Take Home Test - Treau

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1 Question

1. Assess yourself, from 1 to 4, in the following areas or skills. We are not looking for a candidate to have experience with all, or even a majority, of these areas. This question is much less about the magnitude of the numbers and more about their relation – where do you think your strengths are?

1 = Very little or no experience
2 = Some experience, but not yet at a level of full competence and confidence
3 = A lot of experience, generally able to do this work at a professional level
4 = Very experienced, typically the expert on my team or among peers

- PID control
- Model predictive control
- Optimal control methodologies
- Dynamic systems modeling
- Microcontrolers
- Scripting languages
- C/C++
- Software version control
- Experimental design
- Instrumentation
- Data acquisition (NI or other DAQ)
- Project management
- Written communication
- Presentation
- Heat transfer
- Thermodynamics
- Fluid mechanics

Answer

Skill	Level	Description	Support
PID Control	4	—	—
Model Predictive Control	2	—	I need to put in the time on this one, external support not required.
Optimal Control	2	Need to learn more about dynamic programming for dynamic optimization. But I do kalman filters and LQR	—
Dynamic systems modeling	4	ODEs yes. PDEs are within reach	A thermal science expert, to bake what they know into the dynamics
Microcontrollers	3	—	Firmware engineer to own OS/drivers
Scripting languages	4	Matlab	—
C/C++	2	—	Firmware engineer to fill the gap, though I can (and desperately want to) come up to speed with this. I have in the past done all my work including real-time code in Simulink
Software version control	2	I use it regularly	Git Wrangler
Experimental Design	1	I just googled this	—
Instrumentation	2	It's the systems/test engineer that has handled this in my experience, but I can do this. Related skill - I generally pick sensors and decide (with electrical engineer) interfacing with the micro.	I will need to read the manual on thermocouples, anemometers, etc
Data acquisition (NI or other DAQ)	2	Same answer as 'Instrumentation'	—

Project management	3	Part of my responsibility is to scope out my work.	—
Written communication	3	—	—
Presentation	3	—	—
Heat transfer	3	I have a working knowledge of heat transfer. I do not get into the depths of calculating convective heat transfer coefficients.	Thermal Engineer
Thermodynamics	3	Working knowledge, good enough to have a comfortable grasp on refrigeration.	Thermal Engineer
Fluid mechanics	2	—	Thermal Engineer

2 Question

Briefly describe your weakest points in the list above and describe what extra resources or support could help you interface with these topic areas.

Answer

Two weaknesses worth dwelling on more:

1. MPC: This might be important for your product for interior temperature control, to take advantage of energy storage in building capacitance etc. I understand it but I need to spend some time on this to ensure that I can execute production-grade algos on this. I would need support with procuring some paid toolboxes for this.

2. C/C++: I should be really good at this already but I have been doing all my professional work in Matlab/Simulink $\rightarrow$ autocoding. I am very competent in that toolchain, starting from architecting the software for the complete feature set down to creating micro-ready code. So I am not new to coding for real time systems. If you have an engineer that works on C/C++ (firmware engineer?), they can lead this while I come up to speed. In the mean time, I would need you to be okay with me probably introducing some autocoded Simulink so that I can do deploy my algos.

3 Question

Briefly describe your strongest points in the list above and your experience in building those skills.

Answer

I have mostly answered this in question 1 but here's some information:

1. Controls - I learned by doing. Back in school, I thought I would become a simulation engineer, but I was very interested in understanding how ECUs worked. So I got into it working on a project in school. I have self-learned what I know. Secondly, working on thermal systems for EVs requires architecting logic for multiple interacting loops with multiple heat sources/sinks; I consider it a strength of mine.

2. Thermal - Same with this, I have learned this myself. I would rate my system-level understanding as very good. I.e. how does everything need to work together. But I would not know how to design an HX.

4 Question

Tell us about the time you decided you wanted to follow your current career path (engineer/researcher/etc.).

