Observer-based Engine Cooling Control System (OBCOOL)

Project Proposal

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Introduction

Control systems exist in many applications today, from home thermostats and vehicle cruise controls to engine temperature regulation and missile-guidance systems. Many control system designs exist, and one of the newer, more sophisticated concepts in modern control systems is the concept of observers. Observers are algorithms used to predict a system's response. While complex, observers are a powerful addition to a control system and greatly improve the system's performance [1].

Our project will consist of researching observer-based control systems and applying this knowledge to design closed-loop controllers for velocity control and temperature regulation of an engine cooling system. The controllers will be implemented using DSP boards with Simulink auto-code generation. In addition, energy management and controller performance will be evaluated.

Goals

- General
  - Learn software packages for auto-code generation and real-time control via Simulink/DSP interface
  - Design energy management control system in Simulink environment to regulate voltage/current to each subsystem
  - Evaluate controller performance based on system accuracy, speed, and energy use
  - Determine the limitations of the Simulink/DSP interface in terms of real-time execution and program memory
- Thermal Control
  - Understand DSP/cooling system hardware interface
  - Obtain a mathematical model of the cooling system
  - Design closed-loop controllers for temperature regulation of cooling system using observer-based system and energy management software for control of pump and fan
  - Provide temperature data to Engine DSP via CAN bus interface
- Engine Control
  - Understand DSP/motor hardware interface
  - Design software for PWM generation and velocity calculation from rotary encoder
  - Design closed-loop controllers for velocity control using observer-based system
  - Design observer-based system to acquire low noise current and velocity signal with minimal phase lag
  - Design energy management software to limit engine power output based on Thermal DSP data via CAN bus interface and motor power calculation based on observer outputs of velocity and current
  - Provide engine data to Thermal DSP via CAN bus

Functional Description

The engine control workstation consists of the following subcomponents:

- Engine model simulated by a motor-generator system
- Variable load for engine
- Cooling system consisting of a fan, radiator, cooling block, reservoir, pump, flow meter, and three temperature sensors
- Two eZdsp F2812 DSP boards
- PC software GUI (MATLAB/Simulink and Code Composer)

A closed-loop control system will be implemented for both the engine system and the thermal system. While the initial control systems will be developed using EE 431 ("classical") control methods, the final system will incorporate observers to improve the systems' responses.

The overall system functions as follows:

1. Using the PC GUI, the user sets the system inputs (engine RPM, etc.) for the engine.
2. The PC sends data to the DSP boards through Code Composer.
3. The engine control DSP board sets the engine RPM to the desired value using the implemented control algorithm and PWM signals.
4. The thermal control DSP board adjusts the temperature of the engine by changing the pump & fan motor speeds using the implemented control algorithm and PWM signals.
5. The engine control output information and the thermal control output information are sent back to the PC and are displayed in the GUI.

Inputs / Outputs	
Engine	
Inputs	**Outputs**
RPM	RPM
Power Limiter	Current
	Power dissipated
	Output power
	Observer RPM
	Observer current
Thermal	
Inputs	**Outputs**
Temperatures	Temperature of radiator inlet
	Temperature of radiator outlet
	Engine block temperature
	Power of each subsystem
	Observer temperatures

Table 3-1
System Inputs/Outputs

Functional Description, cont.

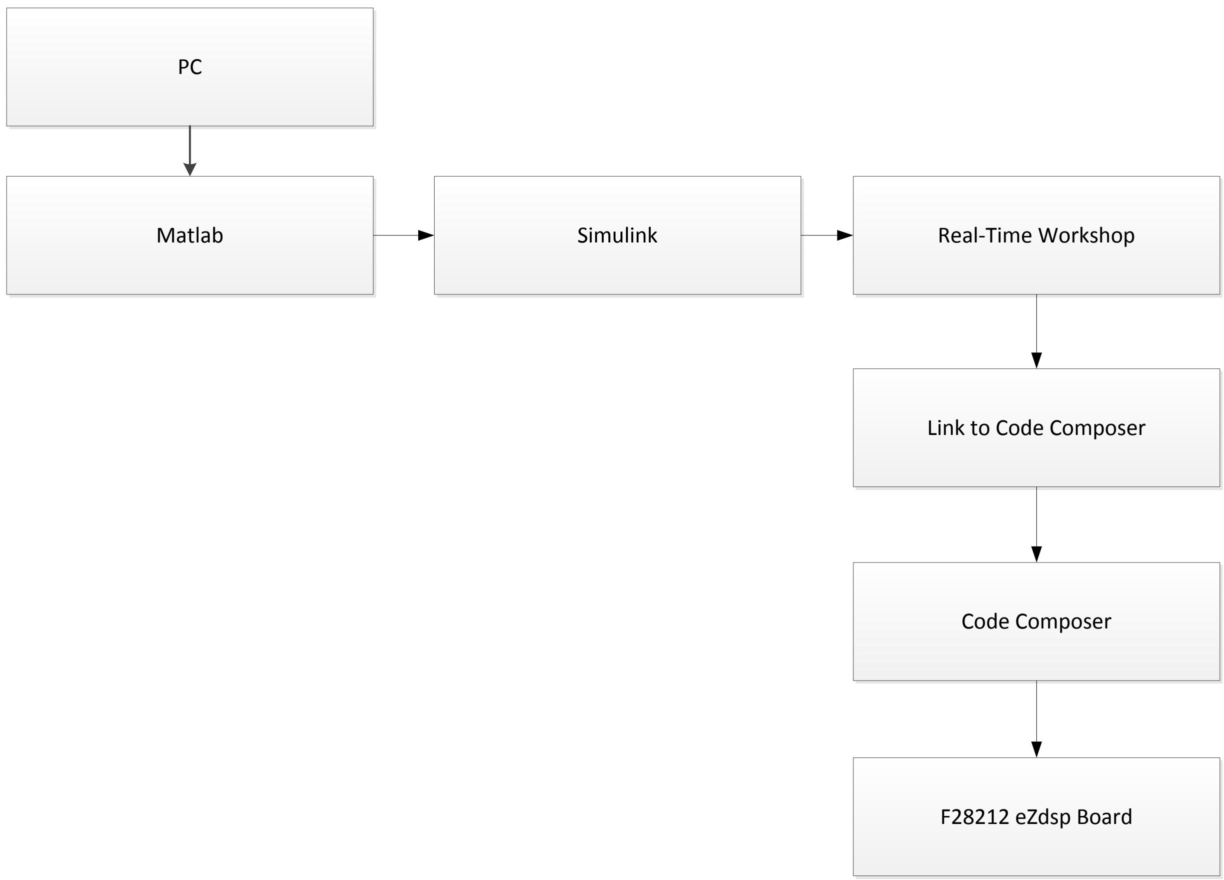


Fig. 4-1
General Software Flow Chart [2]

The eZdsp F2812 DSP board will be used in both the motor control subsystem and the cooling control subsystem. The design and implementation of these control systems is done through the PC. The software packages that will be used are MATLAB, Simulink and Realtime Workshop, and Code Composer 3.

