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Rifat Sipahi[1]
Fellow ASME
Department of Mechanical
and Industrial Engineering,
Northeastern University,
Boston, MA 02115
e-mail: r.sipahi@northeastern.edu

Yasin Yazicioglu
Department of Mechanical
and Industrial Engineering,
Northeastern University,
Boston, MA 02115
e-mail: y.yazicioglu@northeastern.edu

Laurent Lessard
Department of Mechanical
and Industrial Engineering,
Northeastern University,
Boston, MA 02115
e-mail: l.lessard@northeastern.edu

Sze Zheng Yong
Department of Mechanical
and Industrial Engineering,
Northeastern University,
Boston, MA 02115
e-mail: s.yong@northeastern.edu

Tong Ma
Department of Mechanical
and Industrial Engineering,
Northeastern University,
Boston, MA 02115
e-mail: t.ma@northeastern.edu

Seungmoon Song
Department of Mechanical
and Industrial Engineering,
Northeastern University,
Boston, MA 02115
e-mail: s.song@northeastern.edu

Heliostat-Integrated Modules for Engineering Courses in Robotics, System Dynamics, and Control

Heliostats are mirror arrays used in concentrated solar thermal power (CSTP) technology; they offer a rich, physical platform that maps naturally onto canonical topics in kinematics, dynamical modeling, systems analysis, and feedback control. This article presents the design and implementation of heliostat-integrated curriculum modules developed for two core mechanical engineering courses at Northeastern University: ME 3460 Robot Dynamics and Control, and ME 4555 System Analysis and Control. In ME 3460, four homework modules frame the heliostat as a robotic manipulator, requiring students to apply forward kinematics (FK), inverse kinematics (IK), Jacobian analysis, transfer function and state-space representations, and waypoint design for robotic motion planning. In ME 4555, a three-phase sequence of assignments progresses from nonlinear equation-of-motion derivation and linearization, through open-loop transient analysis in MATLAB®, to closed-loop PID design using root locus methods. Over the first 2 years of deployment, the heliostat context was experienced by 64 students in ME 3460 and 440 students in ME 4555. We identify plug-in points for heliostat topics in existing curricula, including possible extensions and integration with MATLAB. The curriculum is transferable to analogous courses in aerospace and electrical engineering. [DOI: 10.1115/1.4072212]

Keywords: engineering education, heliostat, concentrated solar thermal power, robot kinematics, feedback control, curriculum development, MATLAB®, SIMULINK®, SIMSCAPE™, control education, dynamics and control, energy, robotics, solar energy

1 Introduction

Energy is the bedrock of modern society. Nearly every dimension of contemporary life from transportation, manufacturing, and agriculture to healthcare and digital infrastructure depends on a reliable and affordable supply of energy. For most of the industrial era, this supply has rested overwhelmingly on nonrenewable fossil fuels, a dependence that carries compounding risks. From a geopolitical standpoint, nations that lack domestic reserves are strategically exposed: oil and gas supply chains can be weaponized, disrupted by conflict, or destabilized by market manipulation—risks that geopolitical tensions and energy market volatility have repeatedly brought into focus [1]. Beyond strategic vulnerability, fossil–fuel combustion contributes to anthropogenic greenhouse–gas emissions at alarming levels and is identified by leading scientific assessments as the primary driver of human-induced climate change [2,3]. The energy sector is also the leading source of air pollution that affects more than 90% of the world's population [1].

These pressures have accelerated a global pivot toward renewable energy. Europe has committed to carbon neutrality by 2050

[1]Corresponding author.

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[4], investing in wind and solar capacity [5], while China has been significantly investing in solar photovoltaic (PV) and wind capacity [6]. Renewable investment is rising across Southeast Asia, Latin America, and sub-Saharan Africa as the levelized cost of solar PV generation substantially fell, making renewables the most cost-competitive source of new electricity in most markets [7]. In the United States, the Inflation Reduction Act of 2022—the largest climate and energy investment in the nation's history—has catalyzed a significant expansion of domestic clean-energy manufacturing and deployment [8].

Among renewable technologies, solar energy stands out for its resource abundance: the sunlight incident on Earth's surface in 1 h exceeds global primary energy consumption for an entire year [9]. Two main conversion pathways have emerged at utility scale: PV systems, which convert sunlight directly to electricity via the semiconductor photoelectric effect, and concentrated solar thermal power (CSTP), which uses optically concentrated sunlight to drive a thermodynamic cycle. The ability of CSTP to store energy thermally makes it a more reliable dispatchable technology than PV for high-penetration renewable electricity grids [10,11]. At the heart of every CSTP plant is the heliostat field: an array of individually steered flat or slightly curved mirrors that continuously redirect incident sunlight onto a central receiver tower. Heliostats represent 30–50% of the direct capital cost of a utility scale CSTP facility [11], making their performance and cost the dominant levers for improving the economics of the technology.