Answer

I grew up fascinated by cars. By the late 90s, India's experiment with economic liberalization was paying off. The car market was oxygenated by the influx of East Asian and German brands for the first time, which I followed fervently. I had a favorite motorcycle designer, favorite automotive magazine journalists, got the whole family hooked on Formula 1, and googled the Art Center of Design in Pasadena as soon as I got an internet connection.

I pursued mechanical engineering with the sole intent of joining the car industry. By my early 20s, my dogmatic obsession with the market faded, but I persisted with working in clean transportation. Clemson had a collaboration with BMW, which is why I went there (got a fellowship too, free money is cool). We were working on making a hybrid out of a BMW 1-series. I was the guy you went to for your Matlab/Simulink homework. We needed someone to work on the controller for the vehicle, that became me by default. That is how I got into control engineering. A few hours after I flew out to join Daimler, the car ran for the first time.

I joined Daimler to work on their powertrain harware-in-loop simulation team, but a budget cut axed it. They were working on project Supertruck with the DOE, and I knew the same toolchain from the BMW project. By a stroke of serendipity, I landed on a thermal control project.

Faraday Future and Zoox followed. Electric cars have high-fidelity thermal networks. For example, consider 2 condensers, 2 evaps, 2 EXVs, 2 pumps, 3-way valves, 4-way valves, multiple fans in concert to cool, heat pump, heat scavenge etc with variable position/speed actuators. Its a great problem to work on. If I was a company founder (which I am not sure I am *right now*), I would work on building a residential central HVAC unit; a vantage point of controls gives me a different perspective. For example - using one PT sensor to control compressor input superheat *instead of after each evaporator TXV-style*, with independent heat vectoring for a dual evaporator system saves energy by dropping compressor input superheat and therefore the pressure ratio. That is not available on any car last I checked, I am not sure of stationary refrigeration systems. But I want to make that the norm and hence my proclivity for thermal/control engineering.

If Silicon Valley created hardware companies that comported with its environmental values, thermal startups would not be uncommon. Working on this product would be among the better things at present time that I could do to save energy, and hence my application with Treau.

5 Question

Please provide documentation for a control algorithm that you developed for controlling a real-world system. Documentation can include code snippets, system modeling/analysis, data on system performance, and anything else that will help us understand how you approached the problem.

Answer

I will cover a part of my project on Supertruck when I worked with Daimler 2011-14. For context, the only thing changed on the system compared to the stock system was the compressor interior temperature sensors (yes, their best semi did not explicitly control interior temperature) to keep it close to stock so that they could make a business case out of this prototype.