- MATLAB is the main program associated with the project. It will be the host to other software, such as Simulink.
- Simulink is used to build the models of the subsystems.
- The Realtime Workshop is used to convert the Simulink model into C code using Code Composer.
- Link to Code Composer is used to link the Real-time Workshop to Code Composer

System Block Diagrams

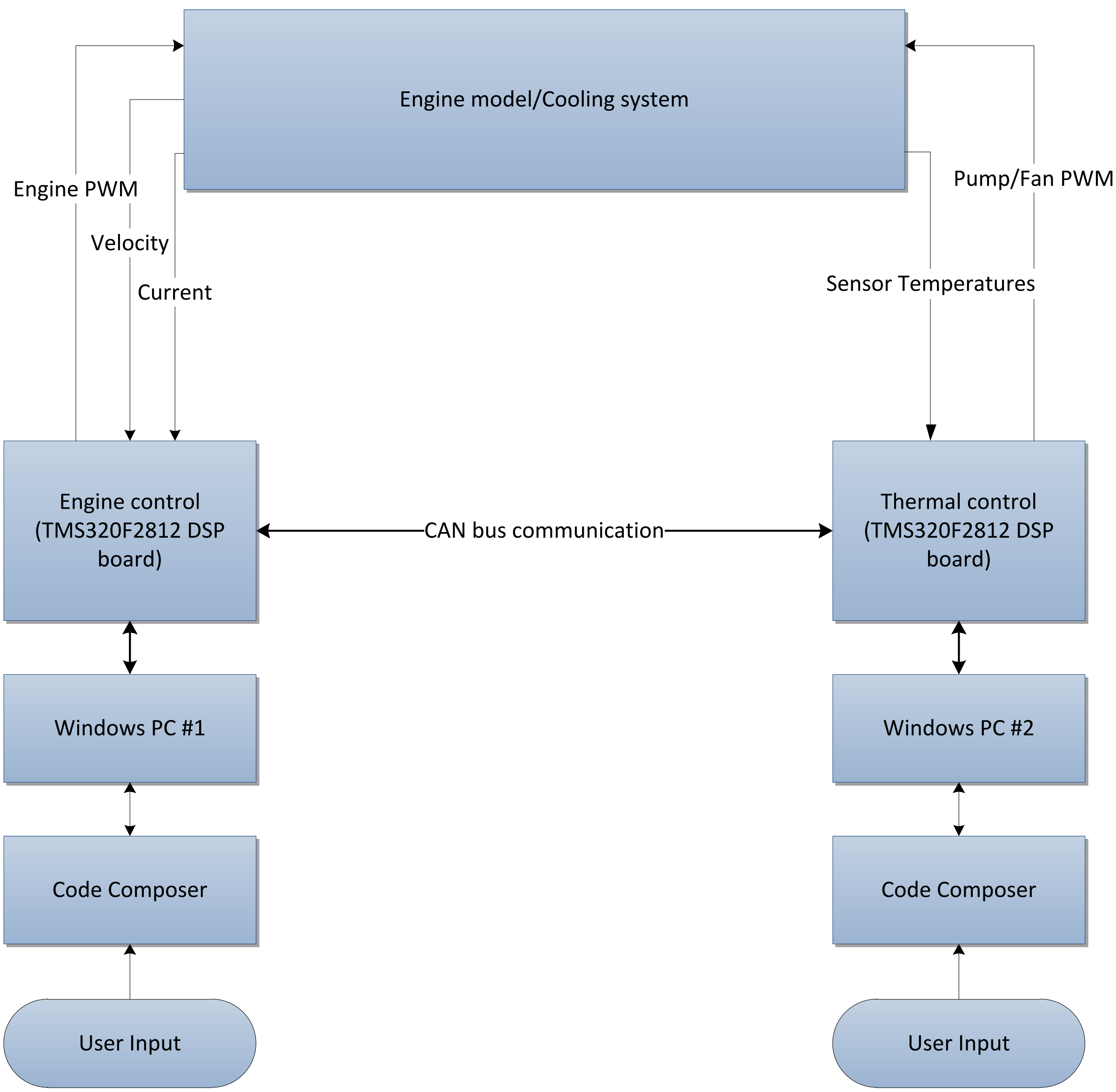


Fig. 5-1
Overall Block Diagram

The overall system consists of the plant (engine/cooling system), the engine & thermal controls (DSP boards), and two Windows PCs with Code Composer interfaces. The user's input will be sent to the DSP boards for processing. After the boards have executed the user's commands, the resulting output will be sent back to the Code Composer interface and displayed.

System Block Diagrams, cont.