Recognizing the centrality of heliostat technology to CSTP competitiveness, the US Department of Energy's Solar Energy Technologies Office (SETO) established the Heliostat Consortium (HelioCon) in 2021, led by the National Renewable Energy Laboratory (NREL) in partnership with Sandia National Laboratories. HelioCon's mission is to advance heliostat technologies across the full development stack, from materials and manufacturing through field deployment and system integration [9]. *Roadmap to Advance Heliostat Technologies for Concentrating Solar-Thermal Power*, published in 2022, identifies existing gaps across research, technology development, field implementation, and workforce training [9]. On workforce and education, the roadmap is unambiguous: the community of engineers and researchers trained in heliostat technology in the United States remains small, public accessibility to CSTP knowledge is limited, and heliostat content is largely absent from engineering curricula. The roadmap explicitly calls for expanded university engagement, targeted classroom instruction, and integration of heliostat content into engineering courses, including at project levels.

This diagnosis was reinforced quantitatively by the HelioCon Resources, Training, and Education (RTE) gap analysis of Mitchell et al. [12], which confirmed that newcomers to heliostat development lack an adequate knowledge base, and that CSTP expertise is concentrated in a small community with limited pathways for new entrants. HelioCon's RFP programs in 2023 and 2024 awarded a combined $6.5 million across multiple projects addressing heliostat technology and workforce development [11]. Among these, Northeastern University received funding to build heliostat curricula spanning the full ME undergraduate program [13]. The resulting program-level integration was recently reported in Ref. [14], covering nine courses from first year cornerstone to a newly designed graduate course. The present article focuses in depth on two specific courses, ME 3460 *Robot Dynamics & Control* and ME 4555 *System Analysis & Control* within that program and provides the readers the directions the authors took to integrate heliostat concepts into these courses, along with integration with MATLAB.

The broader imperative to train engineers for the energy transition has motivated a growing body of curriculum development work in renewable energy education. Ciriminna et al. [15] argued for rethinking solar energy education "on the dawn of the solar economy," emphasizing that effective curricula must build strategic and entrepreneurial competencies alongside technical knowledge, rather than narrowly targeting R&D skills. Islam and Amin [16] demonstrated that a significant fraction of renewable energy technologies, including concentrating solar systems, map naturally onto the mechanical engineering undergraduate curriculum, and outlined a model course covering the full spectrum from resource assessment to power conversion. Belu et al. [17,18] reported on the development of hands-on renewable energy courses and projects spanning solar cell laboratories, two-axis solar tracking, and life cycle assessment, showing that multidisciplinary renewable energy content can be embedded across electrical, mechanical, civil, and chemical engineering programs with measurable student benefit. Zilouchian et al. [19] described a project-based energy course that goes beyond classroom instruction to explicitly target workforce preparation and public dissemination in the green energy sector.

From an engineering education point of view, CSTP and heliostats provide a rich, multidisciplinary teaching platform spanning thermofluids and materials to machine design, systems, and controls. Moreover, as motivated earlier, CSTP provides a promising direction toward energy independence that can potentially address various societal problems, which are critical elements in creating a modernized curriculum that motivates engineering students within a real-world context. For example, the study in Ref. [20] evaluated a grand challenge–based framework that uses real-world societal problems, including the NAE grand challenge to "make solar energy economical," as motivating contexts for engineering coursework. Using multivariate analysis of variance across multiple course cohorts, they found that connecting technical content to societal context strengthens student engagement. Mohd Yusof [21] reported similar findings in a cooperative project-based learning implementation in a process control and dynamics course, showing significant increases in student motivation and engagement when abstract control theory is embedded in authentic engineering contexts.

While the aforementioned efforts are significantly promising toward advancing engineering curriculum, we also acknowledge that there is also the need to incorporate heliostat concepts in courses encompassing vibrations, dynamical systems, robotics, systems, and control. Such an incorporation arrives naturally as it seamlessly bridges courses encompassing thermodynamics, fluid dynamics, and mechanical engineering design with open-ended project-based courses and senior design. To this end, in the context of ME 3460, an undergraduate-level robotics course, we treat heliostats as analogous to two-degree-of-freedom manipulator-type robots with elevation and azimuth angles, while in ME 4555 at the undergraduate systems and controls course, we primarily focus on mathematical modeling, system-level time response analysis, and control design.

