Modelling, Design and Analysis of Automatic Temperature Control of a Room from Indoor Radiator Power

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Abstract

In today's technological age, automatic control has become ubiquitous, this research focuses on the automated control of room heating systems which use appropriate sensors to make the system sensitive to outdoor temperature, occupancy, humidity, and user input, thereby achieving optimal human comfort and response reliability. Using advanced heat transfer methods, sensors and control mechanism, this system improves upon the existing on/off heat control. The simulation of a model room with a knob control system shows promising results. While the current work does not take into account actuator effects or computational fluid dynamics methods for optimizing parameters, it provides a reasonable model with positive results. The results of this study could impact heating systems in homes and hospitals, allowing users to turn on a heater and never worry about further adjustments.

Index Terms— ***Heating systems, Space Heating, Temperature, Temperature Control***

I. INTRODUCTION

Heating has always been one of the most important necessities for life on Earth. Despite being the only known home to life in the observable universe, environment is not hospitable far from the equator. Early human settlements in the northern hemisphere were sparse, but advancements in civilizations made life in colder regions viable. Today, even relatively warmer areas heavily rely on efficient water and room heaters. Unlike traditional fireplaces, modern heating largely employs steam or electric heaters.

Steam radiators, the prevalent choice, work by converting boiled water into steam that travels through pipes to room radiators. As steam releases heat and condenses, it completes a cycle [1]. While historically efficient, these radiators have been outpaced by technology. Thermostats allow precise temperature control, leading to the creation of larger test chambers for assessing heater thermostats [2].

II. LITERATURE REVIEW

Research introduces a logic control algorithm for mushroom nursery temperature and humidity[3]. Three types of mushrooms were suggested to be housed in the nursery measuring 3 by 5 by 3.5 each with their own unique inherent requirements will ensure the control system validity.

Using computational fluid dynamics, air heating, radiating and dissipating properties were studied and optimized [4]. The study employed Navier-Stokes equations for calculations and found underfloor heating to be the most effective solution .

Advanced radiators and software significantly improved temperature control. These developments led to enhanced dimensional management due to thermal accuracy, yielding optimal flow rates. The research presented a new digital heat rate management system, sustaining stability and accuracy [5] Results suggest that the device has excessive balance and high precision.

Fig. 1 A standard home radiator [1]

A novel cabin temperature control [6] approach was proposed, divided into cooling block and zone temperature control. The paper analyzed an area temperature controller using PID and fuzzy control methods, demonstrating superiority over traditional PID control. Results show that this temperature control system is an improvement over the conventional PID control program.

Radiator heat transfer into a room can be modelled into a partial differential equation (PDE) [7]. Function and stability of the two control algorithms were analyzed. An accurate reduced model, represented by Bode diagrams, introduced a new control algorithm with $H\infty$ to enhance room heating system dynamics.

The study involved designing an automatic temperature control device, focusing on time-temperature intelligent control and water circulation control through an electromagnetic valve. The device is advised [8] as fit for use for office, workshop and home use. The device demonstrated energy efficiency benefits, suitable for various settings.

A study presents a small temperature control system using a thermoelectric cooler (TEC), driven by a proportional integral differential (PID) compensation network. Temperature control spans 5° to 55°, with a remarkable accuracy of 0.5 degrees Celsius [9]. The TEC system boasts longevity, robustness, rapid response, wide temperature range, and precise control.

In another research effort, optimization of software and hardware for radiator operation becomes a standard in research and development. An aimed improvement in radiator thermal performance test equipment is achieved, enhancing accuracy *[10]* Addressing structural modeling, automatic control, and constructive aspects, the study introduces a mathematical model of temperature sensor dynamics and proposes structural changes with positive results.

Exploring house heating and hot water systems, data is gathered from sensors, and a MATLAB Simulink model is developed [5], [11] The approach results in cost reduction and energy efficiency, confirming the value of intelligent automatic control systems in various applications.

