Adaptive fuzzy throttle control for an all-terrain vehicle

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Abstract: This paper describes an adaptive fuzzy throttle control for an all-terrain vehicle (ATV) powered by internal combustion engine. The design objective is to provide smooth throttle movement and zero steady state speed error, and to maintain a selected vehicle speed over varying road slopes for a 2–30 mile/h speed range. Unlike modern production vehicles which have microprocessor-based engine management systems, the ATV's engine is mechanically controlled via a carburettor.

A complete mathematical model of the engine is not available, making it very difficult to apply conventional control techniques. Using experience and data collected from extensive experiments conducted on the ATV throttle mechanism, an adaptive fuzzy throttle control algorithm is designed. A candidate Lyapunov function is employed in the adaptive law synthesis to ensure convergence. Experimental results are presented showing the effectiveness of the control algorithm at speeds below 2.74 mile/h (1.2 m/s).

Keywords: fuzzy control, adaptive control, robotics, mechatronics

NOTATION

A, **B**	state space matrices
A/F	air–fuel ratio
J_e	engine moment of inertia
m_a	air mass in the manifold
m_{ai}	air mass flowrate into the intake manifold
m_{ao}	air mass flowrate from the intake manifold to cylinders
N	engine speed (r/min)
P_m	manifold pressure
Q_c	combustion heat
T_f	frictional torque
T_I	indicated torque
T_L	external load torque
$\boldsymbol{u}$	input vector
v_e	engine displacement
v_m	intake manifold
$\boldsymbol{z}$	state vector
α	throttle plate angle
η_e	engine efficiency
η_{vol}	volume efficiency

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1 INTRODUCTION

In this paper, an adaptive fuzzy speed control design for a throttle-regulated internal combustion engine on an all-terrain vehicle (ATV) is presented. The ATV is one of several mobile platforms used in the CyberScout project, at the Institute for Complex Engineered Systems, Carnegie Mellon University. The CyberScout project aims to develop distributed mobile robotic technologies that will extend the sphere of awareness and mobility of small military units while exploring issues of command and control, task decomposition, multi-agent collaboration, efficient perception algorithms and sensor fusion.

Two unmanned ground vehicles (UGVs) have been built by retrofitting two Polaris Sportsman 500 ATVs [named Lewis and Clark, after the famous explorers (Fig.1)], automating their throttle, steering, braking and gearing functions and giving them computation for control, navigation, sensing and communication. The automatic steering, braking, and gearing functions are actuated hydraulically; a radio control servomotor placed in line with the throttle cable controls the throttle. A 2.5 kW generator provides auxiliary power, primarily for the hydraulics. The computational architecture is two tiered; locomotion control is performed by a PC/104, while planning, perception and communications are performed by a laptop personal computer in concert with auxiliary perceptual processors. Navigational sensing is performed by a NovAtel GPS (global positioning system) of 20 cm revolution; perceptual sensing is currently restricted to vision, where attempts are being made

Fig. 1 Cyber-ATV Lewis

to exploit it to the fullest due to its passive unobtrusive nature, and communications with other platforms and with remote users are performed via wireless Ethernet.

The following capabilities have already been demonstrated: remote manual control of the ATV using various input devices (R/C joystick, laptop and wearable computer); autonomous GPS-based waypoint navigation; autonomous convoying based on visual tracking; personnel–vehicle classification using vision. In this paper, one of the subsystems crucial to achieving complete autonomy, the low-level vehicle speed control system, is presented. Since the ATV is equipped with cameras for navigation, it is essential that the vehicle moves smoothly at speeds that will allow real-time processing of the images.

In the literature, several researchers have developed automobile speed control systems (cruise control). A brief review of the techniques employed will be outlined below. In reference [**1**], an adaptive control structure is proposed for different vehicle lines with very little recalibration. Using slow adaptation and sensitivity-based gradient algorithms, the gains of a proportional–integral (PI) controller are adjusted to minimize a quadratic cost function. The cost function was formulated from experimental and simulation studies and was shown to improve the performance of all the tested vehicles over varying road terrain. In reference [**2**] a robust stabilizing controller for an internal combustion engine with throttle driven by a d.c. motor is presented. The control structure consists of two loops; the drive loop and the engine loop. The block control technique is employed in the engine loop to linearize the engine dynamics. Sliding mode control is used in the drive loop to provide fast and precise tracking of the throttle plate angle. Excellent simulation results based on a six-cylinder engine were presented. Similarly, reference [**3**] described an engine throttle control for an experimental automobile using anticipatory band in a sliding phase plane. The anticipatory band is shown to stabilize the system and to reduce output chattering in the experimental results presented.

Reference [**4**] also presented a switching control scheme for a pneumatic throttle actuator. The sliding surface is defined in terms of throttle plate angle error since the throttle plate angle is measurable. Experimental results are presented showing the desired, measured and estimated throttle angle when several input references are supplied to the controller. The proposed control scheme seems to work best at throttle angles that correspond to normal operating highway speeds.

