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FUZZY LOGIC CONTROL DESIGN FOR ADVANCED VEHICLE THERMAL MANAGEMENT SYSTEMS

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ABSTRACT
The coolant temperature of internal combustion engines can be regulated effectively by advanced thermal management systems that feature multiple computer controlled servomotor actuators (*i.e.*, a variable position smart valve, variable speed electric water pump, variable speed electric radiator fan). When the components of the advanced thermal management system function harmoniously, desired thermal conditions can be achieved in a power efficient manner. Hence, fuel consumption and emissions are reduced. In this paper, a fuzzy logic control architecture is proposed for transient temperature tracking. A representative numerical simulation is introduced to demonstrate the functionality of the thermal management system in accurately tracking a prescribed temperature profile.

KEY WORDS
fuzzy control, engine temperature control, thermal management.

1. Introduction

Automotive thermal management systems can improve the coolant temperature regulation during transient and steady-state operation. Using computer controlled servomotor actuators in the cooling system can efficiently reduce the fuel consumption, parasitic losses, and tailpipe emissions [1] despite of the satisfactory performance that the conventional automotive cooling system can achieve. The advanced automotive cooling systems features a variable position smart valve instead of a conventional wax thermostat valve and replace the mechanical water pump and radiator fan with electric and/or hydraulic driven actuators [6]. In this way, the water pump and radiator fan are decoupled from the engine crankshaft. Hence, over/under cooling problem, due to the mechanical coupling, is solved and parasitic losses are reduced at high rotational speeds [3].

A controllable electric water pump in a class-3 medium duty diesel engine truck was investigate by Cho *et al.* [5] and the experimental results showed that the radiator size can be reduced by replacing the mechanical pump with an electrical one. Chalgren and Allen [2] and Chalgren and Traczyk [4] improved the temperature control with less parasitic losses, by replacing the conventional cooling system with an electric cooling system for a light duty diesel truck.

In order to study and analyze an automotive thermal management system efficiently, a model for the vehicle's cooling system has to be created. Wagner *et al.* [14-16] presented a lumped parameter and multi-node thermal models that was utilized to estimate the temperature of internal engine. On the other hand, Eberth *et al.* [7] proposed a mathematical model to predict the dynamics of a 4.6L spark ignition engine with a developed analytical/empirical descriptions to describe the smart cooling system components. A simulation model of powertrain cooling systems for ground vehicles was presented by Henry *et al.* [8] that was validated against test results.

Setlur *et al.* [13] proposed nonlinear control algorithms to regulate the temperature of an emulated-engine utilizing a suite of mathematical models for controllable electromechanical actuators. In their experiments, the thermal system actuators (*i.e.*, water pump and radiator fan) were set to run at constant speeds, while the smart thermostat valve was controlled to track coolant temperature set points. Page *et al.* [10] pursued a set of experimental testing on a medium-sized tactical vehicle to investigate improving the engine's peak fuel consumption and thermal operating conditions. Finally, Redfield *et al.* [11] studied potential energy saving and demonstrated engine cooling performance utilizing a class 8 tractor at highway speeds.

In this paper, a fuzzy logic control (FLC) strategy is presented to actively regulate the coolant temperature in internal combustion engines by controlling the system actuators. The proposed advanced thermal management system featured a three-way servo-driven thermostat valve, variable speed electric water pump and fan, radiator, and internal combustion engine. The proposed FLC, selected to accommodate unknown disturbances and uncertainties in the thermal system, has been verified by numerical simulation. The performance of the FLC was compared with a backstepping nonlinear controller [12] where the proposed FLC demonstrated a better performance when tracking a prescribed time-varying temperature profile.