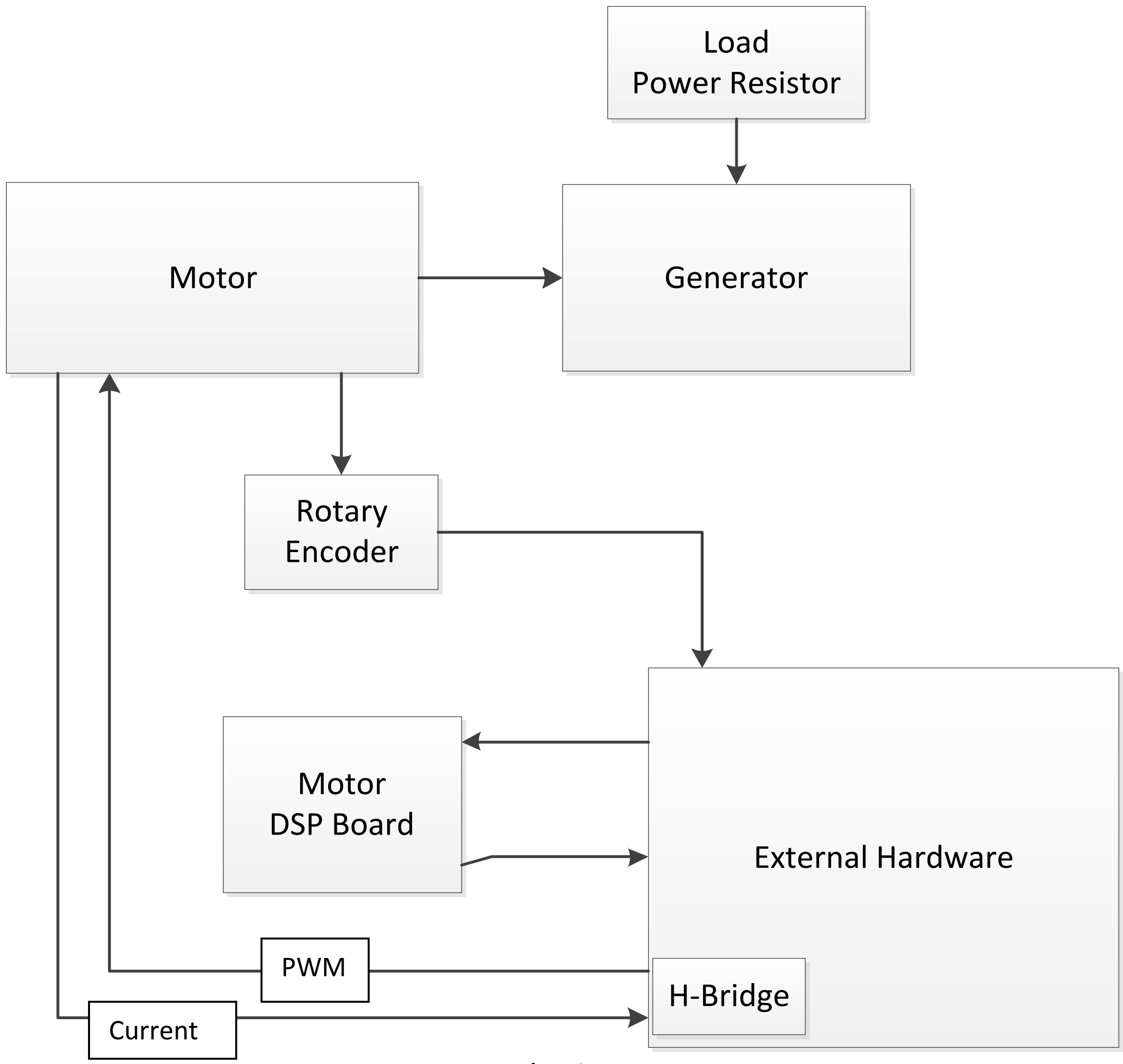


Fig. 6-1
Engine Block Diagram

The engine subsystem includes the motor, generator, load, rotary encoder, external hardware, and one DSP board. [1]

- The load is simulated using a power resistor. This will load the generator, which will load the motor. The system will be designed to accommodate varying loads.
- The rotary encoder is used to detect the speed of the motor, which will be used in the observer calculations
- The H-bridge provides a means to control the motor using a PWM signal from the DSP board.
- The DSP board allows computations to be done quickly. The observers will be done in software on the DSP board.

System Block Diagrams, cont.

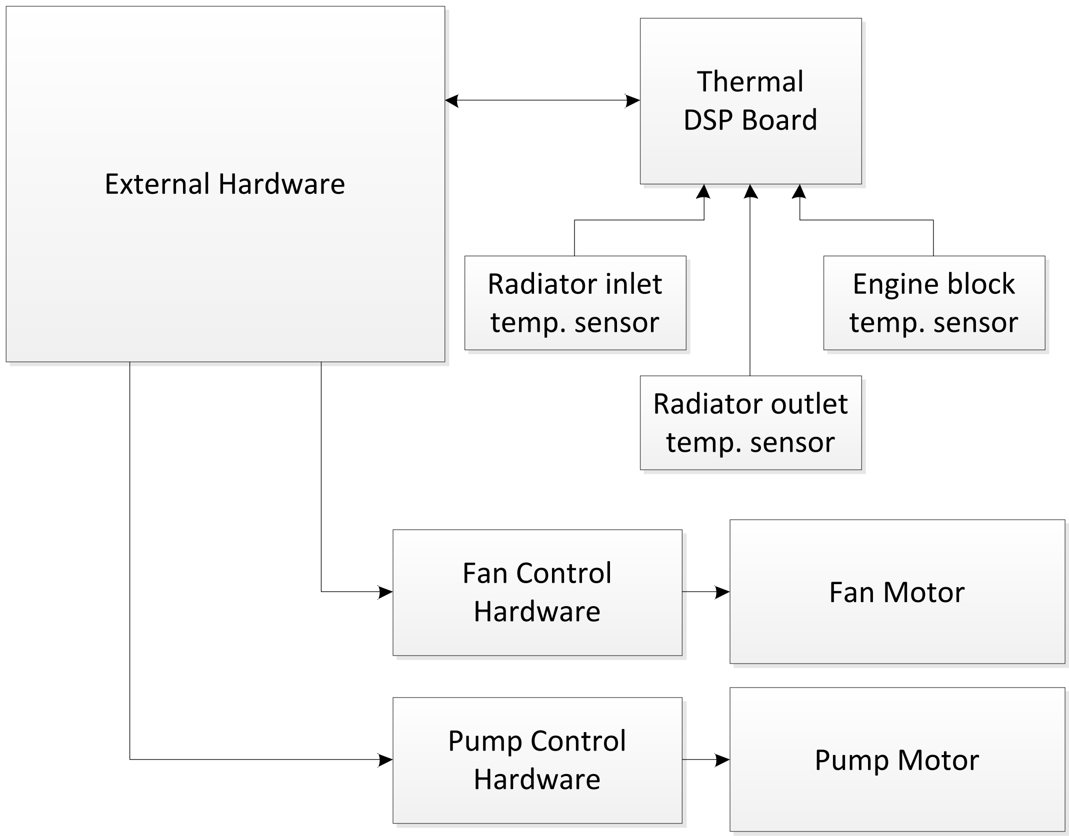


Fig. 7-1
Thermal Control Block Diagram

The thermal subsystem includes the fan & pump motors, hardware for controlling each motor, three temperature sensors, and one DSP board. [2]

- The temperature sensors each contain one thermistor for measuring the temperature. The thermistor's resistance varies with temperature, causing the voltage output of each sensor to change.
- The DSP board converts the voltage levels from the temperature sensors into digital values and calculates the required fan/pump motor speeds required to cool the system.
- The DSP board outputs a PWM signal (through the external hardware) to the fan/pump motors and adjusts their speed.
- The DSP board allows computations to be done quickly. The observers will be done in software on the DSP board.