Architecture

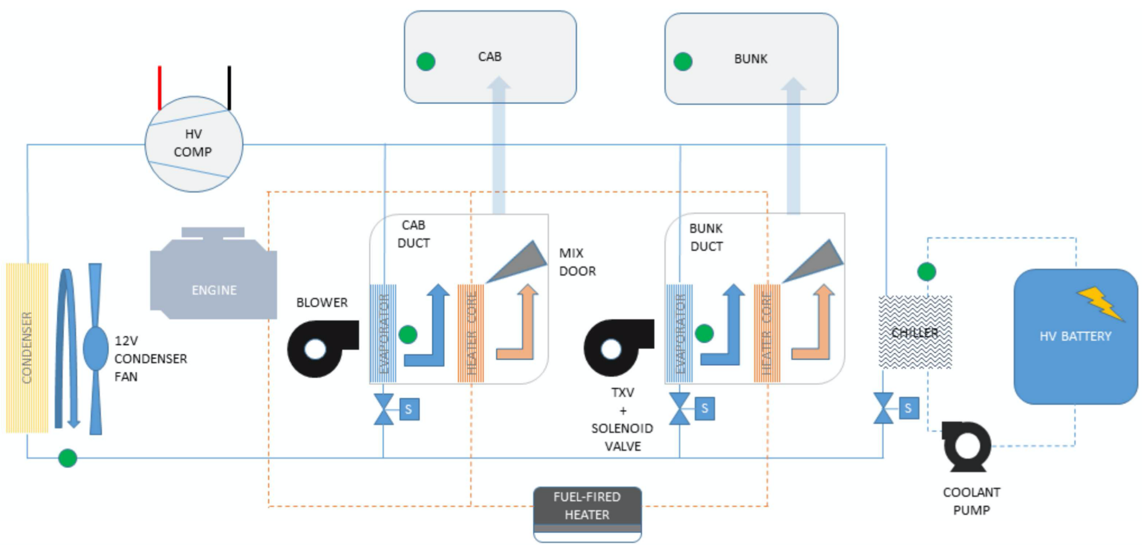

Figure 1: Supertruck Architecture

Interior Temperature Control

The math model for the interior air is:

$$\dot{T} = \frac{\dot{m}C_p(T_d - T) + Q_h + Q_s + Q_{sh}}{MC_p} \tag{1}$$

where:
T - interior air temperature
M - air mass
C_p - specific heat
T_d - duct temperature or evaporator exit air temperature
Q_h - human heat load
Q_s - cabin solar load
Q_{sh} - cabin-shell heat transfer

Rearranging:

$$\dot{T} + \frac{\dot{m}}{M}T = \frac{\dot{m}C_pT_d + Q_h + Q_s + Q_{sh}}{MC_p} \tag{2}$$

Here are the parameters that vary:

1. Blower speed - The coefficient of temperature (T) is $\frac{\dot{m}}{M}$. That means its time constant changes with a change in $\dot{m}$, i.e. a change in blower speed.

2. Air Capacitance - The cabin and bunk region can be divided from each other, or combined, depending on whether the barrier is closed or if the vehicle is in parked mode.

As the vehicle had solenoid TXV valves, the compressor can only explicitly control one region at a time. The blower speed is set by the driver. For the interior air I created a gain-scheduled PI controller to create a target evaporator exit air temperature for the compressor.

Battery Coolant Temperature Control

The battery coolant loop had a 4-way valve that was used for switching between a coolant-to-air HX or a coolant-to-refrigerant HX. When in the latter mode, the Hybrid Powertrain team created a requirement to control the coolant temperature to 30 °C. The compressor controlled this temperature directly.

Compressor Control

For the following cases:

1. Cabin **only** - The compressor had a gain-scheduled PI controller for controlling the evaporator exit air temperature, based on the blower speed.

2. Chiller **only** - The compressor had a PI controller for controlling the coolant inlet temperature into the battery pack.

3. Cabin **and** Chiller - Two controllers need to run in parallel but only one actuator, the compressor:
   (a) The problem is that each controller is creating a new state. The goal is to figure out which controller is 'leading' at every time step, and then get the other controller to follow for that time step.
   (b) The way to do that is, at each time step, calculate the **increment** in compressor speed for each controller. If cabin controller has a higher increment, add that to the compressor speed from the previous time step. The chiller controller integrator is then set to follow the cabin controller for that time step. Reevaluate at each time step.
   (c) At some point it is possible that either the cabin or the chiller could get overcooled as the compressor can only follow one of them. In that case, use the solenoid valve to shut off refrigerant. A hysteresis was used to engage/disengage the controller.

Evaporator freezing - this was fortunately not a problem as the the production vehicle used a temperature sensor in the airstream in front of the evaporator instead of on the fin. For the production vehicle, the map between air temperature and freezing fin temperature had already been empirically determined. I set the minimum possible evaporator air temperature as the lower saturation limit in the cabin temperature controller.

High Side Pressure Control

A PI controller that creates a fan speed request. The fan speed was saturated based on vehicle speed as ram air made the fan ineffective. The high side pressure target was a lookup table provided by the thermal team as a function of exterior ambient temperature.

Heating Control

The system had a mix door that was used to control interior temperature directly. The reason is, the duct air temperature was after the evaporator but before the heater core (this was production design that we carried over), so duct air temperature control with the heater core was not possible.