Another innovation combines solar power generation, automatic room temperature control, and ventilation. A solar panel serves as a shade while generating clean energy. Sensors trigger window servos for ventilation, enhancing heating and temperature control efficiency [12]. However, limitations arise in adverse weather scenarios where programmed controls lack flexibility, potentially leading to system failure.

Research explored diverse temperature control strategies. One study employed a Controller Area Network, achieving 35% enhanced efficiency and cost reduction using thermocouple sensors and programmed software [13] Another module utilized LADRC control algorithm, ZigBee communication, and web configuration software for energy-efficient heat control [14] This device helps improve efficiency and quality of life as well as provides effective data to monitor power consumption and costs. The design and work are very practical and has good engineering and market value.

A microcont roller-based solution integrated an LM35 sensor and LCD screen for AC and heater control. MATLAB and Simulink exhibited stability and efficiency. These approaches, though effective, still seek enhancements for greater sophistication . [15].

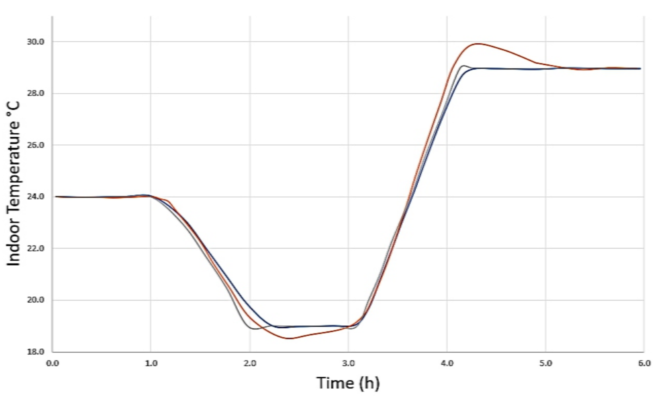

Fig. 2 Indoor temperature response in tracking a sequence of desired ramp variations

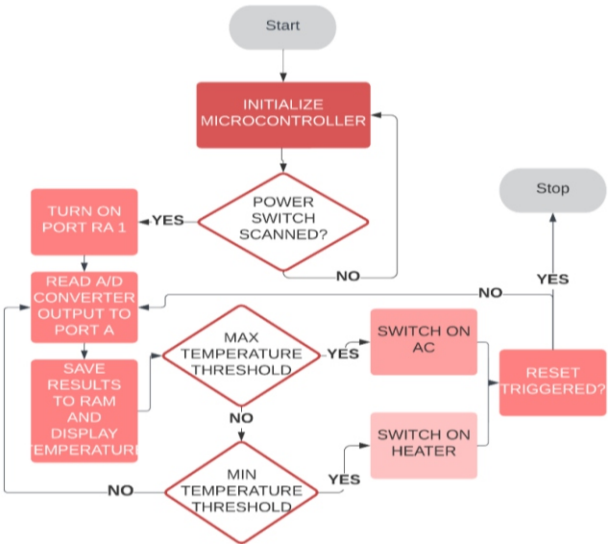

Fig. 3 Flow chart for implementation of micro-controller based automatic temperature control [15]

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The microcontroller gauged temperature, adapting fan speed for comfort, and controlling loads. The heating system is turned on if the ambient temperature is lower than the desired temperature or the cooling system switches when the temperature sensed by the sensor exceeds ambient temperature.

A smart temperature and humidity control system [16] doubles as an agricultural control unit, optimizing barn conditions for maximum output. Actuators such as heaters, windows, and fans modulate the barn environment.

Additionally, a heating control radiator [17] was devised to regulate room temperature, inspired by surface plasmon resonance (SPR) experiments. The study affirms the efficiency of the heating control program for SPR experiments.

Similar research introduces reflector panels and wall insulators to enhance thermal energy retention in buildings [18]. Evaluating different setups under varying sunlight conditions, improved thermal resistance leads to enhanced efficiency.