Circuit Schematics

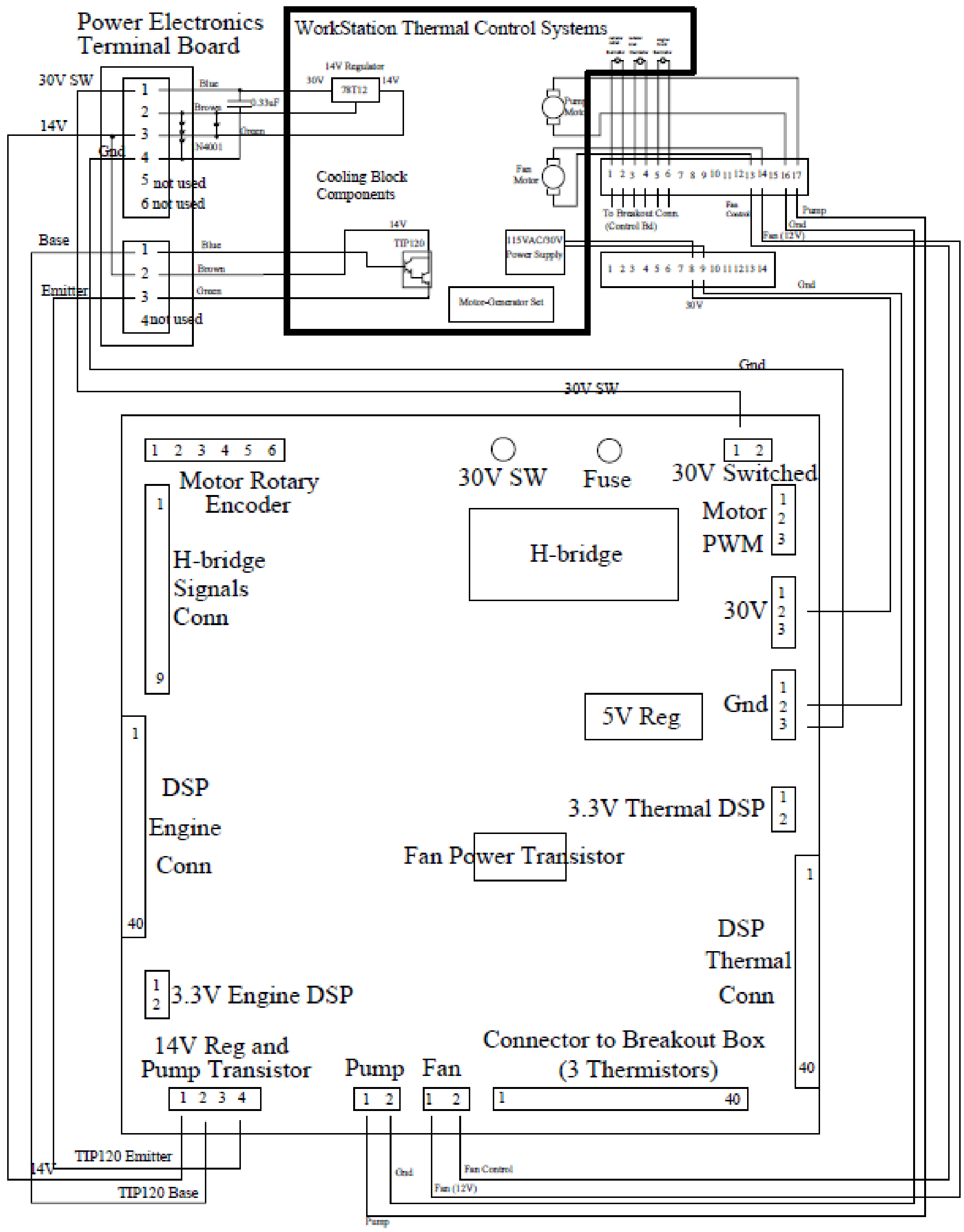


Fig. 8-1
High Level Schematic of Power Electronics [2]

The circuitry of figure 8-1 is of the power electronics for both the engine and thermal subsystems. The main components of the engine subsystem are integrated into the left half of the board. The thermal control components are integrated into the right half of the board. Each subsystem has been isolated from the other and, therefore, each subsystem also has its own ground.

Circuit Schematics, cont.

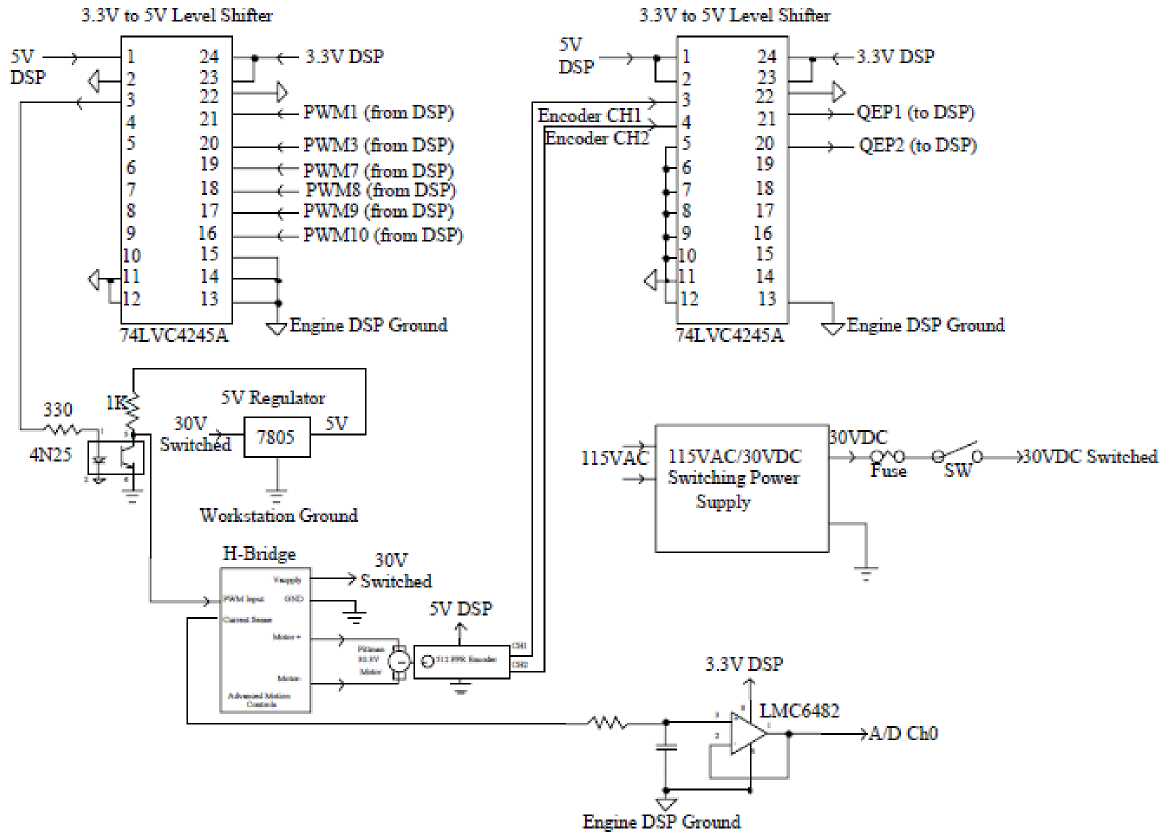


Fig. 9-1
Engine Control Circuitry [2]

The circuit schematic for the engine control subsystem is shown in figure 9-1. The components include the motor, a DSP board, a 3.3V to 5V level shifter, an H-bridge, and A/D conditioning circuitry. This circuitry has already been implemented in a previous senior project.

Circuit Schematics, cont.