Parked mode is a mode for when the vehicle is parked overnight like at a truck stop. A fuel-fired heater was turned on if required. The heater only had binary control available.

Defrost Control

Calculate dew point temperature using exterior ambient temperature. Undercut that by a bias to ensure that air is dehumidified. Reheat air using the mix door for interior temperature control.

More on Cabin Temperature Control

I designed the above in 2012-13. I would explore using an optimal control algo to figure the highest possible evaporator temperature during the pull down period, by using a cost function penalizing the terminal cost and control input cost. The control input cost would be the temperature delta between cabin temperature and duct temperature and have the effect of keeping the evaporator temperature as high as possible. This will save energy.

$$Cost\ Function\ J = fT_h^2 + \int_0^h ru^2 dt \tag{3}$$

where:
T_h - Terminal (target) temperature at the end of the horizon
u - delta between interior and duct temperature
r - weight for u. This reduces the cost during the complete pull down process.
f - weigh for terminal temperature to ensure that system reaches target temperature

This will allow for creating a time to reach target destination that can be changed based on subjective comfort evaluation.

6 Question

A hot tub is 2 m x 2 m square and 1 m tall, and insulated on all sides with polyurethane foam of thickness 15 cm. Due to mixing issues, the thermistor that measures the water temperature responds to changes in the average temperature, T, with a time delay of 3 minutes. The hot tub is heated with a resistive heater. **Design a controller that will respond to changes in the set point Tsp as fast as possible while being robust to disturbances. Describe how the controller will be implemented (i.e. what hardware) and estimate parameters for the controller to the best of your ability.** State any assumptions.

Answer

This documents the output of the 90 mins.

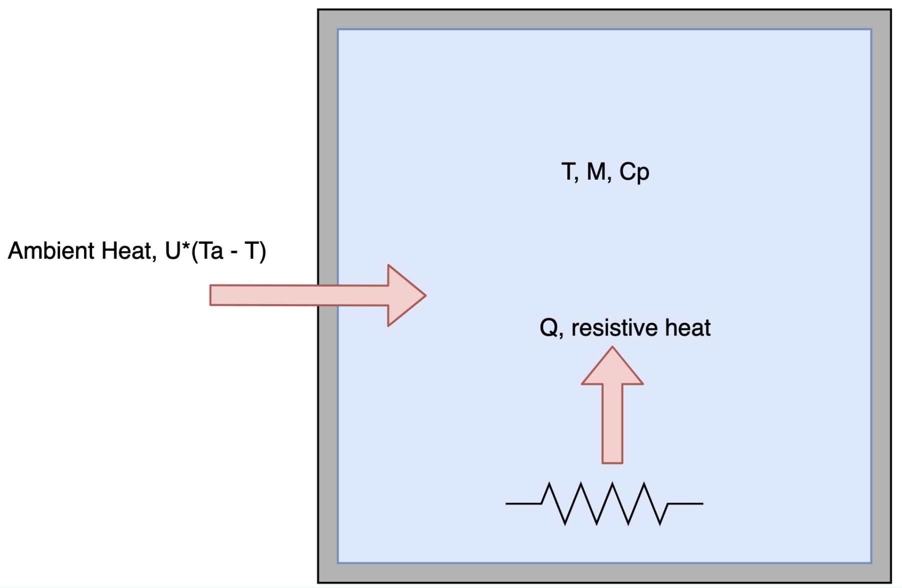

Figure 2: Plant

Modeling the System

Thought process:

1. The water forms one thermal inertia.
2. Does the insulation have large enough an inertia to consider it as a second inertia or can I consider this as a purely conductive element? To ascertain this, I calculated

the inertia of water and of the polyurethane here and found out a ratio of 30:1. So I modeled the polyurethane purely as a conductive element.