III. METHODOLOGY

Efficient energy management in modern buildings is critical. Traditional heating systems, which use simple on/off switches and thermostats, frequently waste energy. To address this challenge, realistic building models and improved control systems are required. Modelling the thermal behavior of a building typically involves the use of equivalent thermal characteristics, such as resistive and capacitive (RC) networks to portray heat flow through surfaces such as walls. In our scenario, we'll model the subject area, such as a room, by assigning thermal resistance to walls and representing their thermal capacity as thermal capacitance—a technique similar to the electrical RC model.

By knowledge of material on walls and surrounding, we can create a system model $G_{sys}(s)$, then design appropriate controller C(s) for the heater. The heater, in this case our actuator, also is supposed to have a transfer function to allow for the effects of the heater to be compensated in design with transfer function, $G_{act}(s)$. To lower the order of the model with appropriate precision, a frequency response approach taken from control engineering is used. The controller is then created. The whole control system is written in computer softwares MATLAB/Simulink, with the results exhibiting good performance under system disturbances as well as lower energy usage than a standard on-off controller.

It is feasible to minimize the order of the construction model using an RC networks technique by studying the impact of each layer's resistance over the heat flow injected in each capacitor. This results in the formation of a dominating layer.

Another method is to calculate the average thermal conductivity of a multi-layered element. The state-space model is the most often used format for model description. The model requires measurement and estimation governed by reason to formulate the apt mathematical model. Or the fundamental values of heat transfer coefficients can be evaluated and a single input single output system is produced.

IV. MATHEMATICAL MODELLING

A room is sampled with total internal capacitance as C and is assumed to not contain heavier elements of much larger or smaller thermal capacitances and its walls are said to provide the thermal resistance when compared to a RC model. Conductance between outside and inside of the wall is U (where thermal resistance R = 1 / U).

Now,

q_{aux} = Auxiliary heating/cooling (+ive/-ve)
T_R = room temperature
T_o = outside temperature
C = Thermal capacitance
U = Thermal heat transfer coefficient

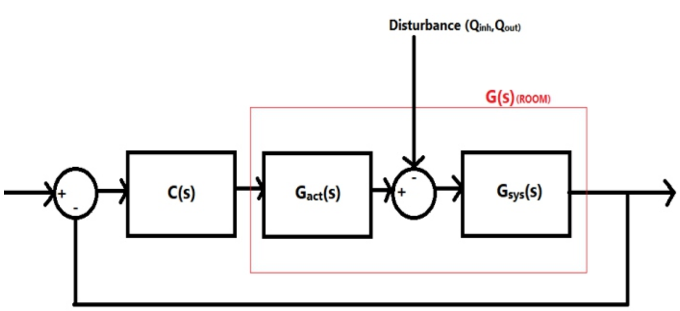


Fig. 4 Schematic diagram of system

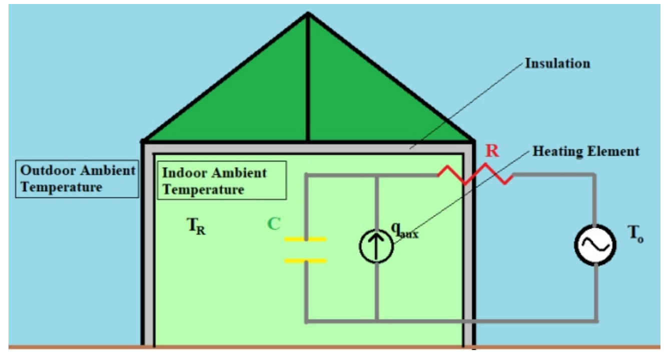


Fig. 5. RC model of the thermal system

An energy balance for the room yields;

Energy Stored + Energy Lost = Heat Input

$$C \cdot \frac{dT_R}{dt} + U \cdot (T_R - T_o) = q_{aux} \tag{1}$$

A building inside temperature is governed by thermals i.e., convection, conduction, and radiation. Convection and conduction are the primary influences on thermal behavior in our model, with radiation, from the sun, acting as a disturbance. Convection and conduction can be considered as follows,

$$qcd = \frac{U_{cd}A}{T_2 - T_3}, \tag{2}$$

$$q_{cv} = U_{cv}A\,(T_2 - T_1) \tag{3}$$

q_{cv} = Thermal energy by convection
q_{cd} = Thermal energy by convection

U is heat transfer coefficient, A is surface area and q is thermal energy.