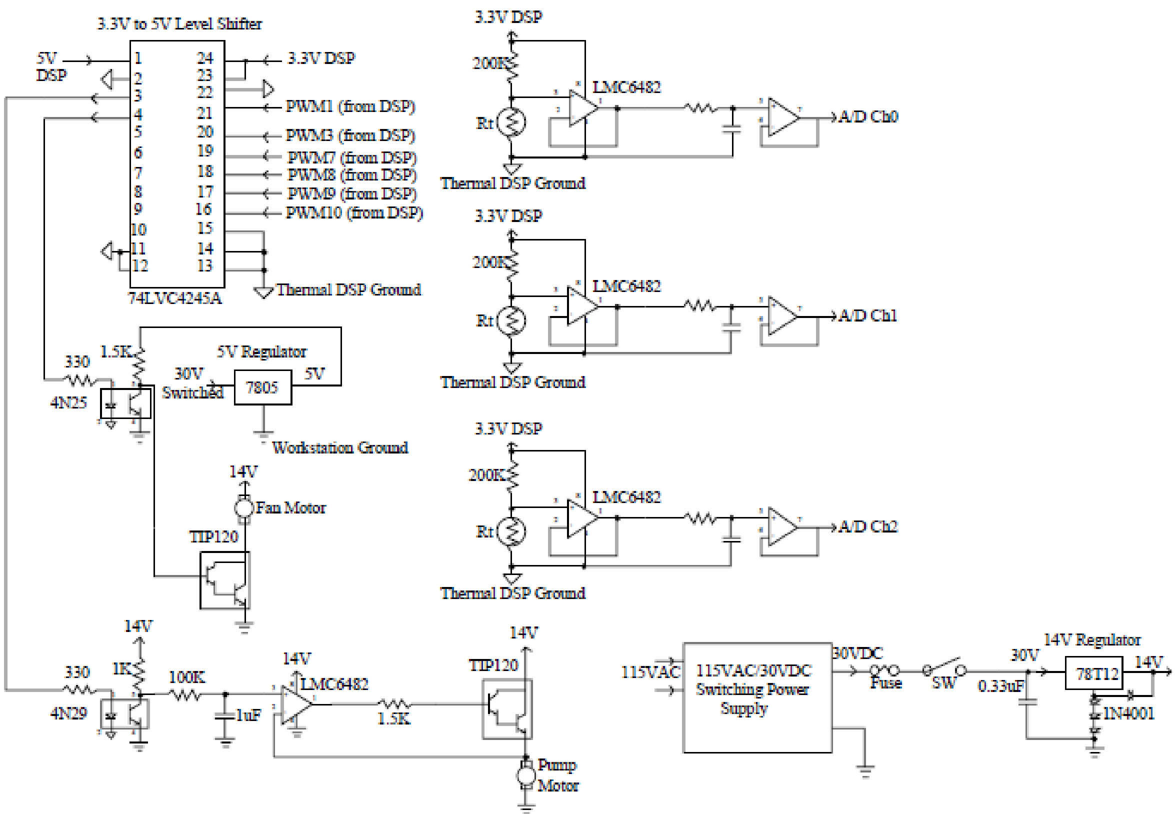


Fig. 10-1
Thermal Control Circuitry [2]

Figure 10-1 shows the circuit components for the thermal control subsystem. The components include a 3.3V to 5V level shifter, transistors, and A/D conditioning circuitry. This circuitry has been implemented in a previous senior project.

Functional Requirements & Performance Specifications

Engine control system

The engine control system will go through multiple designs. A basic proportional controller will be implemented first, followed by PI & PID controllers. The final controller will be observer-based.

The final engine control system shall meet the following specifications using a step input:

- Steady-state error = ± 5 RPM
- Percent overshoot ≤ 10%
- Rise time ≤ 30 ms
- Settling time ≤ 100 ms
- Phase margin = 45°

The data for these specifications will be collected for each method of control. This data will then be compared to make conclusions on the advantages and disadvantages for each control method. Each method will then be implemented in the engine control system. Both theoretical and experimental data will be collected. The control method command input range will vary based on the method used.

Thermal control system

The thermal control system will go through several design iterations. A basic proportional controller will be implemented first, followed by PI & PID controllers. The final controller will be observer-based.

The final thermal system shall meet the following specifications using a step input:

- Steady-state error = ±2° Celsius
- Percent overshoot ≤ 25%
- Rise time ≤ 2 seconds
- Settling time ≤ 10 seconds
- Phase margin = 45°

During system operation, the thermal control system shall ensure that the engine temperature remains below 40° C (104° F). The power consumed by the thermal control system shall remain at a minimum level. Each controller method listed above will be tested against the defined requirements. The method that best meets these requirements will be used in the final thermal control system.

Preliminary Results

Engine control system

Preliminary simulations were done in MATLAB to develop and analyze the engine subsystem. A general model of the engine control subsystem was developed to get a sense of how the system works. The model is shown in figure 12-1.

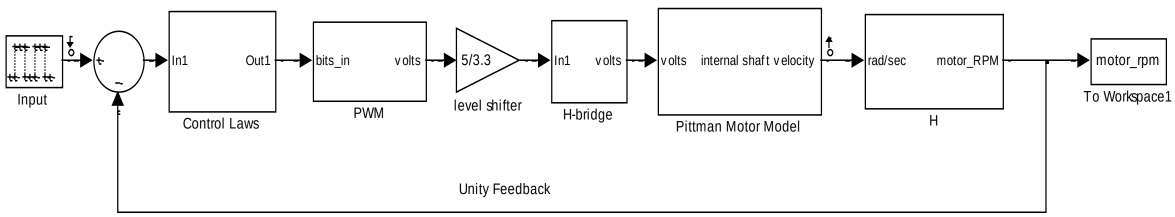


Fig. 12-1
Engine Control System

The first component of the model was based on work done in the senior mini-project. The model of the Pittman motor had already been developed. This model is shown in figure 12-2.