2. Cooling System Dynamics

A reduced order two-node lumped parameter thermal model (refer to Figure 1) is utilized to describe the cooling system's transient response and to minimize the computational burden for in-vehicle implementation. The

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proposed advanced cooling system features a smart valve, variable speed pump, variable speed fan, engine block, radiator, and sensors (temperature, mass flow rate, and power). The engine block and radiator behavior can be described by [12]

$$C_e \dot{T}_e = Q_{in} - C_{pc} \dot{m}_r \left(T_e - T_r\right) \qquad (1)$$

$$C_r \dot{T}_r = -Q_o + C_{pc} \dot{m}_r \left(T_e - T_r\right) - \varepsilon C_{pa} \dot{m}_f \left(T_e - T_\infty\right). \qquad (2)$$

where $C_e, C_r, C_{pc}, C_{pa} \in \mathbb{R}^+$ are the engine block capacity, radiator capacity, coolant specific heat, and air specific heat, respectively, $T_e(t), T_r(t), T_\infty(t) \in \mathbb{R}^+$ represent the coolant temperature at the engine outlet, radiator outlet coolant temperature, and surrounding ambient temperature, respectively, and $\dot{m}_r(t), \dot{m}_f(t) \in \mathbb{R}^+$ denotes the radiator coolant and fan air mass flow rates, respectively. The variable $Q_{in}(t) \in \mathbb{R}$ represents the input heat generated by the combustion process which is transferred to the coolant through the block's water jacket and the variable $Q_o(t) \in \mathbb{R}$ denotes the radiator heat loss due to uncontrollable air flow. Finally, $\varepsilon \in \mathbb{R}^+$ denotes the radiator efficiency.

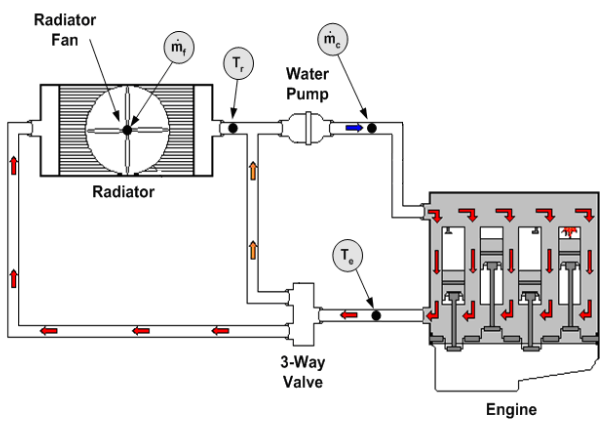

Figure 1. Advanced cooling system with electrical-actuated components.

The radiator coolant mass flow rate, $\dot{m}_r(t)$, is based on the pump flow rate and normalized valve position as $\dot{m}_r = H\dot{m}_c$ where the variable $H(t) \in \mathbb{R}^+$ satisfies the condition $0 \le H \le 1$. Note that $H = 1(0)$ corresponds to a fully closed (open) valve position and coolant flow through the radiator (bypass) loop. To facilitate the boundedness of signal argument, it is assumed that the surrounding ambient temperature $T_\infty(t)$ is uniform and satisfies $T_e(t) - T_\infty(t) \ge \varepsilon_1, \forall t \ge 0$ where $\varepsilon_1 \in \Re^+$ is a constant. In addition, the engine block and radiator temperatures are assumed to satisfy the condition $T_e(t) - T_r(t) \ge \varepsilon_2, \forall t \ge 0$ where $\varepsilon_2 \in \Re^+$ is a constant. Further, $T_e(0) \ge T_r(0)$ to allow the engine and radiator to initially be the same temperature (*e.g.*, cold start). The unlikely case of $T_e(0) < T_r(0)$ is not considered.

3. Fuzzy Logic Control Design

The proposed control objective is to ensure that the actual temperature of the engine, $T_e(t)$, tracks a desired trajectory, $T_{ed}(t) \in \mathbb{R}^+$, while compensating for system uncertainties (*i.e.*, combustion process input heat, $Q_{in}(t)$, and radiator heat loss, $Q_o(t)$) by harmoniously controlling the system actuators (refer to Figure 1). It is important to point out that in equations (1) and (2), the signals $T_e(t)$, $T_r(t)$, and $T_\infty(t)$ are measurable and the system parameters C_{pc}, C_{pa}, C_e, C_r, and ε are assumed to be constant and fully known. In addition, the FLC is designed to operate effectively the thermal system components where the radiator coolant and air mass flow rates, $\dot{m}_r(t)$ and $\dot{m}_f(t)$, respectively, are assumed to be obtained precisely by a controlled drive unit based on the FLC algorithm.