In courses similar to ME 3460, an instructor can tie forward and inverse kinematics (FK/IK), Denavit–Hartenberg (DH) convention, Jacobian computation, and trajectory planning to motion planning and control of heliostats. Along these lines, existing literature can provide valuable directions. For example, Karbassi and Hollot [22] established a MATLAB-based undergraduate robotics laboratory whose assignment structure from FK/IK to Jacobian computation and trajectory planning resonates with the ME 3460 modules described in this article; both can be anchored to well-known textbooks [23–25]. Dansereau [26] demonstrated the use of the MATLAB ROBOTICS TOOLBOX in an introductory robotics course for interactive FK/IK instruction and identified scaffolding of IK implementation as a critical pedagogical consideration. Riley and Hansen [27] provide the foundational geometric treatment of sun-relative pointing for dual-axis azimuth-elevation trackers, which underlies the tracking-angle computation central to both ME 3460 and ME 4555. Moreover, the Google RE<C technical reports on heliostat orientation estimation [34,35] provide supplemental reading on real-world sensor integration and elementary operations to describe kinematics in 3D. Along these lines, Constantinou [36] developed an open-source PYTHON library for computing heliostat tracking angles using inverse kinematics, framing the problem in a way that is directly analogous to teaching robotics at the undergraduate level.

Table 1 Mapping of ME 3460 course topics to heliostat homework modules

Course topic	Module M1 FK	M2 IK	M3 Jacobian/Traj.	M4 TF/SS
DH convention and parameter table	✓	(✓)		
Homogeneous transformation matrices	✓	(✓)		
FK	✓	(✓)	(✓)	
IK		✓	(✓)	
Jacobian and velocity kinematics			✓	
Kinematic singularities		(✓)	✓	
Waypoint and trajectory planning			✓	
Transfer function representation				✓
State-space (SS) representation				✓
Mechanical flexibility/stiffness				✓
SIMSCAPE implementation	(✓)	(✓)	(✓)	(✓)

Note: ✓ = primary; (✓) = supporting use.

In courses similar to ME 4555, an instructor can tie electromechanical modeling, time response analysis, and feedback control of heliostats with prior work. For example, Salgado-Plasencia et al. [28,29] developed a SCADA-based heliostat control system using linearized DC motor dynamics and compared proportional-integral-derivative (PID) and fuzzy logic controllers. Zeghoudi and Chermitti [30] carried out a comparative study of fuzzy logic and neural-network speed controllers for DC motor orientation of a heliostat in MATLAB. Munoz-Vazquez [31] described a SIMULINK/ARDUINO laboratory for teaching closed-loop control of a pendulum that sequences mathematical modeling, open-loop analysis, and PID design as part of a model-based control design effort, verified against hardware. On the simulation side, Das [32] and Russell et al. [33] provide the canonical references for SIMSCAPE-based mechatronic simulations that undergirds a three-dimensional heliostat visualization platform.

Taken together, current literature provides valuable directions both in curriculum development and in pedagogical approaches in engineering education, including opportunities toward creating curricular materials focused on CSTP and heliostats in the context of robotics, dynamics, and control. In this direction, we report our preliminary curricular implementations in ME 3460 and ME 4555, primarily demonstrating strategies on how we incorporated heliostat related topics into these courses, complementing the initial reporting in Ref. [14]. As also discussed in the literature, we acknowledge that inertia in existing teaching methods may slow adoption of new curricular material. Considering this point, and given that engineering curricula have similarities and differences around the world, we aim to provide practical heliostat entry points, at varying levels of complexity, for any curriculum focused on robotics, systems, and controls. Along the way, we present in what ways the presented materials could further be improved and expanded.

The specific contributions of this article are as follows:

(i) Design of homework modules for ME 3460 covering FK, IK, Jacobian computation, transfer functions and state-space modeling, and waypoint trajectory generation, all framed around a two degree-of-freedom heliostat manipulator.
(ii) Design of homework modules for ME 4555 progressing from nonlinear modeling and linearization, through open-loop transient analysis, to closed-loop PID design.
(iii) Connections of the modules with MATLAB, and SIMULINK and SIMSCAPE toolboxes.[2]
(iv) Lessons learned and moving forward after deploying these modules for a total of 64 students in ME 3460 and 440 students in ME 4555.

[2] MATLAB, SIMULINK, and SIMSCAPE are products of the MathWorks, Inc., Natick, MA 01760, USA.

The remainder of the article is organized as follows. Sections 2 and 3 describe motivational examples used to incorporate heliostat system models, respectively, into ME 3460 and ME 4555. These sections lay out the specific topics in each course and how the developed course modules build upon the motivational examples. Each section also includes how the modules can be integrated with computation, such as in MATLAB, what topical plug-in points are there in each course and what possible extensions can be considered in future offerings. Section 4 provides conclusions and discussions, including lessons learned, ways to move forward, and recommendations for future implementations.