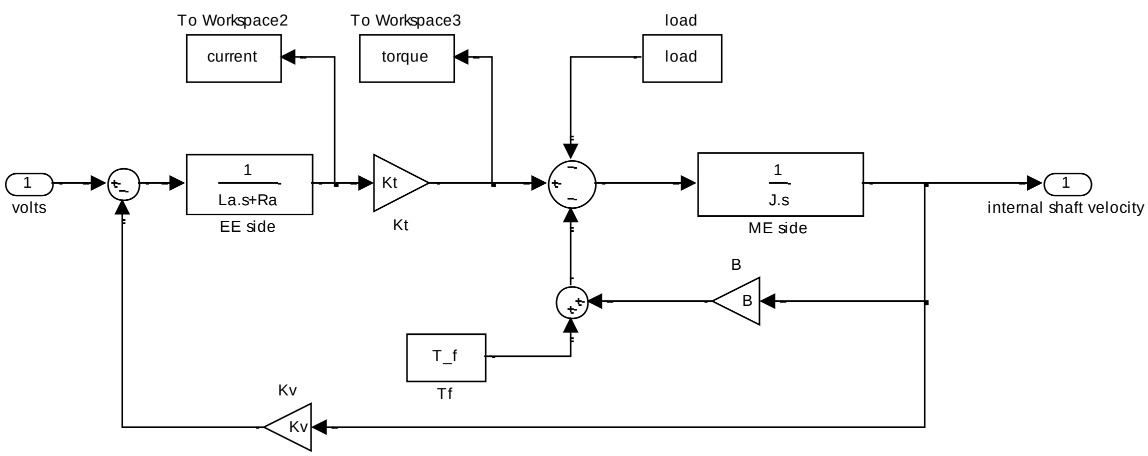


Fig. 12-2
Pittman Motor Subsystem

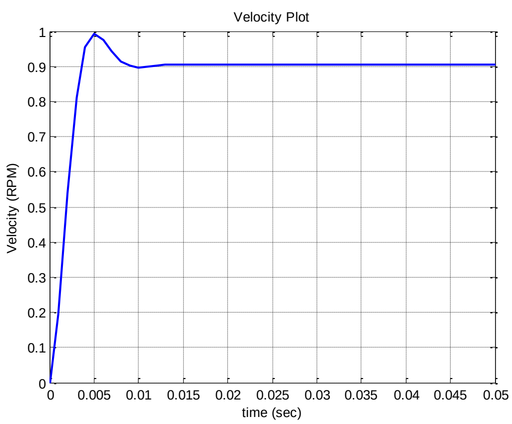
The closed-loop poles of the subsystem shown in figure 12-2 become the open loop poles of the engine control loop. After plugging in values and manipulating the equations, the formula for the plant becomes equation 13-1:

$$Gp = \frac{17}{(\frac{s}{66.6} + 1)(\frac{s}{856} + 1)}$$

EQ 13-1
Plant closed-loop transfer function

The next step was to create a model of the system using the control toolbox in MATLAB. This was accomplished by creating the closed-loop transfer function of the motor, incorporating the gains, and creating the final closed-loop system using the *feedback* command. It was then possible to verify that this model matched the model in Figure 12-1 by incorporating a simple proportional controller. This model will be used for future calculations. Figure 13-2 and Table 13-3 demonstrates that the two models do, indeed, match.

Simulink Plot



Control System Toolbox Plot

Fig. 13-2
Model response comparisons

RiseTime: 0.0026	RiseTime: 0.0026
SettlingTime: 0.0077	SettlingTime: 0.0077
SettlingMin: 0.8966	SettlingMin: 0.8966
SettlingMax: 0.9941	SettlingMax: 0.9941
Overshoot: 9.8049	Overshoot: 9.8049
Undershoot: 0	Undershoot: 0
Peak: 0.9941	Peak: 0.9941
PeakTime: 0.0050	PeakTime: 0.0050
Steady-State: 0.90529	Steady-State: 0.90529

Table 13-3
Model Parameter Comparison

A simple PWM signal was then tested on the engine cooling workstation to determine the time delay of the system. It was determined that the Code Composer graph could not sample at a fast enough rate to capture the percent overshoot or the time delay, so the time delay is assumed to be the 1ms delay programmed into the software.

After determining the time delay of the system, the *pade* command was used in the control toolbox model to simulate time delay to get a more accurate representation of the system. Frequency domain analysis was determined to be the more suitable option in calculation the proportional gain term Kp.

<u>Thermal control system</u>

The first step in the project was to set up the proper conversion for the system temperatures. A linear equation for the thermistor resistance versus temperature was created in order to implement the calculations for the temperature sensors in the control system. The linearization of the thermistor versus temperature can be seen in Fig. 14-1:

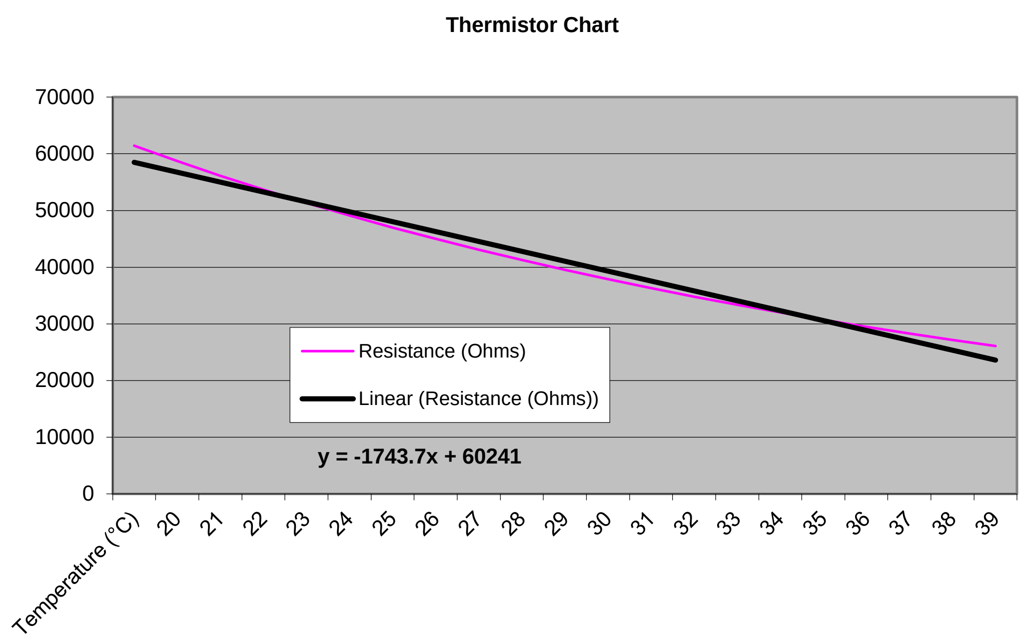


Fig. 14-1
Thermistor Linearization Graph

Next, a simple proportional and proportional-integral controller was created to confirm the basic operation of the system. With some tuning, the Kp and Ki were determined to be about 50 and about 0.0001, respectively. One of the problems encountered early on was integrator windup. While a limit block was used to handle the problem for now, a better solution may be needed in the future. The PI controller can be seen in Fig. 15-1:

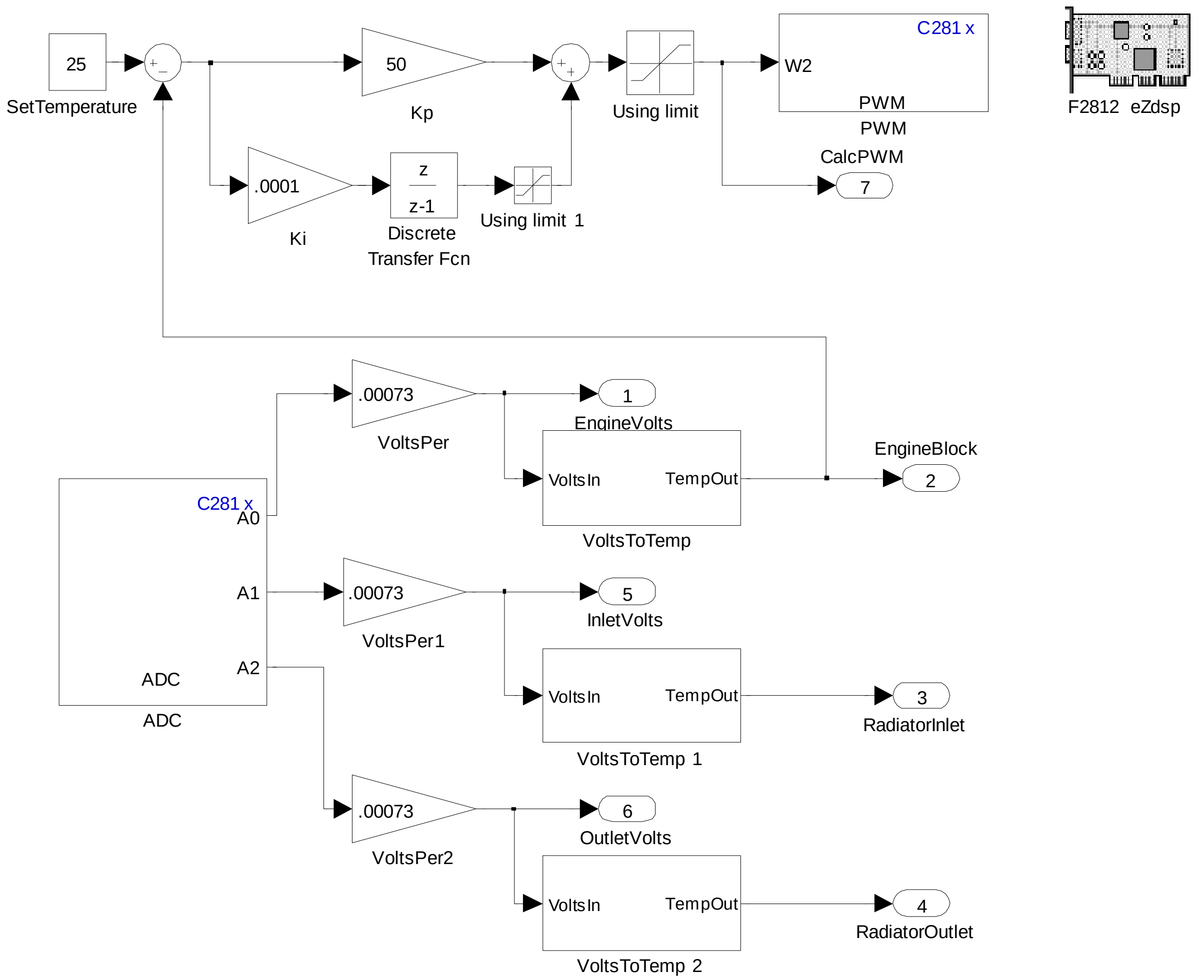


Fig. 15-1
Initial Pump PI Controller

A large majority of the remaining lab time has been spent on system identification, specifically for the pump system. This information is useful for designing the controller due to the extremely slow speed of the system and the difficulty performing standard controller tuning. By using a small amplification circuit, the temperature change from stepping the pump from 50% PWM to 90% PWM could be measured. Using this information, all of the parameters of the pump system were calculated and a Simulink model for use in simulation was created. A sample graph of the system step output can be seen in Fig. 16-1, the system parameters can be seen in Table 16-2, and the system model can be seen in Fig. 17-1:

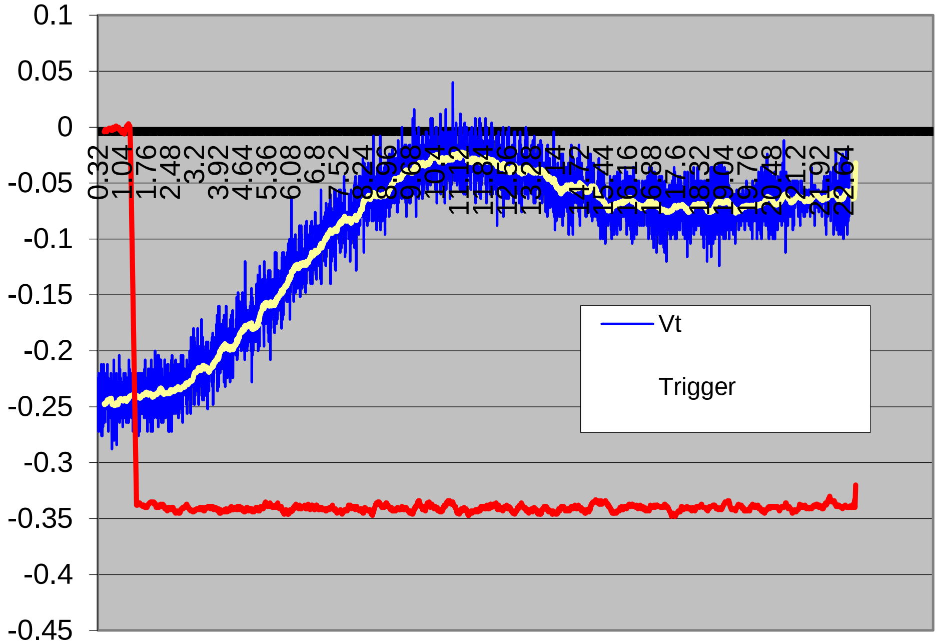


Fig. 16-1
Sample of Pump PWM Step graph

Settings	
Rpot	44890
Fan PWM	100%
Value #1 PWM	50%
Value #2 PWM	90%

Gain											
Test	Before Step	After Step	Difference		Rt #1	Rt #2	Difference		Temp #1	Temp #2	Difference
#1	-0.244	-0.072	0.172		44454	44760.903	306.90143		29.05374	28.87773	0.17600585
#2	0.536	0.676	0.14		45862.87	46120.461	257.59066		28.24576	28.09803	0.147726468
#3	0.744	0.848	0.104		46246.11	46438.939	192.83356		28.02598	27.91539	0.110588714

Measurements									
Test	(time offset)	(step offset)	Td	Ts	tp	Peak value	Final value	%OS	ζ (damping ratio)
#1	1.1	-0.244	1.64	13.34	8.35	0.22	0.172	27.9%	0.376
#2	0.52	0.512	1.71	13.41	8.06	0.204	0.164	24.4%	0.41
#3	1.12	0.748	2	12.49	7.81	0.132	0.1	32.0%	0.341