In general, the fuzzy logic is a soft computing technique which imitates the ability of the human mind to learn and make rational decisions [9]. The FLC has many advantages such as simplicity in implementation and non model-based approach. FLC is also more effective in the cases of nonlinear and time-varying systems compared with other control methods. In addition, the application of FLC on thermal management system has not been investigated in the literature.

In this section, the FLC strategy is described briefly. The design of the proposed FLC is based on expert knowledge about the system to be controlled. Basically, it converts the linguistics information into control strategy. Figure 2 shows the steps-flow of a general fuzzy controller that can be described as follows [9]:

1. *Fuzzification:* each piece of the input data is converted to degrees of one or more of the corresponding membership functions.
2. *Rule base*: as mentioned in the previous paragraph, the FLC contains linguistics information in the form of if-then rules based on Mamdani approach (Figure 3).
3. *Inference engine*: The operators within the latter mentioned rules form the inference engine; the engine looks up the membership values for each rule based on its conditions.
4. *Defuzzification*: the inference results of all rules is then combined into a crisp numerical output in order to be sent to the system as a control signal; center average defuzzifier method is used in this paper for defuzzifiction.

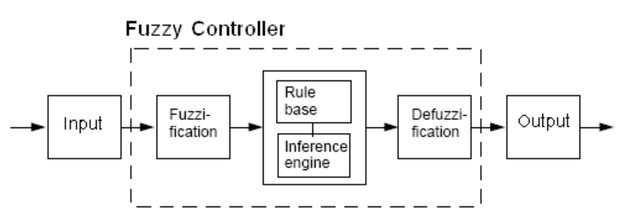

Figure 2. Structure of fuzzy logic control

The input variable to the fuzzy controller is the error signal which is the difference between the desired engine temperature, $T_{ed}(t)$, and actual engine temperature, $T_e(t)$, as shown in Figure 3. The figure shows that the system has two output variables, namely, radiator coolant mass flow rate, $\dot{m}_r(t)$, and fan air mass flow rate, $\dot{m}_f(t)$. The error membership function is plotted in Figure 4 where seven input possibilities of the error are shown. The membership functions of $\dot{m}_r(t)$ and $\dot{m}_f(t)$ are shown in Figures 5 and 6, respectively. Note that based on the selected servo components [12], the radiator coolant mass flow rate range of operation is [0.4, 2] kg/sec and for the fan air mass flow rate is [0, 1.2] kg/sec.