2 ME 3460: Robot Dynamics and Control

ME 3460 Robot Dynamics and Control is an undergraduate elective and is also one of the core courses in Robotics Minor, taken primarily by juniors and seniors in engineering and computer science. Prerequisites include linear algebra and differential equations. The primary learning objectives include: mastery of FK and IK for serial-chain manipulators including with DH notation; computation and geometric interpretation of the Jacobian; derivation of single-input single-output transfer functions; trajectory/waypoint design; as well as joint control using PID controllers. During the first 2 years of the heliostat integration described here, the course enrolled a total of 64 students. A summary of the course modules developed and their mapping to course topics is presented on Table 1.

2.1 Motivation.

In ME 3460, the topics of CSTP and heliostats are first motivated in the first module via a brief description of the technology, and a link to HelioCon/DOE website [37]. In this setting, the heliostat consists of a flat or slightly curved mirror panel mounted on a pedestal and actuated in two orthogonal rotational degrees-of-freedom: elevation ϕ (tilt about a horizontal axis) and azimuth ψ (rotation about a vertical axis). The panel must continuously track the Sun to redirect incident solar radiation onto a fixed receiver at the top of a central tower. To this end, a flat heliostat is first abstracted as shown in Fig. 1, which illustrates the geometry used throughout subsequent assignments and follows the simplified two-axis model described in Ref. [27]. Moreover, students are informed that a heliostat is equipped with sensors at the four corners labeled A, B, C, D, and hence, for an effective operation, one might need to read the sensors and interpret sensor readings so as to adjust ϕ and ψ.

2.2 Course Modules

2.2.1 Module 1. Forward Kinematics. In the first module, the students are provided Fig. 1 as well as a representative figure, such

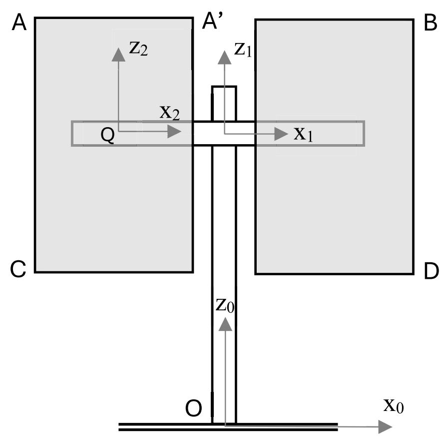

Fig. 1 Simplified two-degree-of-freedom heliostat model with azimuth ψ about Z_0 and elevation ϕ about x1 as well as coordinate frames and corner reference points AD. Figure is inspired from Salgado-Plasencia et al. [28].

as the one in Ref. [28]. The module provides all the relevant dimensions in the figure, and to assist the students in setting up the problem, frames 0, 1, 2 shown with subscripts this module expects students to develop the DH table using the DH convention first. Using this table, students are next asked to develop the homogeneous transformations that relate consecutive frames, with the standard notation ${}^{i}_{j}\mathcal{T}$ between frames i and j. The module ends with using the homogeneous transformations as well as given numerical values of angles ϕ and ψ to compute the 3D locations of the points A–D in frame 0.

2.2.2 Module 2. Inverse Kinematics (IK). The second module builds on the first one, where now the students should use FK analysis to perform IK analysis. Specifically, students are asked to develop the relationships between azimuth and elevation angles and the locations of the four corners A–D in frame 0. For this, the students are provided ${}^{0}_{2}\mathcal{T} = {}^{0}_{1}\mathcal{T} \cdot {}^{1}_{2}\mathcal{T}$ in terms of ϕ and ψ and are asked to relate, in terms of ϕ and ψ, the position of the origin Q of frame 2 with respect to frame 0. Finally, given ${}^{0}_{2}\mathcal{T}$ with numerical entries, students are asked to compute what ϕ and ψ are.

2.2.3 Module 3. Jacobian Computation and Trajectory Planning. In the following module, students are asked to relate the linear velocity of the origin of frame 2 with respect to frame 0, using the standard formula ${}^{0}v_2 = {}^{0}J(\theta)\dot{\theta}$, where θ denotes the vector $\begin{bmatrix} \phi \\ \psi \end{bmatrix}$. This module is concluded with a trajectory design problem where the heliostat moves from one pose to another in a certain amount of time, and the students are asked to compute the trajectory of point A with respect to time. In this last step, students perform trajectory planning by discretizing time into small steps Δ and calculating using forward kinematics how the position of point A is determined at each time-step.