The convection heat transfer coefficient, U_{cv}, is affected by the mean velocity, hydrodynamic and thermodynamic properties of air, and its value varies with temperature and speed. It is extremely difficult to calculate an accurate value of a given spaces' U, but a well-rounded approximation must suffice with very little error.

Note,

Nu = Nusselt Number
Pr = Prandtl Number
Re = Reynolds Number

$$v = \frac{Nuk}{L} \tag{4}$$

$$Nu = 0.664 Re^{\frac{1}{2}} Pr^{\frac{1}{2}} \tag{5}$$

Convection and conduction resistances can be defined by the equation

$$R_{cv} = \frac{1}{U_v A}, \; R_{cd} = \frac{1}{U_d A} \tag{6}$$

q_{cv} = Thermal energy by convection
q_{cd} = Thermal energy by convection

A further implication within this is insulation of wall. Inherent material properties of the walls and the dimensions are used find for constants and values for the thermal capacitance, thermal transfer coefficient and thermal resistances. The thermal capacitance is calculated

Element	Material	k	c_p	ρ	Thickness	Area
Wall	Lightweight concrete	0.19	1000	600	0.2	435.95
Roof	Asbestos tile	0.55	837	1900	0.025	522.16
Windows	Glass	0.7	837	2500	0.01	6
Insulator	Cellulose fill	0.043	837	10	0.2	-
Interior	Air	-	1005.4	1.225	-	-

as;

c_p = specific thermal conductance

$$C = mc_p \tag{7}$$

The paper [19] we referred for this work by Hector et. al. the problem presented will be used as reference in our work.

The problem was a model house with cellulose insulated walls (40m x 4m) and 4 windows(1m x 1m). The paper modelled thermal capacitance and resistivity of each wall and window, including the roof.

The state-space model provides information on the house's dynamic thermal behavior. However, its direct use necessitates the measurement of all system state variables. For control system design, a SISO model representation in the frequency domain is used instead of a state feedback controller. The paper made a state space model using some sample values which were compiled and searched for a sample room sourced from the literature review.

A transfer function relating the heat input (Q_u) and the temperature (T_H) was established with,

$$G(s) = \frac{T(s)}{Q_u(s)} = C\,(sI - A)^{-1}B \tag{8}$$

Table. II Properties and inherent constants of the materials assumed to be used in the house construction for use in calulations

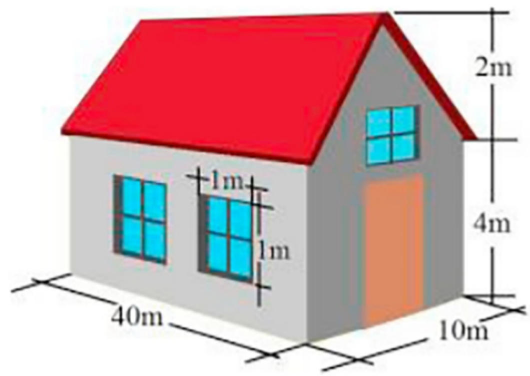


Fig. 6 Model of house showing number of windows and door by Hector et. al. 2018

V. IMPLEMENTATION OF MODEL

A) System

A frequency response approach is used to scale down the 6th order transfer function making calculations and compensator simpler. Done in two portions:

1. Showing the Bode diagrams for each transfer function of the set defined by the transfer function,

	Insulated House
Roof-Insulator	$C_R\dot{T}_R = [R_{8v} + R_{9d}](T_a - T_R) + [R_{9d} + R_{10d}](T_{RI} - T_R)$
Insulator-Interior	$C_{RI}\dot{T}_{RI} = [R_{9d} + R_{10d}](T_R - T_{RI}) + [R_{10d} + R_{11v}](T_H - T_{RI})$
Insulator-Wall	$C_{WI}\dot{T}_{WI} = [R_{1v} + R_{2d}](T_a - T_{WI}) + [R_{2d} + R_{3d}](T_W - T_{WI})$
Wall-Interior	$C_W\dot{T}_W = [R_{3d} + R_{2d}](T_{WI} - T_W) + [R_{3d} + R_{4v}](T_H - T_W)$
Windows	$C_{ws}\dot{T}_{ws} = [R_{5v} + R_{6d}](T_a - T_{ws}) + [R_{6d} + R_{7v}](T_H - T_{ws})$
Interior	$C_H\dot{T}_H = [R_{3d} + R_{4v}](T_W - T_H) + [R_{6d} + R_{7v}](T_{ws} - T_H) + [R_{10d} + R_{11v}](T_{RI} - T_H) + Q_R - Q_L + Q_u$

Table. I Mathematical model of the individual component of the house to the overall thermal behavior [34]

$$\begin{bmatrix} \dot{T}_{WI} \\ \dot{T}_W \\ \dot{T}_{ws} \\ \dot{T}_R \\ \dot{T}_{RI} \\ \dot{T}_H \end{bmatrix} = \begin{bmatrix} (-R_1 - R_2)/C_{WI} & R_2/C_{WI} & 0 & 0 & 0 & 0 \\ R_2/C_W & (-R_2 - R_3)/C_W & 0 & 0 & 0 & R_3/C_W \\ 0 & 0 & (-R_4 - R_5)/C_{ws} & 0 & 0 & R_5/C_{ws} \\ 0 & 0 & 0 & (-R_6 - R_7)/C_R & R_7/C_R & 0 \\ 0 & 0 & 0 & R_7/C_{RI} & (-R_7 - R_8)/C_{RI} & R_8/C_{RI} \\ 0 & R_3/C_H & R_5/C_H & 0 & R_8/C_H & (-R_3 - R_5 - R_8)/C_H \end{bmatrix} \begin{bmatrix} T_{WI} \\ T_W \\ T_{ws} \\ T_R \\ T_{RI} \\ T_H \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1/C_H \end{bmatrix} [Q_u] + \begin{bmatrix} R_1/C_{WI} \\ 0 \\ R_4/C_{ws} \\ R_6/C_R \\ 0 \\ 0 \end{bmatrix} [T_a],$$

$$y = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 1]\mathbf{x} + [0]Q_u\,.$$

***Eq. 1a** State space model of the room from [34]*

$$G(s) = \frac{T_H(s)}{Q_u(s)} = \frac{5.075_{-7}s^5 + [6.17_{-10}, 7.65_{-10}]s^4 + [2.65_{-13}, 4.08_{-13}]s^3 + [4.58_{-17}, 8.85_{-17}]s^2 + [2.39_{-21}, 6.15_{-21}]s^1 + [6.21_{-27}, 2.21_{-26}]}{s^6 + [1.3_{-3}, 1.62_{-3}]_5 s^5 + [6.10_{-7}, 9.7_{-7}]_4 s^4 + [1.26_{-10}, 2.61_{-10}]s^3 + [1.07_{-14}, 3.07_{-14}]s^2 + [3.07_{-19}, 1.28_{-18}]s^1 + [5.5_{-25}, 2.72_{-24}]}$$

***Eq. 1b** Transfer function. Note that 5.075_{-7} means $5.07x10^{-7}$. And the two values in zeros and poles are ranges of values since exact number could not be computed with number of variables.*

2. Suggesting a system $g_a(s)$ that as closely as feasible matches G(s). reducing the system to second order and giving, natural frequency ω_n and damping ratio ζ by,

$$g_a(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{9}$$

To improve approximation, a new zero is introduced to the equation. Natural frequency is taken as $0.9\text{x}10^4$ and damping ratio of 1.5. by using MATLAB, the following equation is approximated,

$$g_a(s) = \frac{5.443 \times 10^{-7}s + 4.536 \times 10^{-11}}{s^2 + 0.000135s + 4.05 \times 10^{-9}} \tag{10}$$

B) Actuator (Heater)