Table 16-2
Pump System Parameters & Measurements

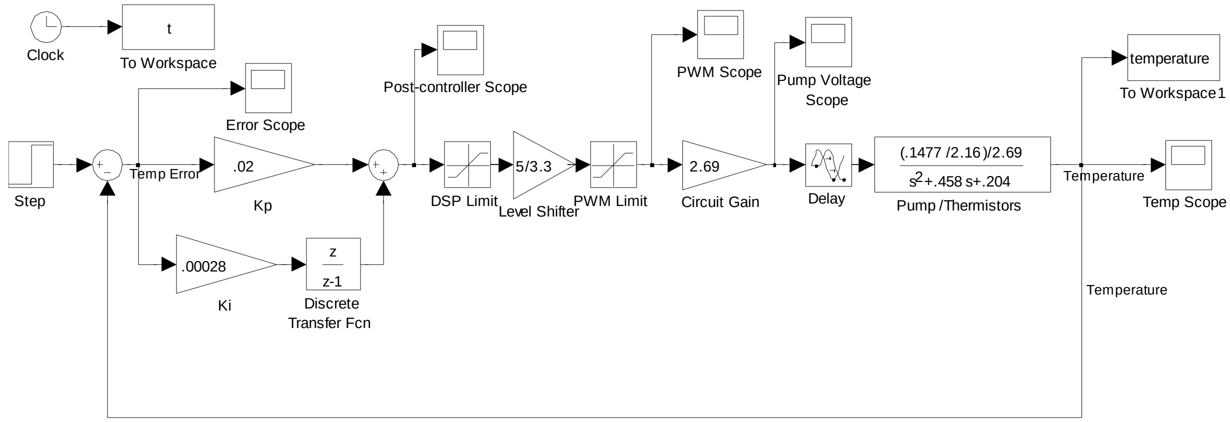


Fig. 17-1
Pump System Simulink Model

The last portion of the project worked on thus far was implementing and tuning the PI controller based on the pump system model. The new Kp value was found to be 0.02, and the new Ki was found to be 0.00028. When these values are implemented in the physical system, however, the windup from the integrator caused issues again. An anti-windup system was implemented as seen in Fig. 17-2. This system effectively removed the integral windup, and the system is currently very responsive.

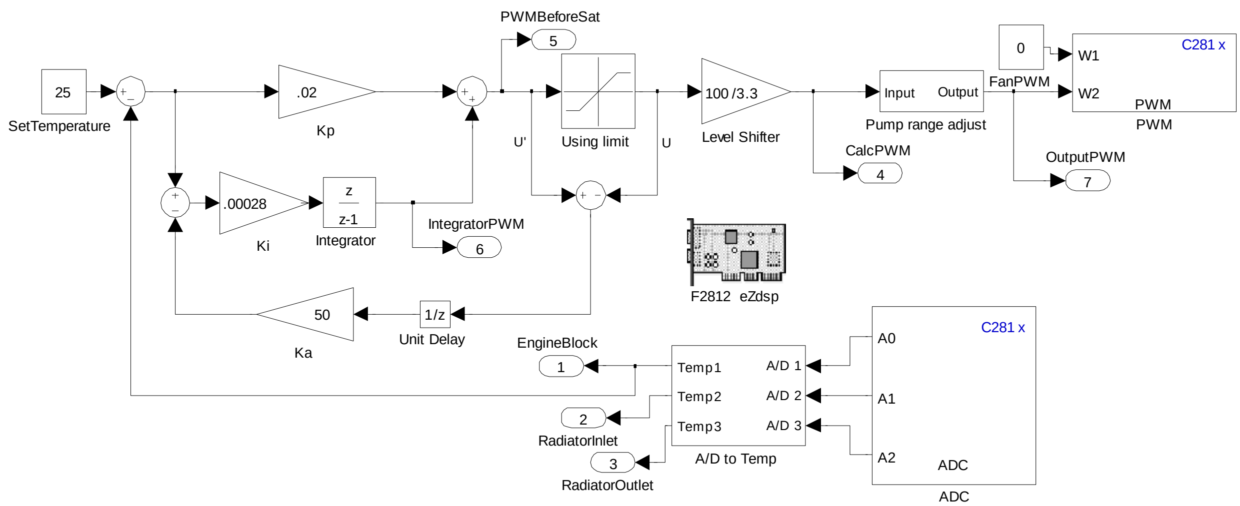


Fig. 17-2
Revised Pump PI Controller with Anti-Windup

Future Work

Engine control system

The design Kp value was successfully implemented on the engine cooling workstation. A PI control method will be implemented next. The design process will be similar to that of the proportional control. Observers will not be implemented until the other control methods are successfully implemented. Once the observer-based method is successfully implemented, all of the control methods will be compared and analyzed.

The motor current reading will be integrated into the software model after the other steps have been completed. The engine control algorithm will then be designed to change velocity based on the engine current. If all of the previous steps have been completed successfully, the algorithm will be adjusted to communicate with the thermal cooling subsystem.

Thermal control system

Once the PI controller for the pump system has been tuned properly, a control system for the radiator fan will be required next. This will follow a similar identification process as the pump; however, different methods of identifying parameters may be needed due to differences in the two systems. Once PI controllers have been implemented for both systems, work will begin on observers. After the observer-based method is successfully implemented, all of the control methods will be compared and analyzed.

The thermal control algorithm will be designed to change pump and fan velocity based on the motor and system temperature. If all of the previous steps have been completed successfully, the algorithm will be adjusted to communicate with the engine control subsystem.

Future Work – Schedule

The schedule for the remaining time allotted for the project is shown below in Table 18-1:

Week	Thermal Control System	Engine Control System
1	P/PI Control	PI Control
2	P/PI Control	Feed-Forward Control
3	Alt. Advanced Control	Feed-Forward Control
4	Observer-based Control	Observer-based Control
5	Observer-based Control	Observer-based Control
6	Observer-based Control	Observer-based Control
7	Energy management & power calculations	Engine governor & power dissipation calculations
8	Energy management & power calculations	Engine governor & power dissipation calculations
9	CAN Bus	CAN Bus
10	CAN Bus	CAN Bus
11	Performance Evaluations	Performance Evaluations
12	Performance Evaluations	Performance Evaluations
13	Final Report & Presentation	Final Report & Presentation
14	Final Report & Presentation	Final Report & Presentation

Table 19-1
Project Schedule

Equipment List

The equipment used and costs for the project are listed below in Table 19-1. However, all of the equipment has already been purchased from previous projects. The only additional cost for this year's work on the Engine Cooling System is the cost of two copies of Observers in Control Systems by George Ellis ($118 each).

Parts Description	**Cost**
Fan	$11
Radiator	$29
Cooling Block	$55
Reservoir and Pump	$117
Flow meter	$20
Coolant	$15
Code Cathode	$11
Temp Sensors (4)	$40
Pittman Motors (2)	$160
Motor Heat Sinks	$20
Tubing, hose clamps	$10
30Volt, 315 Watt Switching Power Supply	$75
Advanced Motion Controls H-Bridge (6A) (donated)	$350
Control and Interfacing Circuitry	$30
eZdsp F2812 Texas Instruments DSP Boards (2)	$975
Sub-total	$1,918
Heat Sink Machine Shop Work 10 hours x $75/hr	$750
Cooling Station Construction 40 hours x $75/hr	$3,000
Software Installation 10 hours x $75/hr	$750
Sub-total	$4,500
Total	$6,418

Table 20-1
Engine Cooling System Equipment & Costs

References

[1] George Ellis. “Observers in Control Systems”, Academic Press, 2002.
[2] Gary Dempsey. “Engine Control Workstation System Overview”, Electrical and Computer Engineering Department, Bradley University, September 2010
[3] Gary Dempsey. “Observer-based Engine/Cooling Control System”, Electrical and Computer Engineering Department, Bradley University, August 2010