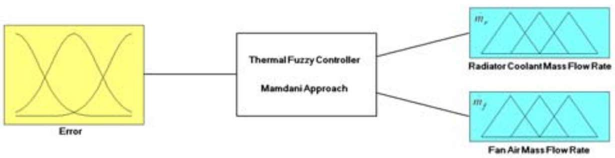

Figure 3. Input/outputs of fuzzy logic control

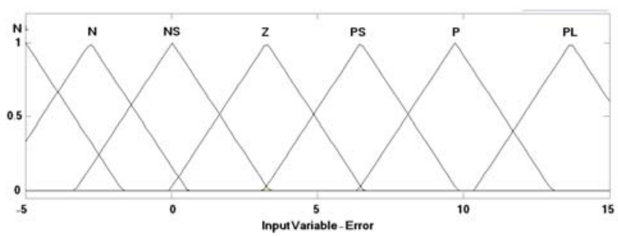

Figure 4. Engine temperature tracking error membership functions

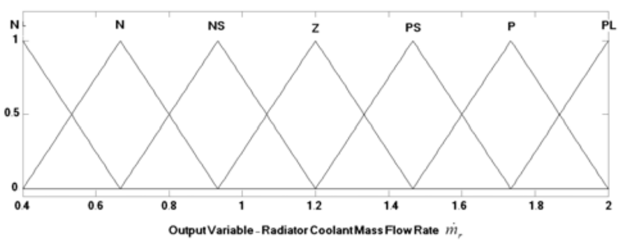

Figure 5. Radiator coolant mass flow rate membership functions

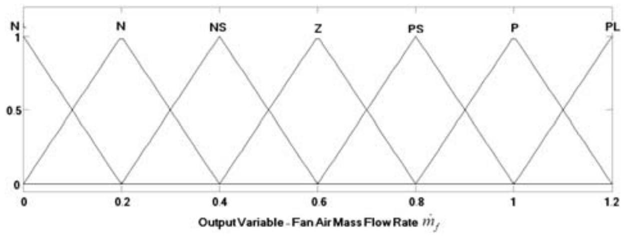

Figure 6. Fan air mass flow rate membership functions

From practical point of view, the fuzzy controller should drive the water pump and radiator fan faster when a bigger temperature error exists, and fill the temperature gap as quick as possible. Therefore, the fuzzy logic rules are designed as follows:

1. If the error is negative large (NL) then $\dot{m}_r(t)$ is positive large (PL) and $\dot{m}_f(t)$ is positive large (PL).
2. If the error is negative (N) then $\dot{m}_r(t)$ is positive large (PL) and $\dot{m}_f(t)$ is positive large (PL).
3. If the error is negative small (NS) then $\dot{m}_r(t)$ is positive large (PL) and $\dot{m}_f(t)$ is positive large (PL).
4. If the error is zero (Z) then $\dot{m}_r(t)$ is negative (N) and $\dot{m}_f(t)$ is negative large (NL).
5. If the error is positive small (PS) then $\dot{m}_r(t)$ is negative large (NL) and $\dot{m}_f(t)$ is negative (N).
6. If the error is positive (P) then $\dot{m}_r(t)$ is negative large (NL) and $\dot{m}_f(t)$ is negative (N).
7. If the error is positive large (PL) then $\dot{m}_r(t)$ is negative large (NL) and $\dot{m}_f(t)$ is negative large (NL).

4. Numerical Simulation

In this section, a numerical simulation is presented to evaluate the FLC design and compare its performance with the backstepping nonlinear control design presented in [12]. Two cases are presented to demonstrate the effectiveness of the fuzzy control technique. Case I introduced a constant external ram air disturbance (Q_o = 5kW) to emulate a vehicle traveling at 20km/h with a constant input heat of $Q_{in} = 50$kW (heavy thermal load). In Case II, a time-varying external ram air disturbance ($Q_o = 2\sin(0.5t) + 5$ kW) was introduced with a time-varying input heat of $Q_{in} = 5\sin(0.5t) + 50$ kW in order to more challenge the proposed fuzzy logic controller. The thermal model parameters used in the simulation are C_e = 17.14kJ/ºK, C_r = 8.36kJ/ºK, C_{pc} = 4.18kJ/kg.ºK, C_{pa} = 1kJ/kg.ºK, ε = 0.6, and $T_\infty(t)$ = 293ºK [12]. The initial simulation conditions were $T_e(0)$ = 350ºK and $T_r(0)$ = 340ºK. The desired engine temperature varied as $T_{ed} = 363 + \sin(0.05t)$ ºK. This time varying set-point allows the controller's tracking performance to be studied. To simulate a real thermal management system, a band-limited white noise was added to the system temperature measurements with a noise power equal to 0.0001. To investigate the water pump's ability to regulate the engine temperature a fixed smart valve position of $H = 1$ (*e.g.*, fully closed for 100% radiator flow) has been applied.

In Figures 7, 8, and 9, the response of engine temperature, coolant mass flow rate through the water pump, and air mass flow rate through the radiator fan are introduced, respectively, for Case I while Figures 10, 11, and 12 demonstrate the response of engine temperature, coolant mass flow rate through the water pump, and air mass flow rate through the radiator fan, respectively, for Case II.