Although some of the reviewed automatic speed controllers in the literature have been implemented on production vehicles, the control techniques are not directly applicable to the ATV throttle control problem. First, the ATV's engine is mechanically controlled via a carburettor, unlike most production vehicles, which have microprocessor-based engine management systems which guarantee maximum engine efficiency and horsepower. Second, the ATV carburettor clearance makes it difficult to incorporate a sensor to measure the throttle plate angle, which is required in virtually all the automotive speed controllers in the literature. Third, and importantly, although most modern automobiles are equipped with automatic speed control (cruise control) they are generally recommended to be used at speeds greater than 30 mile/h. At speeds below 30 mile/h, most internal combustion engines exhibit considerable torque fluctuations, a highly non-linear phenomenon which results in considerable variation in engine speed and crankshaft angular speed. This makes it extremely challenging to design an effective control algorithm for speeds below 30 mile/h. Finally, the ATV throttle is actuated via the R/C servo instead of a pneumatic actuator, the preferred actuator in most production vehicles. Although the R/C servo set-up has the potential to provide faster and more accurate throttle plate control, it provides no explicit feedback of the servo's angular position.

An adaptive fuzzy throttle control scheme is proposed for the ATV. Fuzzy rules are formulated from extensive experiments conducted by human operators and quantitative data. The organization of the rest of the paper is as follows. In Section 2 a brief overview of the ATV's throttle and power train systems is presented. The engine mathematical model is presented in Section 3. Section 4 presents the control law formulation and results, and Section 5 gives conclusions.

2 OVERVIEW OF ATV THROTTLE ACTUATION AND POWER TRAIN SYSTEM

The ATV is a Polaris Sportsman 500 equipped with a four-stroke liquid-cooled engine with a 34 mm Mikuni carburettor. The primary input for controlling the speed for an internal combustion engine vehicle is the closing and opening of the throttle plate. The Polaris Sportsman 500 is equipped with a Mikuni CV carburettor. The carburettor incorporates a mechanically operated throttle plate and a vacuum-controlled slide valve as shown in Fig. 2.

Because the throttle plate opening regulates the torque generated by the engine, accurate control of the opening is essential for effective speed control. Figure 3 depicts the ATV's retrofitted throttle control set-up. A Futaba R/C servomotor has been introduced in the cable connecting the throttle lever to the throttle plate. This preserves a rider's ability to control the throttle manually using the lever, while allowing autonomous control via the R/C servo.

The throttle plate set-up incorporates a torsional spring, which applies a closing torque on the throttle plate sufficient to back drive the servo to idle throttle position when the power is turned off. The choice of

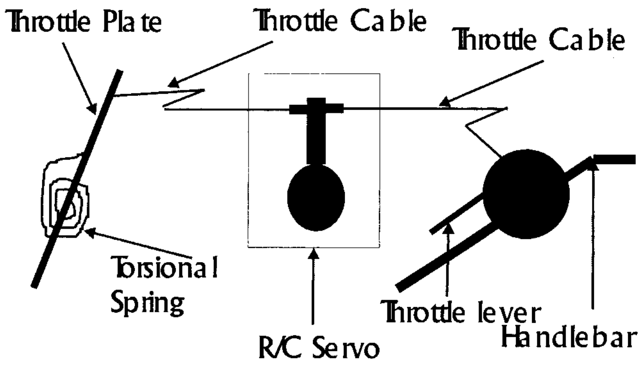

Fig. 3 Modified throttle system including throttle actuator, ATV handle bar and throttle plate

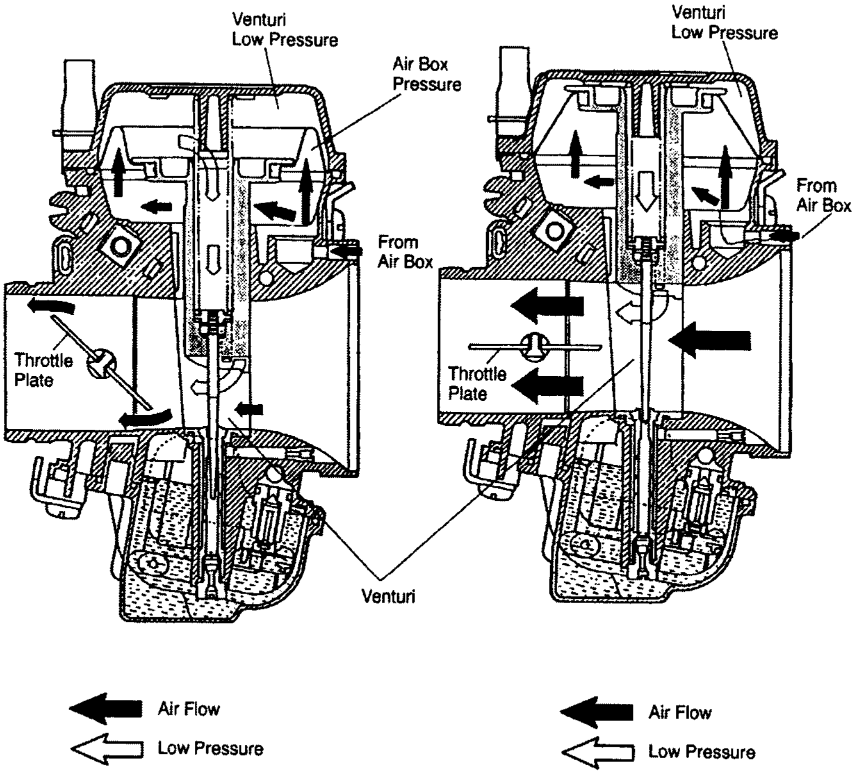

Fig. 2 Diagram of the Mikuni CV carburettor [5]

an R/C servo for throttle actuation is based on its low cost, small size, internal closed-loop position control, low power consumption and easy control signal generation.

