The Light Tracker: An Off-the-Shelf Control Design Project

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Abstract

This paper describes the development of an off-the-shelf design project in applied control. The project is aimed toward developing insight into the design process through an open-ended, hands-on experimental procedure. Reinforcement of classroom topics and introduction to the difficulties of real design are emphasized. Particular focus is placed on the flow of system development, from problem statement, component selection and system identification through implementation and tuning of a PD controller. This design project has been integrated into the junior level curriculum in the Systems Engineering department at the United States Naval Academy.

1. Introduction

It is well known that classroom discussion of the theory of control can be greatly enhanced through appropriate experimental investigations. Students unable to grasp the concepts of feedback and system response through lectures are often more receptive to hands-on demonstrations and investigations. Further, many topics relating to the process of system design are difficult at best to teach in a lecture format. It is extremely challenging to motivate in the classroom the difficulties of real implementation of control systems to be designed based only on system specifications.

Design projects are, by nature, motivational and instructive, drawing all facets of classroom discussion together in a unified procedure. While it is often instructive to perform theoretical design projects, the combination of theoretical development and experimental verification is an excellent tool for enhancing the learning experience, and gives the student ownership of the final result, and insight into the difference between theory and application.

It is possible to generate design projects that are too unstructured for the average junior level student to complete successfully. Similarly, it is easy to generate a design project that incorporates too much structure, stifling creativity and returning the students to the step-by-step procedure following framework of traditional laboratories. The goal of our design project development is to generate a lightly-structured problem and set of investigations that allow independent though and effort, but incorporate enough guidance that the relatively inexperienced experimentalist can succeed and learn.

The test bed that we have chosen to investigate is the design and implementation of a one-axis light tracking system. The light tracker system is an electro-mechanical device intended to perform fixation on a mobile light source. Students perform component and system identification, sensor calibration, signal conditioning and control of DC motors.

2. Learning Objectives

When developing a capstone design project, it is necessary to fully integrate all facets of the design in the framework of learning objectives. The light tracker project primarily emphasizes the progressive flow of design, focusing on inter-related modules with learning objectives concerning environmental interaction and measurement as well as modeling and control of the full system. The primary focus of the design is on selection and identification of sensors, motors, motor drivers, and control circuit elements for an integrated system.

The light tracker design project admits varying levels of specificity with regards to both implementation and performance, allowing the assignments to be as detailed or as sparse as is required for emphasis of a given learning objective. Topics that can be given particular emphasis include DC motors and motor drivers, various sensing modalities (for both environmental and plant state measurement and feedback), PD control and tuning and circuit design for tunability (including sensitivity analysis). Each module of the full project depends on the results of the previous experiments, so that the design is carried out in a systematic manner. Care must be taken, however, to allow flexibility and divergence among students while still guaranteeing complete follow-through on all design steps in the sequence.

The delicate task of allowing variation between independent students or groups while still achieving each milestone in the design process requires substantial planning and faculty involvement. A suitable solution for the junior level is limitation of the components to some set that is both universally available and sufficiently understood by the students. The use of rigid milestones can also be implemented, but can be left somewhat open. As an example, a sensing module might have a milestone of generating a sensing system that outputs a voltage between ±5 volts with a range of at least one foot for a given test light. The details regarding the implementation that we have chosen, as well as selected results of the procedures, are discussed in Sections 3 and 4.

3. A Sample Laboratory Setup

In the past, servo-motor labs at the United States Naval Academy were performed on prepackaged workstations. Although the prepackaged components for these workstations were convenient, the students often viewed the components as black boxes in which they simply connected wire “A” to wire “B”. The students would gain no appreciation for the servo-motor hardware, and often lost sight of the lab’s overall objectives.

With the introduction of the light tracker project, this situation was corrected by having the students use common off-the-shelf electronic components in their designs. The off-the-shelf components consisted of DC motors, high and low power op-amps, photo diodes, and resistors which can be found at most electronic supply stores. The students bread-boarded the components for each phase of their design.