2.2.4 Module 4. Transfer Functions and State Space. The last module is in a simpler version of the heliostat, where the goal is to provide an opportunity for students to practice expressing transfer functions and state-space dynamics of linear systems. To this end, the heliostat is first abstracted as a single degree-of-freedom system about ψ, i.e., ϕ is fixed, and an input azimuth angle is provided to the heliostat. Here, the pedestal keeping the heliostat upright is assumed flexible, not rigid, and the students are asked to express the arising system as a transfer function between the input azimuth angle and the output azimuth angle and the state-space model of the dynamics. Due to mechanical flexibility, input azimuth angle and the output azimuth angle are in general different from each other.

2.3 MATLAB® Integration. While the developed modules are not confined to a single software platform, in our instructional course delivery, we utilize MATLAB. To this end, students can implement all the modules directly in MATLAB by coding the solutions in a .M file. Instructors often encourage students to use function definitions for FK and IK analyses, so that their code is more modular and reusable.

Moreover, the instructors have the option to leverage SIMULINK and SIMSCAPE toolboxes of MATLAB to teach students electromechanical modeling, foundations of feedback control, and time-domain simulations of heliostat motion, all visualized as 3D animations. To this end, we designed a two degree-of-freedom heliostat dynamics in SIMSCAPE, which includes inertia, friction, DC motors for each joint actuation, and a PI controller for each DC motor. This SIMSCAPE diagram is the final product in achieving end-effector position control and encompasses majority of the course concepts learned throughout the semester. It also allows students to evaluate how well they control the heliostat motion. Students can then quantify the tracking error and interpret its implications for energy conversion efficiency.

Overall, before building the complete SIMSCAPE diagram, the instructor should introduce relevant materials step by step:

- Start with first demonstrating how to build forward kinematics model of a heliostat in SIMSCAPE, without any focus on dynamics and control. Students at this stage will first apply predetermined torque signals to generate motion.
- As the semester continues, teach DC motor modeling and incorporate DC motors with gearboxes at the joints of a heliostat in SIMSCAPE, or this can be a part of a homework assignment. At that stage, students will feed predetermined voltage profiles to the DC motors to generate open-loop motion.
- Later in the semester, when the foundations of PID controllers are covered, incorporate PID controllers to properly regulate the voltage profile to the motors to achieve joint control.
- Finally, the desired end-effector motion is mapped to desired joint angles via IK, and next, these desired joint angles are utilized in PI control of DC motors at the joint level.

2.4 Plug-In Points and Extensions. Overall, viewing heliostats as two degree-of-freedom robotic manipulators provides a meaningful entry point in ME 3460 and can potentially be leveraged in similar courses at the undergraduate level. With this starting point, main plug-in points are forward and inverse kinematics, and along these lines includes the DH convention as well as using the DH convention to generate the homogeneous transformations. This knowledge can further build toward the computation of Jacobian to calculate relative velocities between frames. Moreover, for starters, we can assume we have precise knowledge of which direction a heliostat must turn to maximize energy efficiency at any given time. Such an assumption will therefore enable prescribing a desired end-effector trajectory, which can then be tracked using PI controlled DC motors.

The above-described modules can be further extended as follows. In modules 1–2, students can also be asked to build the SIMSCAPE diagram and validate the coordinates of points A–D. One can also consider adding a normal vector on the surface of the heliostat pointing toward the sun. The point P where this normal vector is place can be the "end-effector" and the normal vector determines the pose. Students may be asked to use FK to compute the location of this point and the direction of the normal vector as viewed from frame 0. In module 2, students can then use IK to compute the location of the end-effector at point P. In module 3, instead of FK, students may be asked to perform IK. For example, given a trajectory of point P as a function of time,

Table 2 Mapping of ME 4555 course topics to heliostat homework modules

Course topic	Phase		
	Ph. 1 modeling	Ph. 2 analysis	Ph. 3 control
Mathematical modeling			
Free-body diagram and Newton's second law	✓		
Nonlinear equation of motion	✓		
Equilibrium and linearization	✓	(✓)	
Coupled electromechanical modeling (gearbox + DC motor)	✓		
System analysis			
Laplace transform and transfer function	(✓)	✓	(✓)
Open-loop impulse, step, and ramp response		✓	
Time constant identification		✓	
MATLAB/SIMULINK time-domain simulation		✓	(✓)
Feedback control			
Closed-loop block diagrams (including with SIMULINK)			✓
Steady-state error and final value theorem			✓
PID design via pole placement			✓
Root locus analysis			✓
MATLAB `rlocus`			✓

Note: ✓ = primary; (✓) = supporting use.

compute what elevation and azimuth angles are as a function of time. Module 4 can help students appreciate the presence of stiffness and how it can affect the motion dynamics. To this end, one may calculate how energy efficiency is impacted for a given deviation of joint angles from their intended values. This exercise can help students appreciate the level of precision needed in positioning heliostats for maximal efficiency. Realistic sun-tracking reference trajectories derived from a solar position algorithm, see, e.g., Ref. [38] can help strengthen modules 3–4.