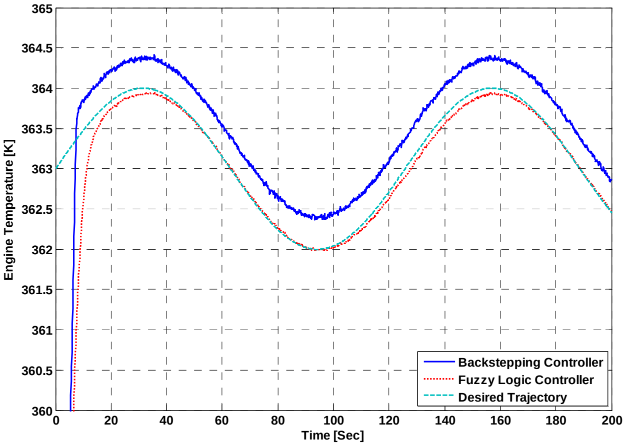

Figure 7: Simulated engine temperature response (Case I)

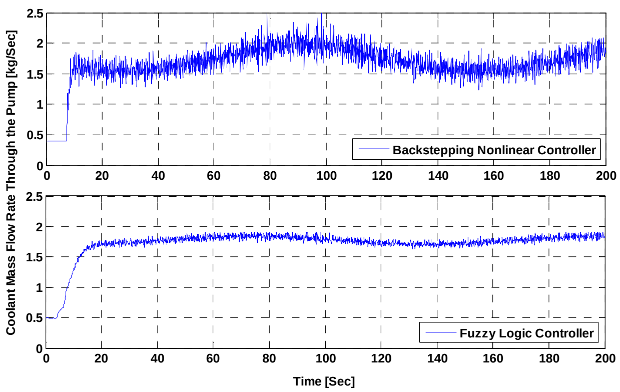

Figure 8: Simulated coolant mass flow rate through the pump (Case I)

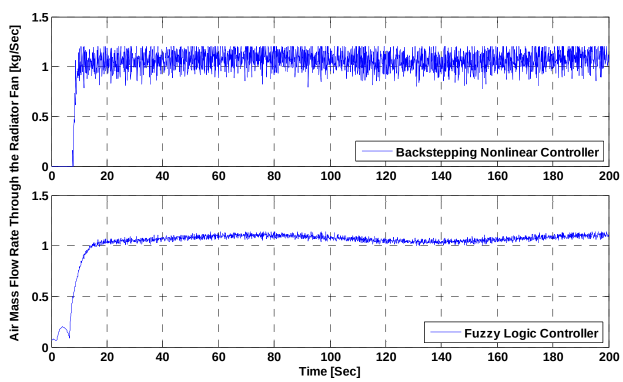

Figure 9: Simulated air mass flow rate through the radiator fan (Case I)

The following measure was also computed to quantify the performance of each controller,

$$M \triangleq \int_0^T |\dot{m}(\tau)|^2 \, d\tau \tag{3}$$

where $M = Mp$ and $M = Mf$ are the measure of energy expanded by the controller over the period of operation of the system (*i.e.*, T=200) for the water pump and radiator fan, respectively. The variable $\dot{m}(t)$ is the mass flow rate of either the coolant pump or the radiator fan. Table 1 shows a comparison of the performance for the proposed FLC and backstepping nonlinear controller.