Math Model:

$$\dot{T} = \frac{Q + U * (T_a - T)}{M * C_p} \tag{4}$$

where:
T - Temperature of hot water tank
Q - controlled heat source
T_a - ambient temperature
M - mass of water
C_p - specific heat of water
$U = \frac{k*A}{L}$ overall heat transfer coefficient of conduction

Rearranging:

$$MC_p\dot{T} + UT = Q + UT_a \tag{5}$$

This gives a transfer function of temperature over heat input as:

$$G(s) = \frac{T(s)}{Q(s)} = \frac{1}{MC_ps + U} \tag{6}$$

Designing the Controller

Assume that the reference temperature (i.e. desired temperature) is T_{ref}.

Two considerations for the control design are:

1. This is a first order linear system.
2. This has a time delay.

For the first part:

1. A feedforward component of $U * (T_{ref} - T_a)$. I am adding this as there is a delay, so an open loop control will help in reaching the target.
2. A feedback component $C(s)$ - proportional control. In reality, a small integrator will also be required as the feedforward will not be perfect. The proportional gain can be tuned using stability/performance criteria.

For the second part, I will augment the controller with a smith predictor. Here is how a smith predictor works:

1. The process dynamics are $G(s) * e^{-\tau s}$ where $e^{-\tau s}$ is the laplace transform of the pure delay.
2. The smith predictor can be understood in two steps:
   (a) Cancel out $G(s) * e^{-\tau s}$
   (b) Replace it with the function $G_p(s)$, which is a simulated version of $G(s)$

The process diagram with the controller is shown below. For reference, **blocks highlighted in blue are in in the ECU**, the rest is the real plant:

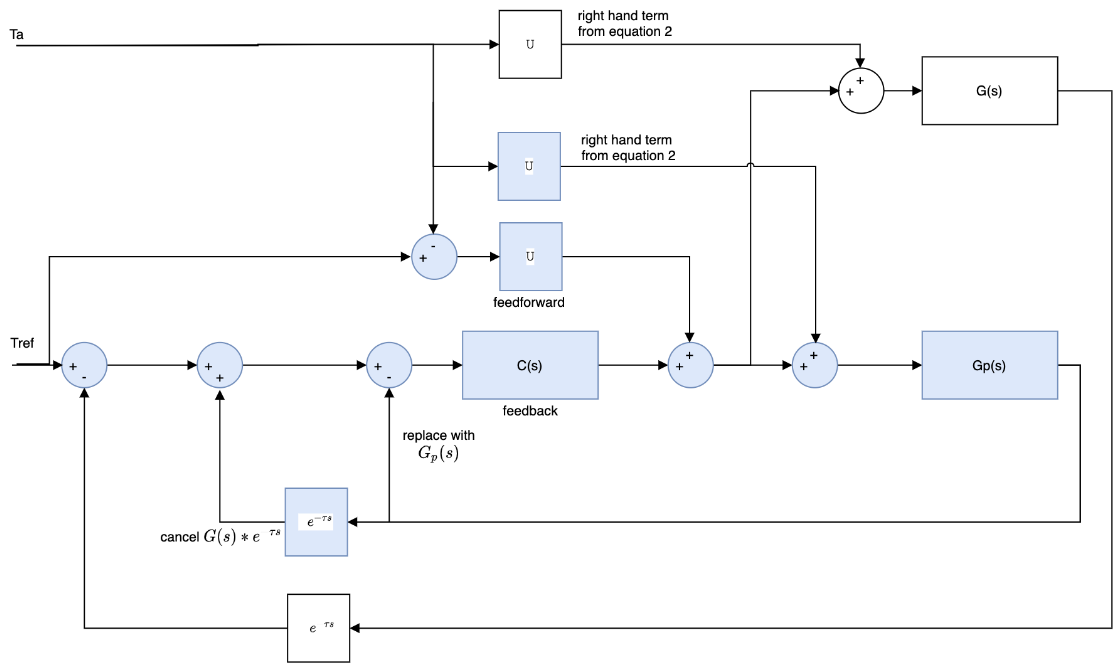

Figure 3: Process Diagram

The End