3 ME 4555: System Analysis and Control

ME 4555 system analysis and control is a required core course for all mechanical engineering students at Northeastern, taken by juniors and seniors. The course is organized in three sequential parts: mathematical modeling, system analysis, and feedback control, each taking up about a third of a semester. These topics have recently been integrated into a coherent text book available publicly [39].

During the first 2 years of heliostat integration, the course enrolled a total of 440 students across multiple sections. The heliostat assignments were designed to mirror the three-phase course structure, with earlier problems focusing on electromechanical system models (more applied) and later ones on systems and controls, which are inherently more abstract. Given the rapid movement toward institutionalizing CSTP topics in our curriculum, upper-level courses such as ME 4555 also benefit from students' exposure to heliostats in several courses prior to taking ME 4555. Hence, a degree of transition from applied to abstraction in ME 4555 is also justified. A summary of the course modules developed and their mapping to course topics is presented in Table 2.

3.1 Motivation. As in the case of ME 3460, the topics of CSTP and heliostats are first motivated in the first module of ME 4555 via a brief description of the technology, and a link to HelioCon/DOE website [37]. In ME 4555, the heliostat panel is abstracted as a single degree-of-freedom rotational dynamical system with inertia J subject to an input torque $T(t)$ and an additional torque due to gravity g acting on the mass imbalance described with distance ℓ from the pivot point, see Fig. 2. Here, the mass imbalance represents an infrastructure that cannot be perfectly balanced when built, and/or cases whereby mass imbalance can help preload to remove backlash in gearing. While ME 4555 focuses on single and multiple degrees-of-freedom systems, in the context of heliostats, we opted not to mix the azimuth dynamics into the problem.

Given that under relatively slow motion of the heliostat, the coupling between the axes will be negligible, and hence focusing on just the elevation angle provides a good starting point.

3.2 Course Modules

3.2.1 Mathematical Modeling. With a motivational discussion in the opening module on heliostats, students are provided the single degree-of-freedom heliostat in Fig. 2 and are asked to apply Newton's second law to derive the equation of motion of the heliostat, given by

$$J\ddot{\phi}(t) = T(t) - mg\ell\cos(\phi(t)) - b\dot{\phi}(t)$$

where a resistance torque due to viscous friction is also incorporated, with b representing the viscous friction constant. Students are asked to utilize the course concepts to show why the above differential equation is nonlinear and are asked next to linearize the dynamics around an equilibrium elevation angle ϕ_0. At equilibrium, a fixed torque T_0 is required to keep the heliostat at ϕ_0. The amount of this torque can be computed from static equilibrium conditions.

Considering small variations about the equilibrium, $\delta = \phi - \phi_0$, and under small variations in the torque $\tau = T - T_0$, the students next linearize the dynamics under these small variations using first order Taylor's expansion. They are asked to show that the dynamics is indeed linear, and explain whether ℓ acts like a spring or a dashpot/damper in the linear regime. With this

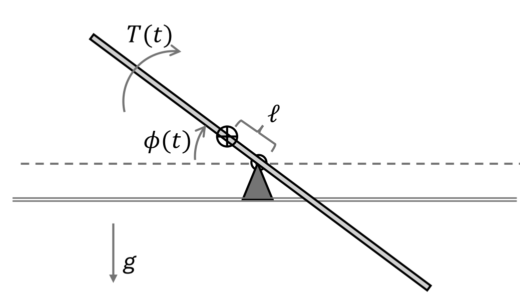

Fig. 2 Model abstraction of a single degree-of-freedom heliostat with elevation angle $\phi(t)$ subject to torque $T(t)$, gravity g, and center of mass offset l

linearization performed, a large set of analysis and design toolkit becomes available to the students as explained next.

Going forward, students are asked to assume $\ell = 0$. This is justified under the simplifying assumption that ϕ is precisely known and hence one could apply a feedforward torque T_0 to effectively make the heliostat act as though the mass imbalance does not exist. With this reasonable assumption in mind, the next step is for the students to incorporate a gearbox $N:1$ with gear and pinion inertia J_g and J_p, respectively, with input torque T_{in} and output torque driving the heliostat.

The above content can be delivered either in a single homework with multiple steps or can be progressively built over several homework assignments. Given that some assignments may also need to assess other course concepts, distributing the content over three assignments generates consistency and is also feasible given the timeline of course topics covered.