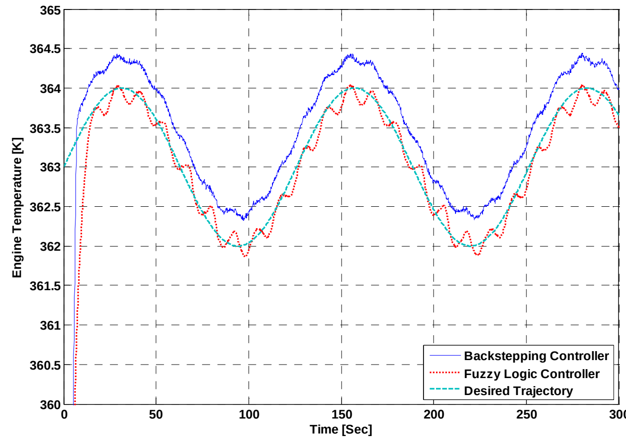

Figure 10: Simulated engine temperature response (Case II)

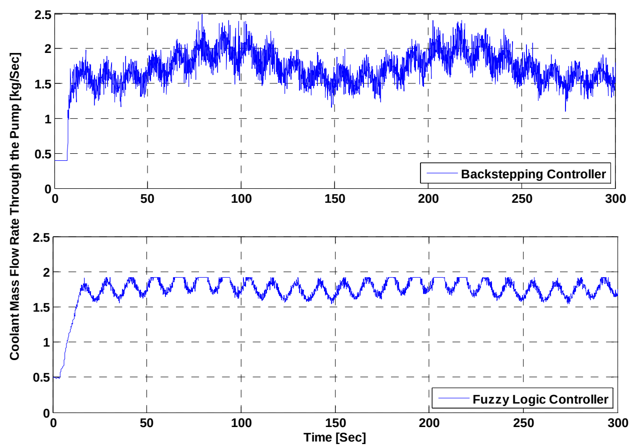

Figure 11: Simulated coolant mass flow rate through the pump (Case II)

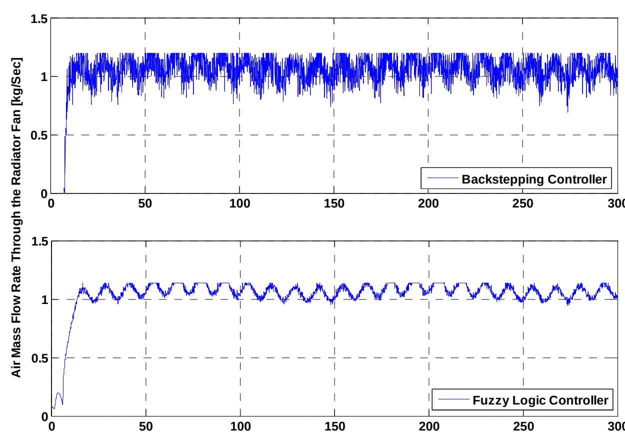

Figure 12: Simulated air mass flow rate through the radiator fan (Case II)

Table 1
Comparison of error and controller effort measures.

Controller	Case I		Case II	
	M_p	M_f	M_p	M_f
FLC	951.5	568.5	954.2	568.6
Backstepping	924.9	568	926	568.3

As shown in Figure 7 for Case I, the FLC can achieve a maximum steady state absolute value temperature tracking error of 0.14ºK while for the backstepping nonlinear controller the maximum steady state absolute value temperature tracking error is 0.45ºK. On the other hand, in Figure 10 for Case II, the FLC can achieve a maximum steady state absolute value temperature tracking error of 0.3ºK while for the backstepping nonlinear controller the maximum steady state absolute value temperature tracking error is 0.5ºK. The response of the water pump and radiator fan, when operated using the backstepping nonlinear controller for Cases I and II, demonstrate more fluctuations when compared with the FLC as shown in Figures 8, 9, 11, and 12. However, it can clearly be seen from Table 1 that both controllers expanded the same effort to regulate the engine temperature but overall the FLC performs better than the backstepping nonlinear controller and seems to be less complicated and does not need a lot of computational efforts.

5. Conclusion

Advanced automotive thermal management system can improve the response of the gasoline and diesel engine cooling systems. In this paper, a suit of servo-motor based-cooling system components have been controlled using a fuzzy logic technique. The control algorithm has been investigated using only numerical simulation test and compared with a backstepping nonlinear technique. The proposed controller successfully maintained the engine temperature to a prescribed temperature with small error percentage. Overall, the controller performance demonstrated a satisfactory performance in tracking a desired engine temperature profile.

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