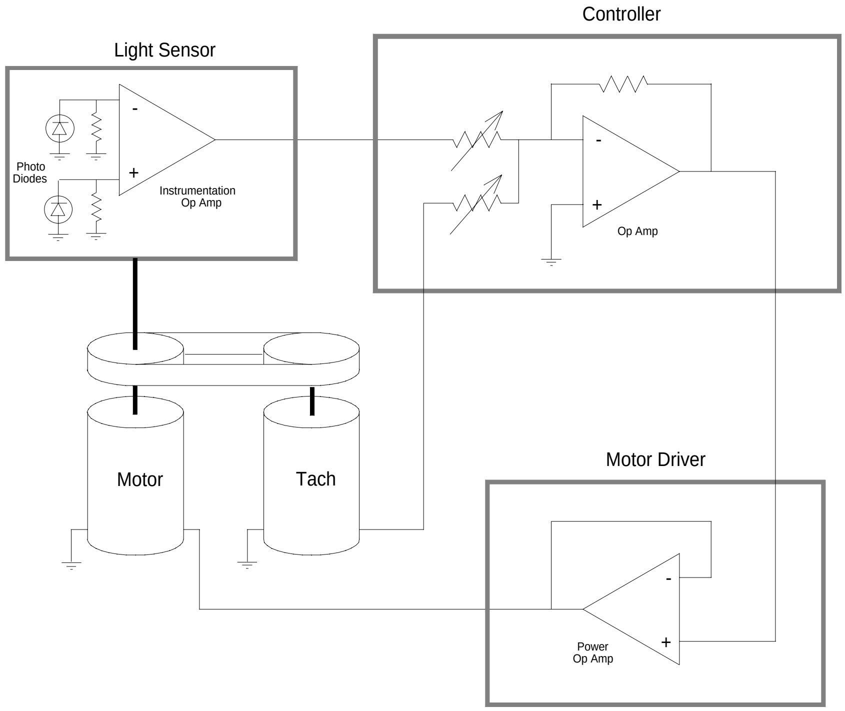

Figure 1. Light Tracker Schematic

A schematic of the light tracker design is shown in Figure 1. The light tracker consists of two DC motors with their shafts coupled by pulleys. The first motor is used as the drive motor and is connected directly the light sensor. The second motor is used as a tachometer, sensing the angular velocity of the drive motor (as measured from the induced armature voltage). The light sensor is composed of two photo diodes canted 10 degrees with respect to each other as shown in Figure 2. The two diodes produce signals consistent with angles $\theta+5^{\circ}$ and $\theta-5^{\circ}$. An error signal is produced by subtracting the two diode signals with an instrumentation op-amp. Proportion and rate feedback is implemented with an op-amp summing junction [1, 2].

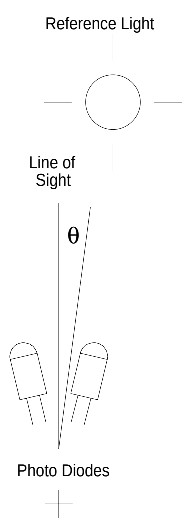

Figure 2 Two Photo Diodes Canted With Respect to Reference

4. Interpreting the results: system identification

The "Light Tracker" laboratory project served as the capstone of the junior year curriculum in control systems. The students examined various aspects of linear control system analysis and design from theoretical and practical points of view. In particular, linear models of a DC motor, a photodiode sensor, and a tachometer had to be identified. The models were developed using the basic physical relationships and experimental data. In this process, two important issues were raised: the determination of a linear model from nonlinear data (linearization) and the role of *a priori* assumptions in model identification.

The calibration of the photodiode sensor and the tachometer was accomplished using least squares estimation, and provided an exercise in linearization. The identification of the tachometer gain was straightforward because the relationship between the motor's angular velocity and the tachometer voltage was very nearly linear. Figure 3 shows the relationship between the angular velocity and measure tachometer voltage (indicated by *) along with a linear approximation determined using least squares methods. The slope of this line is 0.023 with a 95% uncertainty (2 standard deviations) of 0.000431.