We will be using a step heater with only on-off function. The need for a transfer function of $G_{act}(s)$ is not needed. So,

$$G_{sys}(s) = G(s) \tag{11}$$

C) Controller

Industry standard closed response standards include a settling time T_s, at least 4000 s and a maximum overshoot of 10%. These are taken as initial estimates only and can be improved on further iterations. When translated to frequency domain the specifications become, damping ratio ζ=0.59, with a phase margin of a minimum 58° and a bandwidth $\omega_{bw} \geq 0.007$ rad/s. A PI controller is designed as follows:

$$C(s) = k_p + \frac{k_i}{s} = 0.065 + \frac{2.7 \times 10^{-6}}{s} \tag{12}$$

But by implementing PID tuning, inputting the G(s) in the MATLAB Sisotool. Controller in the paper was obtained using techniques like Bode shaping to achieve a phase margin of 90°. To avoid a large energy demand, a new bandwidth ω_{bw}=0.0034 rad/s was adopted. The controller transfer function was obtained as;

$$C\,(s) = \frac{(1 + 1.13 \text{ x } 10^2 s)\,(1 + 1.6 \text{ x } 10^3 s)}{s\,(1 + 76s)} \tag{13}$$

The model of the controller was made to accommodate the least gain. Note the more the gain, the more power requirements and physical specifications of the actuator.

D) Simulation

We modelled a relatively large room, now we will simulate it on Simulink with different conditions. The simulation run time is set to 10,000 seconds. Instead of importing the controller design directly from Sisotool, We model the exact controller on Simulink, and tested against step input shown in results at the end.

The Sisotool model can be directly imported into a Simulink platform from the UI. The results generated by this built in software were identical and reproducible compared to the manually arranged control configuration.

VI. RESULTS

a. Sinusoidal Input (0.0005 Hz and 40 degrees amplitude)

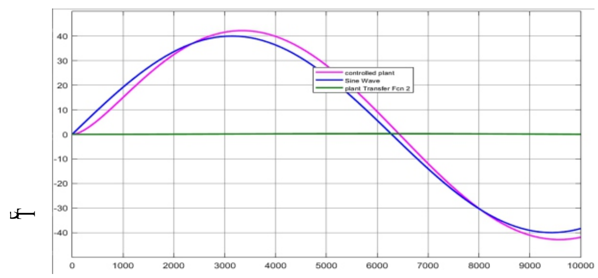


Fig. 8a Plot of Sin input and System response (-40 to 40°C) against time (0-10,000 seconds)

b. Step input

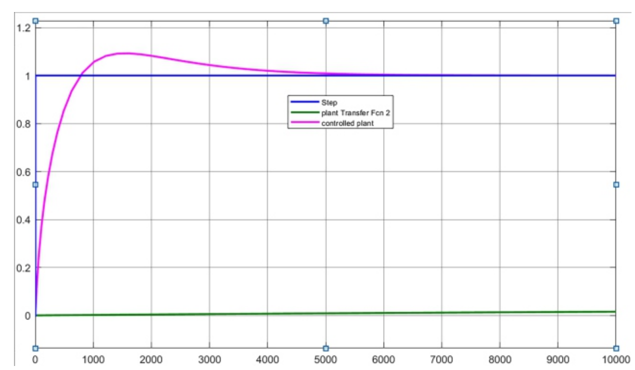


Fig. 8b Plot of Step input (blue) and System response (green) against time (0-10,000 seconds)