3.2.2 System Analysis. Building on from the previous modules, the next step is to incorporate a DC motor whose shaft is connected to the input of the gearbox. Modeling follows from the well-known DC motor dynamics, assuming negligible armature inductance ($L \approx 0$), resistance R, torque constant k_t, and back electromotive force constant k_b. Students can now build a transfer function $G(s)$, with s representing the Laplace variable, relating input motor voltage $V(s)$ to angular displacement of the heliostat $\Delta(s)$ about the equilibrium. This transfer function can be utilized for example in MATLAB to study time evolution of $\phi(t)$ for a given voltage profile applied to the DC motor. For conceptual problems, students are also asked, using $G(s)$, to identify the time constant of a heliostat and its physical meaning, and also to characterize the response of $\phi(t)$ as well as angular velocity $\dot{\phi}(t)$ for standard input waveforms, such as unit impulse, unit step, and ramp representing the voltage profiles sent to the DC motor. Combined with MATLAB simulations, students can then validate how course concepts inform expected behavior of the elevation angle dynamics.

These exercises ground abstract Laplace-domain results in intuition about actual heliostat behavior. Depending on the course timeline, they can be combined in a single homework assignment or can be built over several assignments as more course material relevant to these topics is covered.

3.2.3 Feedback Control. Students augment the open-loop heliostat transfer function $G(s)$ (from voltage to angular displacement) with a controller $C(s)$ in a negative unity feedback. They investigate two cases, proportional (P) control, where $C(s) = K_p$, and PID control, where $C(s) = K_p + K_i/s + K_d\, s$ with controller gains K_p, K_i, and K_d. In the case of P control, students are asked to find the steady-state error in tracking a unit step reference input. For this, students utilize the final value theorem while ensuring that closed-loop stability is retained. With $G(s)$ being a type-1 system, the steady-state error is found to be zero. In the case of PID controller, students are asked to compute the controller gains achieving a required closed-loop settling time and damping ratio ζ. This design task follows from pole placement techniques. If needed, students can utilize the `PID Controller` block in SIMULINK to tune the PID gains and/or calculate the maximum torque/power requirements on the DC motor using SIMULINK. We designed two demos to illustrate these tasks [40,41].

Building on the above knowledge, students next advance their pole placement design in two directions. First, they are given the desired closed-loop pole values and are asked to compute the PID controller gains. Next, they fix K_p and K_i, and perform a parametric study over the controller gain K_d. To this end, they express the closed-loop system characteristic equation $1 + G(s)C(s) = 0$ in the standard root locus form: $1 + K_d G_{eq}(s) = 0$, where $G_{eq}(s)$ depends on $G(s)$ and the fixed K_p and K_i. In this setting, it then becomes possible to leverage for example the `rlocus` command in MATLAB to investigate how closed-loop poles change as K_d varies and determine the range of K_d for which the closed-loop system is stable and has desirable transient performance.

The above approach can also be implemented with most controllers of interest. For example, in a problem with $C(s)$ as a lead/lag compensator, students were asked to compute the steady-state error given that the elevation angle must follow a ramp trajectory, and to compute the compensator parameters such that the closed-loop system achieves a desired phase margin determined from Bode diagrams.

Depending on the timeline of covering the course materials, the above topics will likely be spread over three homework assignments, as one topic requires the knowledge of pole placement, one on root locus, and the other on Bode diagrams.

3.3 MATLAB® Integration. The modules described above can all be implemented straightforwardly in MATLAB. Specifically in ME 4555, the instructors cover useful MATLAB command line functions and SIMULINK implementations. By writing scripts (either .M files or live scripts), students utilize commands to build transfer functions, obtain open-loop and closed-loop step/impulse responses, calculate closed-loop transfer functions, obtain step response characteristics (e.g., settling time, percent overshoot), perform partial fraction expansion, design controllers using root locus, and analyze frequency response using Bode diagrams.

On the SIMULINK side, students learn how to build transfer functions and block diagrams with transfer functions, create different waveforms to be used as input signals, test their controllers, and perform various plotting tasks. Students also learn to automate their work by running an .M file to load their SIMULINK simulation parameters.

Instructors are recommended to hold in-class demo/tutorial sessions to cover MATLAB and SIMULINK used to serve course objectives and to consistently assign homework exercises that build upon the in-class demos. It is also convenient to provide a sidebar in the homework summarizing key MATLAB commands and syntax, which can then guide the students to easily apply that knowledge to the homework problems.

3.4 Plug-In Points and Extensions. Viewing heliostats as a single degree-of-freedom dynamical systems with rotational inertia allows a reasonable connection to the real-world problem while at the same time providing a level of abstraction suitable for an upper-level course like ME 4555. With this abstraction, integration of heliostat concepts into a curriculum covering mathematical modeling, system analysis, and feedback control will not face major barriers. In the modeling area, plug-in points include free body dynamics, modeling of coupled dynamical systems, and linearization. In system analysis, plug-in points include transfer functions, open-loop system response, and time-domain simulations, and in feedback control, they include block diagrams, closed-loop systems, and controller design.