To control the servo a pulse train with ON time pulse width between 1 and 2 ms is required. The OFF time pulse width can be between 10 and 20 ms since it is not critical to the correct operation of the servo. In the case of the ATV throttle control set-up shown in Fig. 3, a pulse width of 1 ms corresponds to idle throttle, 1.5 ms half-throttle and 2 ms full throttle. Speed feedback is obtained via a tach generator mounted in the gearbox. The tachometer is a Servo-Tek SB-763-2A, designed for use in applications requiring an output signal between 1 and 10 V and 1000 r/min. The output of the tachometer is connected to a DM5416 Real-Time Devices analogue–digital input–output board on the PC/104 stack.

2.1 Polaris variable transmission

The power train set-up of the ATV employs an automatic transmission system called the Polaris variable transmission (PVT). The PVT effectively transmits the torque generated by the engine to the four wheels. The PVT changes engine-load requirements by either up-shifting or down-shifting. The PVT system consists of three key components: drive clutch, drive belt and driven clutch.

The drive clutch and driven clutch control the ATV's clutch engagement, from initial vehicle movement to clutch up-shifting and down-shifting. The drive clutch is essentially a speed-sensing unit which effectively transfers the maximum amount of horsepower from the engine to the ground.

The driven clutch is primarily a torque-sensing unit. The drive clutch and driven clutch combine to move the drive belt up and down their sheaves in order to maintain optimum engine speed in the face of various engine loads [**5**].

A drawback of the PVT is slippage as a result of overheating or ingestion of oil, water, etc., into the PVT system. Moving the vehicle at very low speeds (5 mile/h and lower) induces slippage, since the PVT is optimized for speeds above 15 mile/h.

2.2 Design objectives

The speed control system should be designed to provide smooth throttle movement, zero steady state speed error, constant vehicle speed over varying road slopes, and robustness to system variations and operating conditions for a 2–30 mile/h speed range. Additionally, the number of control calibrations for different vehicle applications should be minimal.

3 ENGINE MATHEMATICAL MODEL

The rotational dynamics of the engine can be modelled as [**2**]:

$$J_e \dot{N} = T_I - T_f - T_L \tag{1}$$

where N is the engine speed (r/min), J_e is the engine moment of inertia, T_I is the indicated torque, T_f is the frictional torque and T_L is the external load torque (assumed to be constant or slowly varying in comparison with the other variables). This assumption holds if the vehicle is to be deployed in a fairly level terrain and it moves at fairly low speeds.

The frictional torque can be expressed in terms of the engine speed as follows:

$$T_f = d_1 N + d_2 \tag{2}$$

where d_1 and d_2 are constants. The engine indicated torque is applied at the crankshaft due to cylinder pressure during the combustion stroke action through the piston connection rod assembly and the crankshaft angular speed. The indicated torque is defined as

$$T_I = c_t \frac{\dot{m}_{ao}}{N} \tag{3}$$

where

$$c_t = \frac{\eta_e Q_c}{A/F}$$

where η_e is the engine efficiency, Q_c is the combustion heat and A/F is the air–fuel ratio.

The air mass flowrate m_{ao} from the intake manifold to the cylinders is defined as

$$\dot{m}_{ao} = c_e \eta_{vol} m_a N \tag{4}$$

where

$$c_e = \frac{v_e}{4\pi v_m}$$

where v_m is the intake manifold, v_e is the engine displacement and η_{vol} is the volume efficiency of the engine. The air mass flowrate into the intake manifold, m_{ai}, can be approximated by a function in terms of the manifold pressure P_m and the throttle plate angle α and is defined as follows:

$$\dot{m}_{ai} = G(P_m) V(\alpha) \tag{5}$$

where $V(\alpha)$ is modelled as a second-order polynomial [**6**], defined below:

$$V(\alpha) = D_2 \alpha^2 + D_1 \alpha + D_0 \tag{6}$$

where D_2, D_1 and D_0 are constants. The function $G(P_m)$ is an air flow function of the manifold pressure. Whenever the manifold pressure is less than half the atmospheric pressure, the pressure ratio across the throttle plate valve is less than half. Under these conditions, air flow is sonic and the function $G(P_m) = 1$ [**6**].

For most engines, idle manifold pressure will be such that idle air flow is sonic. Conservation of mass within the manifold requires that

$$\dot{m}_{\mathrm{a}} = \dot{m}_{\mathrm{ai}} - \dot{m}_{\mathrm{ao}} \tag{7}$$

Substitution of equations (3), (2) and (4) into equation (1) after some manipulations gives

$$\dot{N} = \frac{-d_1}{J_{\mathrm{e}}} N + \frac{c_{\mathrm{t}} c_{\mathrm{e}} \eta_{\mathrm{vol}}}{J_{\mathrm{e}}} m_{\mathrm{a}} - \left(\frac{d_2}{J_{\mathrm{e}}} - \frac{T_{\mathrm{L}}}{J_{\mathrm{e}}} \right) \tag{8}$$

The time derivative of $\dot{N}$ is

$$\ddot{N} = \frac{-d_1}{J_{\mathrm{e}}} \dot{N} + \frac{c_{\mathrm{t}} c_{\mathrm{e}} \eta_{\mathrm{vol}}}{J_{\mathrm{e}}} \dot{m}_{\mathrm{a}} \tag{9}$$