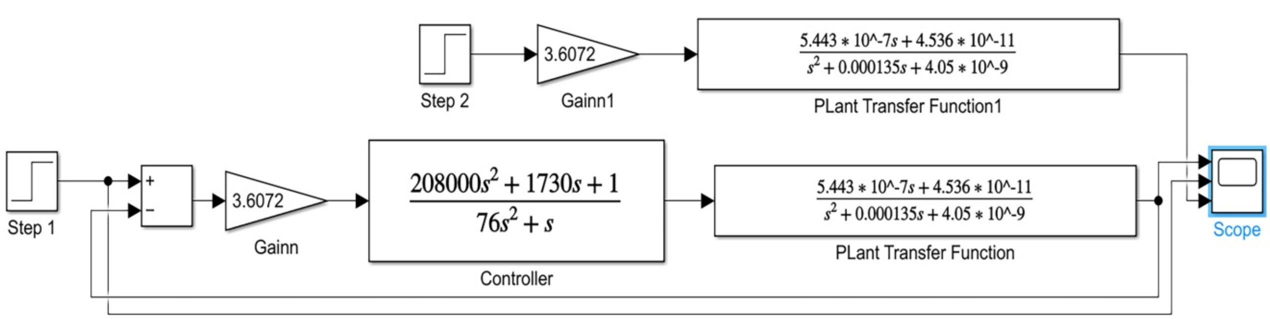


Fig. 7 Schematic model of control system with one input from uncompensated system going to output plot shown in results.

c. Ramp input

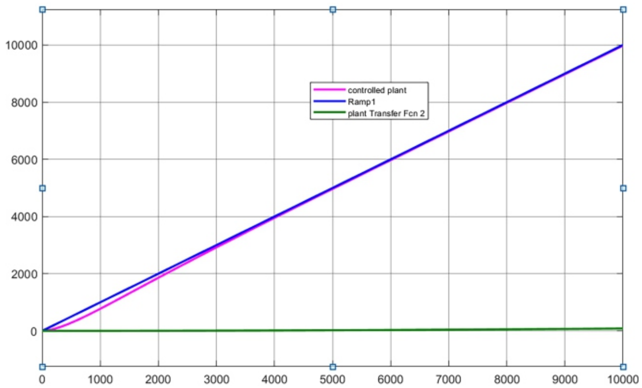


Fig. 8c Plot of ramp input (blue) and System response (0-10,000°C) against time (0-10,000 seconds)

d. Parabolic input

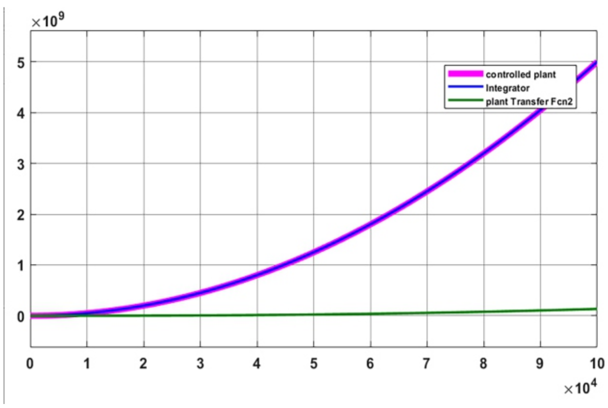
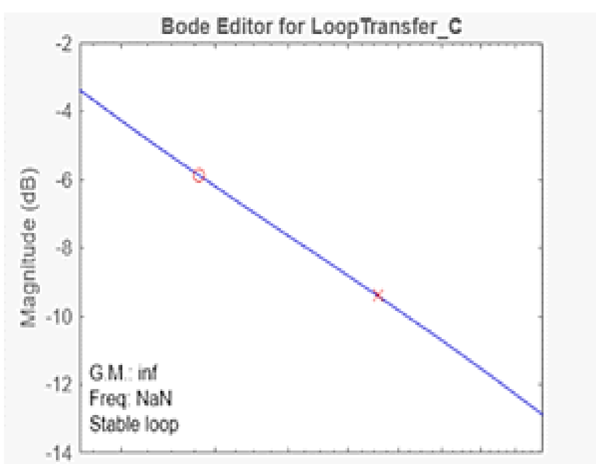


Fig. 8d Plot of parabolic input (blue) and System response (0-5e+7°C) against time (0-10,000 seconds)

e. Bode plot of Phase and Magnitude of compensated system:



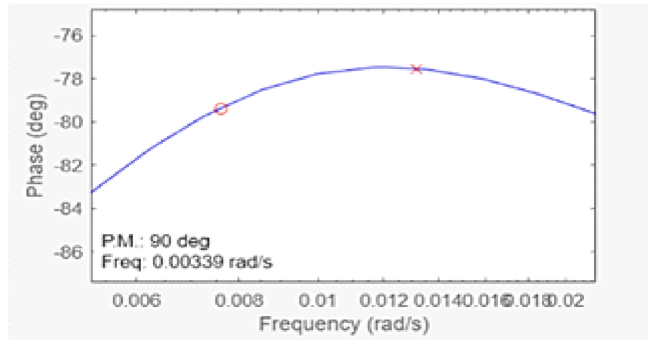


Fig. 8e Phase/Magnitude and frequency plots

f. Simulink Generated control loop of the Sisotool integrated with a thermostat knob which was adjusted during the simulation.

VII. DISCUSSION

In simulation, the system was tested with various inputs—Step, Ramp, Parabolic, and Sinusoidal—yielding consistent and stable responses as per the earlier emulated mathematical model. Fig. 8 b illustrates the step response closely following the input (blue line). The room of 40m by 10m reached a stable temperature range with a Peak Overshoot of 1.09 and a settling time of around 4000 seconds [Fig. 8 e].

To strengthen the results, a ramp input—an initial order change—was applied. The room's temperature responded linearly to rising input, as depicted in Fig. 8 c, demonstrating promising stability. Similarly, the parabolic input— representing a second-order change—resulted in a response aligned with the input, generating the intended outcomes [Fig. 8 d].

For stability and robustness assessment, the system underwent a recommended sinusoidal input test—a sinusoidal function with a frequency of 0.0005 Hz and an amplitude of 40ºC, alternating between 40ºC and -40ºC over 2000 seconds [Fig. 8 b]. The response closely tracked the input, maintaining stability and smoothness, indicating its readiness for swift and robust heat control in the modeled environment.

In simulation, the Simulink model incorporated input from a knob, producing results consistent with earlier findings [Fig. 8 f]. The response closely followed the input with minimal lag, displaying maximum robustness in the face of sudden changes.

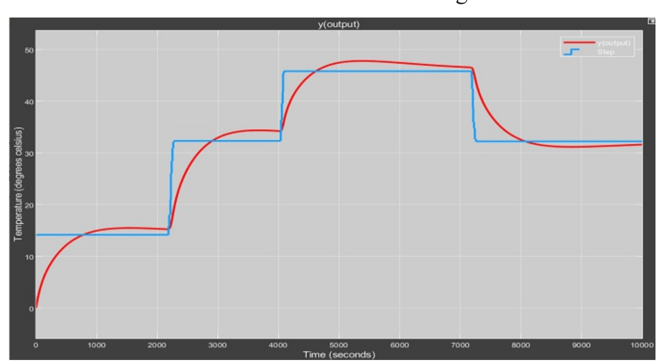


Fig. 8f Shows response on a knob input (from 14 to 32 to 45 and back to 32 ºC in steps) and temperature response of system with respect to user demand plotted against time (10,000 seconds).

VIII. CONCLUSION

We modelled a temperature control device for a 40x10 meter room affected by conduction and convection from outdoor temperature and a step heating element. The process goes through mathematical modelling needed to represent room walls and conditions by using knowledge of thermal physics and materials. The mathematical model is built upon to arrive at a control system befitting to the scenario. After developing controls for the given environment, the system is simulated and tested on MATLAB and Simulink. Results show promise by step, ramp, parabolic and even sinusoidal inputs and stays stable to give sensible outputs for its size and constraints. The Simulink model can be used to make a program for control and use of Virtual Instrumentation can further advance our work. The controller can be made to fit the original system and construct a compensator around that environment. The control solution can serve as a base model for automatic temperature control with slight modifications to accommodate sensors and actuators.

We can further make an ecosystem of controls to further regulate temperature control and model the actuator transfer functions. The results can be checked and cross referred to standard systems and then efficiency to simple radiator heater can be compared with. The model is a solid base for building a physical control system and then compare experimental results to further advance its validation.

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