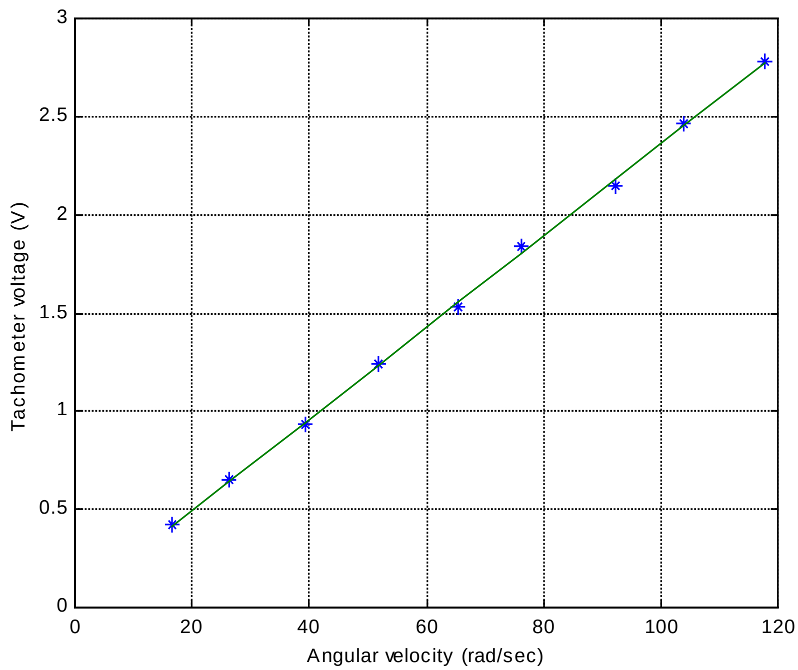

Figure 3: Relationship between the tachometer voltage and the motor's angular velocity.

The photodiode response is much more nonlinear, as shown in Figure 4 (where the measured data is indicated by (*)). The determination of a linear model for the photodiode sensor depends on the range of angular displacements that are considered. Two linearizations were performed as indicated by *Line 1* and *Line 2* on Figure 4. The results for *Line 1* are valid for displacements in the range of $\pm 2°$ and yields a nearly linear relationship with a photodiode constant $K_p = 4.30$

with negligible uncertainty. However, for displacements outside of $\pm 10°$, the photodiode output decreases and the sensor's utility decreases as well. For *Line 2*, the maximum range of useful data is used ($\pm 10°$). As expected, the relationship is more nonlinear and the photodiode $K_p = 1.46 \pm 0.455$ (95%) is less certain. To accommodate the largest operating range, the model from *Line 2* was used in the subsequent analysis

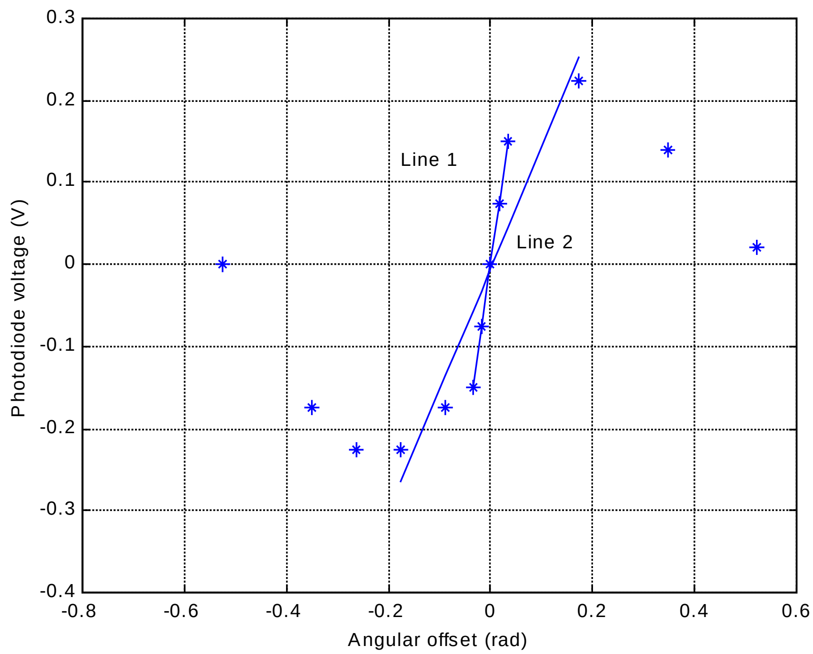

Figure 4: Relationship between the photdiode voltage and angular displacement of the light source.