The modules described above can be further extended as follows. In mathematical modeling, both elevation and azimuth angles can be considered, either as two decoupled dynamics or coupled dynamics. Students could also be asked to evaluate, for slow speeds, how well the decoupled dynamics approximate the coupled dynamics. Along these lines, students can also be asked to model wind forces in the heliostat and how such forces, e.g., as a gust (impulse) or as noise of a particular frequency (sinusoid), could affect the precision of a heliostat. This can be a natural plug-in point for studying transient behavior or frequency response. In system analysis, the students can also be asked to simulate the full nonlinear model and compare it against the predictions of the linear model. Additional tasks could include evaluating DC motors with different specifications and determining closed-loop tracking effectiveness, and incorporating gear backlash in the model to determine how this influences the precision of motion control in a heliostat. In feedback control, realistic elevation and azimuth angle trajectories as a function of time can be provided to the students, and these trajectories can be subjected to noise, or the heliostat subject to wind forces, and the student can evaluate how well the controller works and how much energy efficiency is sacrificed due to imprecise tracking.

4 Conclusion and Discussion

The heliostat context exposes students to a system in which proficiency in a single discipline is necessary but not sufficient. Effective heliostat operation requires accurate sun-angle sensing, precise azimuth-elevation control, structural rigidity under wind loading, thermal performance of the absorber, and robust power electronics. While ME 3460 and ME 4555 address robotics and control specifically, instructors can use the heliostat narrative to motivate the importance of contributions from materials engineering, heat transfer, and power electronics, thereby reinforcing the value of cross-disciplinary collaboration that students will encounter in industry.

The ME 3460 modules align with the standard robotics sequence (forward kinematics, inverse kinematics, trajectory planning, joint control) found in virtually all introductory robotics courses. The three-phase structure of the ME 4555 assignment sequence (modeling, analysis, control) is essentially universal among undergraduate dynamics and control courses in mechanical, aerospace, electrical, and systems engineering programs. Instructors wishing to adopt these materials need to ensure only that the relevant conceptual prerequisites (DH notation for ME 3460; Laplace transforms and basic feedback theory for ME 4555) have been covered before assignment. An overview of these modules can also be found in Ref. [42].

Based on the student work, the instructors have some observations and recommendations. In ME 4555, in mathematical modeling, the main difficulty for some students was correctly identifying the nonlinear term in the system equations due to mass imbalance. In system analysis, some students did not provide time simulations, some made minor errors, such as when identifying the steady-state value, and to a lesser degree some did not notice that their solutions were inconsistent with the previous parts of the same problem. In control design, the root locus concept was for some students challenging. Students either did not find the correct condition on the derivative controller gain and/or did not read the correct pole locations from the root locus plot. In ME 3460, one of the common errors was due to sign mistakes when filling out the DH table. This error then propagated into subsequent steps. Moreover, while students were able to solve problems parametrically, when it came to computing the solution some made minor errors such as using sine instead of cosine or using arctan instead of arctan2 functions.

Future work in our curriculum implementation will focus on five directions:

(1) Integration of the SIMSCAPE platform into ME 3460 homework assignments requiring students to validate analytical waypoint designs.
(2) Extension of the ME 4555 modeling module to two degrees-of-freedom, enabling coupled/decoupled azimuth-elevation dynamics.
(3) Implementation of realistic sun-tracking reference trajectories based on established solar position algorithms [38], replacing simplified step and ramp references.
(4) Systematic comparison of PID, lead-compensator, and model-based controller architectures in terms of tracking performance.
(5) Development of a quantitative link between heliostat tracking error and CSTP energy conversion efficiency, which would close the loop between control-systems pedagogy and the original energy engineering motivation.

Overall, this article described the development and first-cycle deployment of heliostat-integrated homework modules in two mechanical engineering courses at Northeastern University. The modules span the full arc from forward and inverse kinematics and Jacobian analysis (ME 3460), through open-loop dynamic analysis, to closed-loop PID and lead-compensator design (ME 4555), all anchored to the physically motivated problem of steering a heliostat mirror to track the sun, and with a transition from more applied to more abstract level modules consistent with upper-class courses. Over the first two deployment years, 504 students in total were exposed to the heliostat context. While informal feedback from students and instructors' evaluation of student work is promising, the instructors also plan to further improve on the developed materials and ultimately assess their impacts on learning outcomes through pre-/post testing and comparative cohort studies.

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Conflicts of Interest

There are no conflicts of interest. This article does not contain any studies involving human participants or identifiable human data. Ethical approval and informed consent were not required. Informed consent not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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