Substitution for $\dot{m}_{\mathrm{a}}$ in equation (9) after some simple manipulation gives

$$\begin{bmatrix} \dot{N} \\ \ddot{N} \end{bmatrix} = \begin{bmatrix} \dfrac{-d_1}{J_{\mathrm{e}}} & 0 \\ \dfrac{-c_{\mathrm{t}} c_{\mathrm{e}}^2 \eta_{\mathrm{vol}}^2 m_{\mathrm{a}}}{J_{\mathrm{e}}} & \dfrac{-d_1}{J_{\mathrm{e}}} \end{bmatrix} \begin{bmatrix} N \\ \dot{N} \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{c_{\mathrm{t}} c_{\mathrm{e}} \eta_{\mathrm{vol}} D_1}{J_{\mathrm{e}}} \end{bmatrix} \alpha + \boldsymbol{E} \tag{10}$$

where higher-order, cross-coupling terms and load torque have been lumped into $\boldsymbol{E}$, which is a column vector. Equation (10) represents a primitive mathematical model of the dynamics of an internal combustion engine and by no means captures all the non-linear parameters of the engine.

4 SPEED CONTROL DESIGN AND RESULTS

The two main challenges in designing an effective speed controller for the ATV are are follows:

(a) the lack of a complete mathematical model for the engine and
(b) the highly non-linear nature of the engine dynamics, especially for the targeted low-speed range 3–30 mile/h.

Both of these factors make the use of classical control strategies such as proportional–integral–derivative control ineffective.

One of the main reasons for these challenges is the ATV's carburettor. Carburettors are generally calibrated for a fixed range of altitudes and ambient temperatures. Since maximum engine efficiency and horsepower are directly related to proper carburettor setting, any significant changes in altitude and ambient temperatures require recalibration of the carburettor, a tedious task. In contrast, modern engine control systems employ microprocessor-based systems to control fuel injection and ignition point. Engine control strategies depend strongly on the current operating point, and there are no complete mathematical models of the engine parameters. As a result, most engine controllers use look-up tables to represent the control strategy. These tables are generated from extensive field experiments and engineering expertise. Therefore, it is very difficult to employ conventional control techniques that require a precise mathematical model to synthesize a speed control algorithm.

Our initial work involved conducting open-loop experiments on the throttle set-up shown in Fig. 3. Experiments conducted on level terrain showed that humans could not easily drive the ATV at speeds below 10 mile/h shed light on the non-linear nature of the problem. Valve openings below half-throttle did not generate constant speeds. Also, the throttle valve-opening threshold for initiating vehicle movement varied from one trial to the next, indicating a shifting operating point.

An incremental approach with respect to complexity was taken in closing the control loop. A simple initial strategy was a proportional or on–off controller but, due to non-linearities, including delay, involved with the carburettor control action and the PVT, hunting and overshoot of the commanded speed occurred. An obvious modification to the proportional control law was the addition of an integral component to form a PI controller. Although the PI controller has been shown to be a good solution to fixed operating-point plants, it fails when applied to moving operating points. (The measured speed signal is very noisy; therefore it was not feasible to implement a derivative component for a PID controller.) The operating point of the ATV's engine moves with respect to changing load conditions, slippage in the PVT and the carburettor characteristics as shown in Fig. 4. Nevertheless, a PI controller can be used for higher speeds where the carburettor operation is fairly linear, i.e. throttle openings above one-half and speeds above 15 mile/h, covering the upper portion of our target speed range. This result indicates that a possible approach is to use more than one control strategy via look-up tables, depending on the speed range.

Another approach to the control problem is to apply adaptive control techniques. However, a complete mathematical model of the engine parameters is not available, and developing this model requires information about the engine from the manufacturer which they were unwilling to provide. An alternative control approach is fuzzy logic control (FLC), since the extensive quantitative and qualitative results can be employed effectively in fuzzy systems. From the quantitative data collected, a very primitive engine model was developed using equation (10).

4.1 Fuzzy logic speed control

FLC has been demonstrated to solve some practical problems that have been beyond the reach of conven-