The model of the DC motor as an electromechanical device is well known [2]. In this project, a first order model of a DC motor was developed by neglecting the armature inductance. In general, the values of the various internal quantities are unknown and system identification is required. From the first order model, the DC gain and the time constant were estimated using the experimental frequency response of the motor-tachometer system. This process served two purposes: to supplement the mathematical model with experimental data and to measure the frequency response of a system experimentally. The result of this analysis is shown in Figure 5, where (*) indicates an experimental point and the curve is defined by the transfer function model $0.789/(0.0829s+1)$. The experimental frequency response matched the first order model very closely and validated the assumption that the armature inductance is negligible.

From these analyses, students were able to design tunable PD controllers for fixation of the stereo sensor head on a point light source. Individual implementations varied, but the primary focus was design for tunability and interpretation of the difference between theoretical system gains (developed using the models derived above) and experimentally determined gains for the PD controller. Students quickly discovered that tuning a two-gain system requires some significant insight, reinforcing concepts relating to frequency response and second-order system behavior.

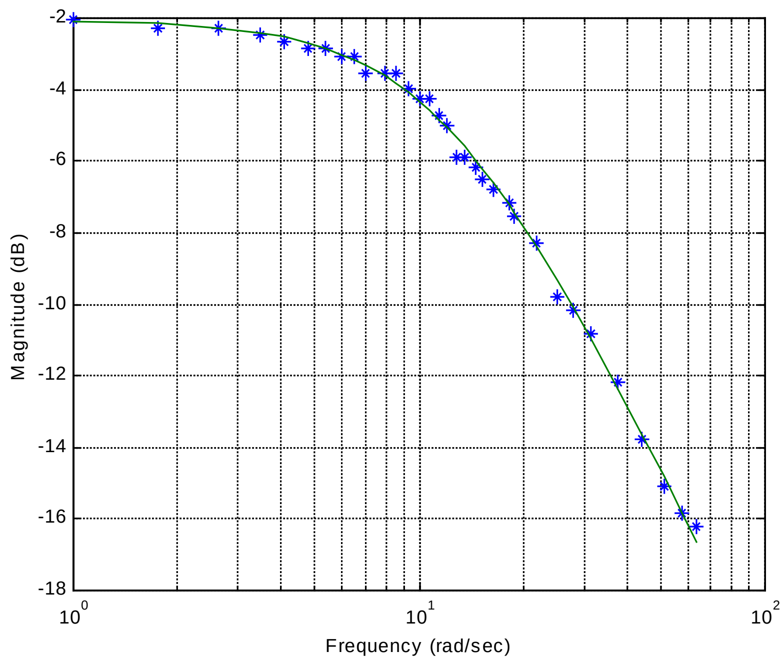

Figure 5: Comparison of the experimental frequency response data and the frequency response of the first order model.

5. Results and Conclusions

The light tracker experiments strongly emphasize the complete design methodology for real control systems and allow the use of a variety of off-the-shelf sensors, actuators and circuit devices, depending on availability and familiarity to the students. Student become familiar with all facets of the design process, from specification, component selection, modeling and identification through implementation and tuning of real systems. The nature of the problem allows for a highly modular implementation, indicating that milestones and intermediate design specifications can easily be included to enhance development of experimental design skills.

The light tracker project is an excellent capstone for the junior year systems engineering curriculum, and provides an excellent lead-in for a senior year capstone design project by strengthening the student's mastery of the appropriate approach to design of real-world systems. The final design specifications can be made open-ended to encourage innovation in design. The light tracker project proved to be successful in developing understanding of the design process and fostering confidence that is proving significant in the senior year design projects required by the Department of Weapons and Systems Engineering. Additionally, working within fixed laboratory groups, as was done in our implementation, aids in preparation for carrying out task assignment and systems integration tasks on larger projects in the senior year.

6. References

[1] Carstens, J.R., Electrical Sensors and Transducers, Prentice Hall, Englewood Cliffs, NJ, 1993.

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