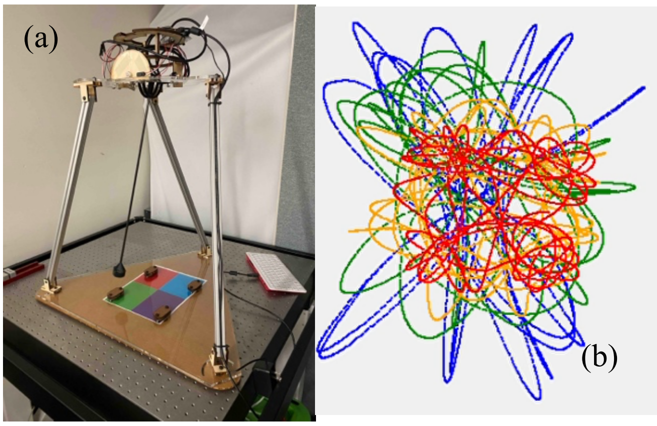

Figure 1): (a) The student-designed spherical magnetic pendulum, and (b) representative measured trajectory (the color varies with time along the trajectory for visualization.

References

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