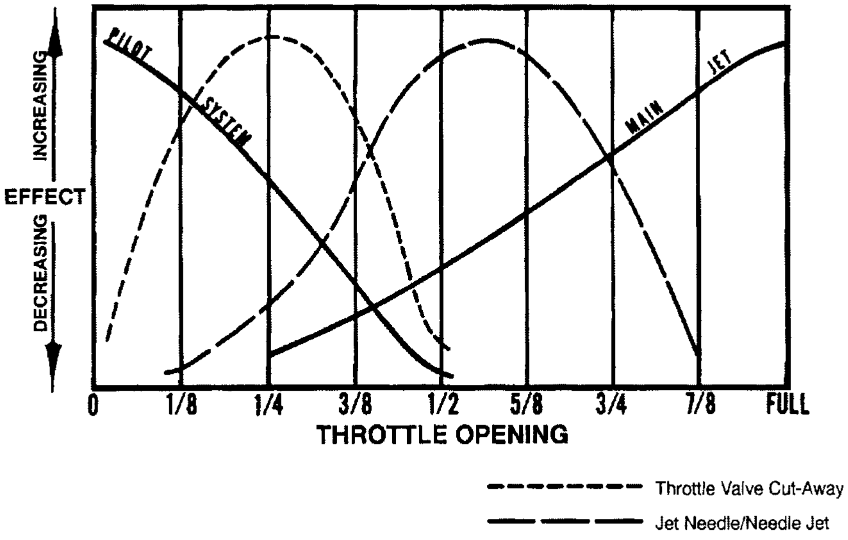

Fig. 4 Throttle opening chart

tional control techniques. FLC is a knowledge-based control that uses fuzzy set theory, fuzzy reasoning and fuzzy logic for knowledge representation and inference [**7**]. The apparent success of FLC can be attributed to its ability to incorporate expert information and to generate control surfaces whose shape can be individually manipulated for different regions of the state space with virtually no effects on neighbouring regions.

In this paper a fuzzy system consisting of a fuzzifier, a knowledge base (rule base), a fuzzy inference engine and defuzzier will be considered. The knowledge base of the fuzzy system is a collection of fuzzy IF–THEN rules.

FLC is ideal for the ATV control problem, since there is no complete mathematical model of the engine. However, human experience and experimental results, can be used in the control system, design. The design goal for the speed control is to minimize the magnitude of the speed error defined as

$$\text{Speed error} = \text{desired speeed} - \text{actual speed} \tag{11}$$

Human operators control the speed of the ATV via the throttle lever, which opens and closes the throttle valve to increase or reduce the speed of the ATV. From this experience, fuzzy rules were formulated using speed error and change in control input to the throttle actuator (CTO). CTO is defined using the two past values of the control input, which can be expressed as follows:

$$\text{CTO} = \text{control input}_{(k-1)T} - \text{control input}_{(k-2)T} \tag{12}$$

Discrete time $t = kT$, where $k = 0, 1, 2, \ldots, n$, and T is the sampling and control update period. The derivative block in Fig. 5 represents the CTO.

A block diagram of the control structure is shown in Fig. 5. Five triangular membership functions were defined for speed error (Fig. 6), namely negative large (NL), negative small (NS), zero, positive small (PS) and positive large (PL). The triangular membership function centres are as follows: $A = -0.5$ m/s, $B = -0.25$ m/s, $C = -0.15$ m/s, $D = 0.42$ m/s and $E = 1.05$ m/s. Similarly three triangular membership functions were defined for the CTO (Fig. 7) and they are as follows: negative small (NS), zero, and positive small (PS). The triangular membership function centres are as follows: $A = -0.03$, $B = 0.0$ and $C = 0.05$. In addition, five triangular membership functions were defined for throttle opening (Fig. 8) and they are zero, small, medium, large and very large. The triangular membership function centres are as follows: $G = 1.095$ ms, $H = 1.1075$ ms, $I = 1.110$ ms, $J = 1.120$ ms and $K = 1.140$ ms. The ranges of these variables were determined by experimentation and the physical constraints of the sensors employed, e.g. R/C servomotor input command range from 1 to 2 ms. The zero membership function centre for throttle opening is defined to be slightly above idle engine speed.

The complete fuzzy rules are shown in Fig. 9. Rule 1 is as follows.

Rule 1

If the speed error is PL AND the CTO is zero, THEN the throttle opening is very large.

This rule is fairly intuitive since, if there is a large positive speed error, the throttle should be opened wider, especially if the throttle opening has changed very little or remained the same from the previous opening, as implied by the fact that the CTO is zero. The rest of the rules are derived similarly. The label names used here give an intuitive sense of how the rules apply. Through experimentation and tuning of the membership functions, it was determined that the number of rules was sufficient to encompass all realistic combinations of inputs and outputs. The above fuzzy logic controller

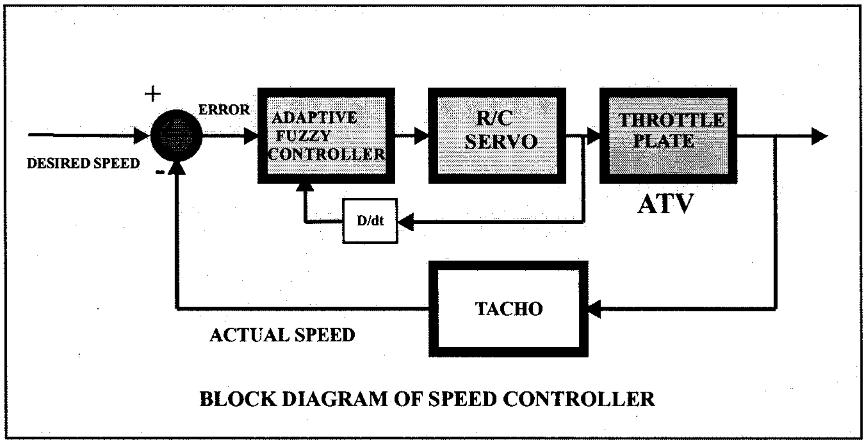

Fig. 5 Block diagram of the FLC scheme

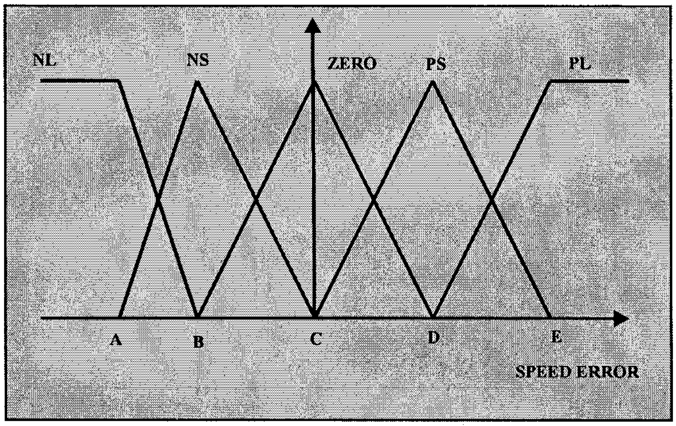

Fig. 6 Speed error membership function

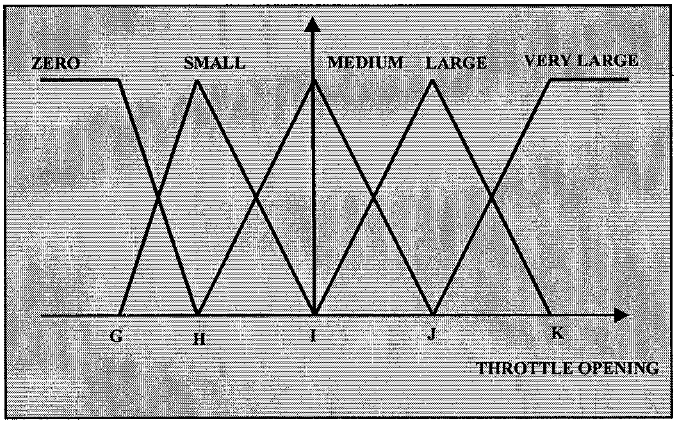

Fig. 8 Throttle or control input membership function

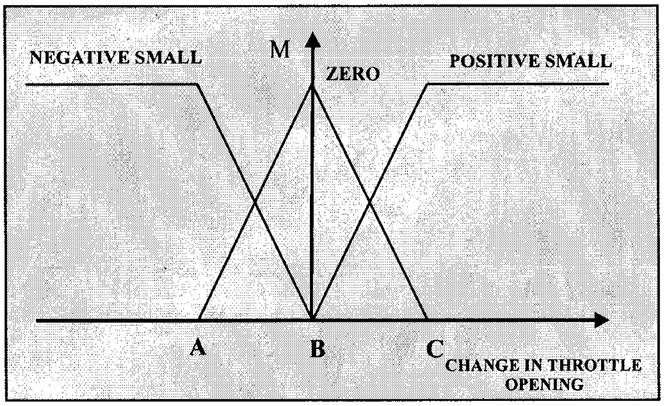

Fig. 7 CTO membership function

CTO / ERROR	NS	ZERO	PS
NL	ZERO	ZERO	ZERO
NS	SMALL	SMALL	SMALL
ZERO	ZERO	ZERO	ZERO
PS	SMALL	LARGE	MEDIUM
PL	MEDIUM	VERY LARGE	LARGE

Fig. 9 Fuzzy rule table for ATV speed controller

was implemented using product inference and a centre-average defuzzifier.

Figure 10 depicts the speed response of the ATV using the above FLC scheme. There was a fairly large steady state error, but the ATV response was very smooth. Nevertheless, for substantial changes in the terrain (uphill and downhill) the steady state error was found to increase to an unsatisfactory degree. Several attempts to tune the member functions for fuzzy variables did not

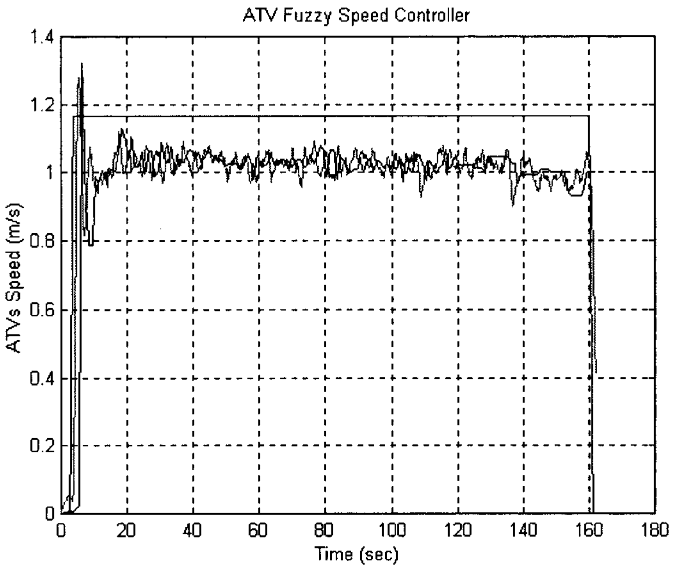

Fig. 10 ATV speed response for fuzzy controller commanded speed of 2.3 mile/h (1.0 m/s)

significantly reduce the steady state error, suggesting the need for adaptivity. Since the FLC scheme worked fairly well, an adaptive control law based on fuzzy control was considered. The detailed derivation of the adaptation law and control scheme is discussed below.

4.2 Adaptive fuzzy speed control

Assume that the rule base consists of multiple-input single-output (MISO) rules of the form

$$R^{(j)}: \text{IF } x_1 \text{ is } A_1^j \text{ and } \ldots \text{ and } x_n \text{ is } A_n^j, \text{ THEN } \boldsymbol{y} \tag{13}$$

where $\boldsymbol{x}=(x_1 \ \cdots \ x_n)\in N$, $\boldsymbol{y}$ denotes the linguistic variables associated with inputs and outputs of the fuzzy system. A_i^j and C^j are linguistic values of linguistic variables $\boldsymbol{x}$ and $\boldsymbol{y}$ in the universes of discourse N and S respectively, $j=1, 2, \ldots, Q_{\mathrm{R}}$ (number of rules). A fuzzy system consisting of a singleton fuzzifier, product inference, centre-average defuzzifier and triangular membership functions can be written as [8]

$$f(\boldsymbol{x})=\frac{\sum_{j=1}^{Q_R} \bar{y}^j[\prod_{i=1}^{n} \mu_{A_i^j}(x_i)]}{\sum_{j=1}^{Q_R} [\prod \mu_{A_i^j}(x_i)]} \tag{14}$$

where $f: N\subset \Re^n \rightarrow \Re$, $\boldsymbol{x}=(x_1 \ \cdots \ x_n)^{\mathrm{T}}\in N$, $\mu_{A_i^j}(x_i)$ is a triangular membership function and $\bar{y}^j$ is the point in S where μ_{C^j} is a maximum or equal to 1. If the $\mu_{A_i^j}(x_i)$ values and $\bar{y}^j$ values are free (adjustable) parameters, then equation (14) can be written as

$$f(\boldsymbol{x})=\boldsymbol{\vartheta}^{\mathrm{T}}\boldsymbol{\Psi}(\boldsymbol{x}) \tag{15}$$

where $\boldsymbol{\vartheta}=(\bar{y}^1 \ \cdots \ \bar{y}^{Q_{\mathrm{R}}})$ is a parameter vector and $\boldsymbol{\Psi}(\boldsymbol{x})=(\psi^1(\boldsymbol{x}) \ \cdots \ \psi^{Q_{\mathrm{R}}}(\boldsymbol{x}))^{\mathrm{T}}$ is a regression vector with the regressor given by

$$\psi_i(\boldsymbol{x})=\frac{\prod_i^n \mu_{A_i^j}(x_i)}{\sum_{j=1}^{Q_{\mathrm{R}}} (\prod \mu_{A_i^j}(x_i))} \tag{16}$$

Equation (15) is referred to as an adaptive fuzzy system [8]. There are two main reasons for using adaptive fuzzy systems as building blocks for adaptive fuzzy controllers. Firstly, it has been proved in reference [8] that they are universal function approximators. Secondly, all the parameters in $\boldsymbol{\Psi}(\boldsymbol{x})$ can be fixed at the beginning of adaptive fuzzy system expansion design procedure, so that the only free design parameters are $\boldsymbol{\vartheta}$. In this case, $f(\boldsymbol{x})$ is linear in the parameters. This approach will be adopted in synthesizing the adaptive control law in this paper. The advantage of this approach is that very simple linear parameter estimation methods can be used to analyse and synthesize the performance and robustness of adaptive fuzzy systems. If no linguistic rules are available, the adaptive fuzzy system reduces to a standard non-linear adaptive controller.

4.2.1 Adaptive law synthesis

The engine mathematical model given by equation (10) can be expressed as follows [9]:

$$\dot{\boldsymbol{z}}=\mathbf{A}\boldsymbol{z}+\mathbf{B}\boldsymbol{u}+\boldsymbol{E}(\boldsymbol{z}) \tag{17}$$

where $\boldsymbol{E}(\boldsymbol{z})$ is the uncertainty in the model expressed as a function of the state $\boldsymbol{z}$, and $\mathbf{A}$ is Hurwitz. Therefore there exists a unique positive definite matrix $\mathbf{P}$ that satisfies the Lyapunov equation

$$\mathbf{A}^{\mathrm{T}}\mathbf{P}+\mathbf{P}\mathbf{A}=-\mathbf{Q} \tag{18}$$

If the control input $\boldsymbol{u}$ is expressed as an adaptive fuzzy system, then equation (17) becomes

$$\dot{\boldsymbol{z}}=\mathbf{A}\boldsymbol{z}+\mathbf{B}\boldsymbol{\vartheta}^{\mathrm{T}}\psi(\boldsymbol{z})+\boldsymbol{E}(\boldsymbol{z}) \tag{19}$$

Let [7]

$$\dot{\hat{\boldsymbol{z}}}=\mathbf{A}\hat{\boldsymbol{z}}+\mathbf{B}\boldsymbol{\vartheta}^{*\mathrm{T}}\psi(\hat{\boldsymbol{z}}) \tag{20}$$

be the ideal engine model with no uncertainty (identification model) with $\boldsymbol{\varepsilon}=\boldsymbol{z}-\hat{\boldsymbol{z}}$, where $\boldsymbol{\vartheta}^*$ denotes the optimal defined as

$$\boldsymbol{\vartheta}^* \equiv \arg \min_{|u|\leq M} \left[\sup_{z\in\Omega} |\boldsymbol{u}(\boldsymbol{z}|\boldsymbol{\vartheta}^*)-\boldsymbol{u}(\boldsymbol{z}|\boldsymbol{\vartheta})|\right] \tag{21}$$

Therefore

$$\dot{\boldsymbol{\varepsilon}}=\mathbf{A}\boldsymbol{\varepsilon}+\mathbf{B}\boldsymbol{\phi}^{\mathrm{T}}\psi(\boldsymbol{\varepsilon})+\hat{\boldsymbol{E}} \tag{22}$$

where $\boldsymbol{\phi}=\boldsymbol{\vartheta}-\boldsymbol{\vartheta}^*$ and $\hat{\boldsymbol{E}}$ is an estimate of the upper bounds of the uncertainties. To derive a control law that ensures that $\boldsymbol{\varepsilon}\rightarrow\mathbf{0}$ as $t\rightarrow\infty$ a candidate Lyapunov function is defined as [9]

$$V=\frac{1}{2}\left(\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{P}\boldsymbol{\varepsilon}+\frac{\boldsymbol{\phi}^{\mathrm{T}}\boldsymbol{\phi}}{\gamma\|\hat{\mathbf{E}}\|}\right) \tag{23}$$

where $\gamma>0$ is a design parameter. The time derivative of V is

$$\dot{V} = -\frac{1}{2}\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{Q}\boldsymbol{\varepsilon} + \boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{P}[\hat{\boldsymbol{E}} + \mathbf{B}\phi^{\mathrm{T}}\psi(\boldsymbol{\varepsilon})] + \frac{\phi^{\mathrm{T}}\dot{\phi}}{\gamma\|\hat{\boldsymbol{E}}\|} \quad (24)$$

Rearranging equation (24) yields

$$\dot{V} = -\frac{1}{2}\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{Q}\boldsymbol{\varepsilon} + \boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{P}\hat{\boldsymbol{E}} + \phi^{\mathrm{T}}\left(\|\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{PB}\|\,\psi(\boldsymbol{\varepsilon}) + \frac{\dot{\phi}}{\gamma\|\hat{\boldsymbol{E}}\|}\right) \quad (25)$$

Now choosing the adaptive law (recalling that $\dot{\phi} = \dot{\vartheta}$),

$$\dot{\phi} = -\gamma\|\hat{\boldsymbol{E}}\|\,\|\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{PB}\|\,\psi(\varepsilon) \quad (26)$$

Equation (25) reduces to

$$\dot{V} = -\tfrac{1}{2}\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{Q}\boldsymbol{\varepsilon} + \boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{P}\hat{\boldsymbol{E}} \quad (27)$$

Equation (27) can be recast using vector norms:

$$\dot{V} = -\tfrac{1}{2}\lambda_{\min}(\mathbf{Q})\|\boldsymbol{\varepsilon}\|^2 + \|\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{P}\|\,\|\hat{\boldsymbol{E}}\| \quad (28)$$

Let $\|\hat{\boldsymbol{E}}\|$ be selected such that

$$\|\hat{\boldsymbol{E}}\| \geqslant \frac{\tfrac{1}{2}\lambda_{\min}(\mathbf{Q})\|\boldsymbol{\varepsilon}\|^2 - \alpha_1\|\boldsymbol{\varepsilon}\|}{\|\boldsymbol{\varepsilon}^{\mathrm{T}}\mathbf{P}\|} \quad (29)$$

where $\alpha_1 > 0$ is a control parameter; substituting for $\hat{\boldsymbol{E}}$ in equation (29) gives

$$\dot{V} \leqslant -\alpha_1\|\boldsymbol{\varepsilon}\| \quad (30)$$

Therefore the control law of equation (26) will ensure that the state $\boldsymbol{\varepsilon}$ converges. To implement the above adaptive fuzzy control law, the fuzzy rule in Fig. 9 was used and the insight gained from the non-adaptive fuzzy logic control was used to select the ϑ values to lie within the interval [1.0, 2.0]. The remaining control parameters were set as follows: $\mathbf{Q} = \mathrm{diag}(3, 3)$, $\hat{\boldsymbol{E}} = [120\ \ 0]^{\mathrm{T}}$, $\gamma = 0.000\,25$, $\boldsymbol{\varepsilon} =$ desired speed − actual speed and $\boldsymbol{\Psi}(\boldsymbol{\varepsilon})$ was formulated using the IF part of the fuzzy rule in Fig. 9. **P** is obtained from the solution of equation (18) in an iterative process. Similarly $\hat{\boldsymbol{E}}$ and γ are obtained by experimentation. The adaptive fuzzy controller was also implemented on the ATV. Figure 11 depicts the ATV speed responses to selected speeds. As can be seen from the figures, significant improvement can be observed with respect to steady state error. Considerable improvement was also observed with respect to disturbance rejection (load and terrain). The adaptive algorithm responds to the varying terrain by continuously minimizing the speed error by tuning the centre of the input fuzzy membership functions.

Figure 12 depicts the ATV's response to a speed command of 2.3 mile/h (1.0 m/s), a very slow speed. As can be observed from the ATV's response, there is an overshoot, and it takes about 30 s for the speed to settle. The ATV is back-heavy; hence, when it is on a slight incline, considerable momentum is required to initiate motion. At about 80 s (Fig. 12) there is a considerable drop in the ATV's speed to well below the commanded speed of 1.0 m/s, which can be attributed to a slippage in the PVT system. The throttle control responds with a small increase, rather than the large response that a PI controller would generate, and regains the commanded velocity without significant overshoot once the slipping stops.

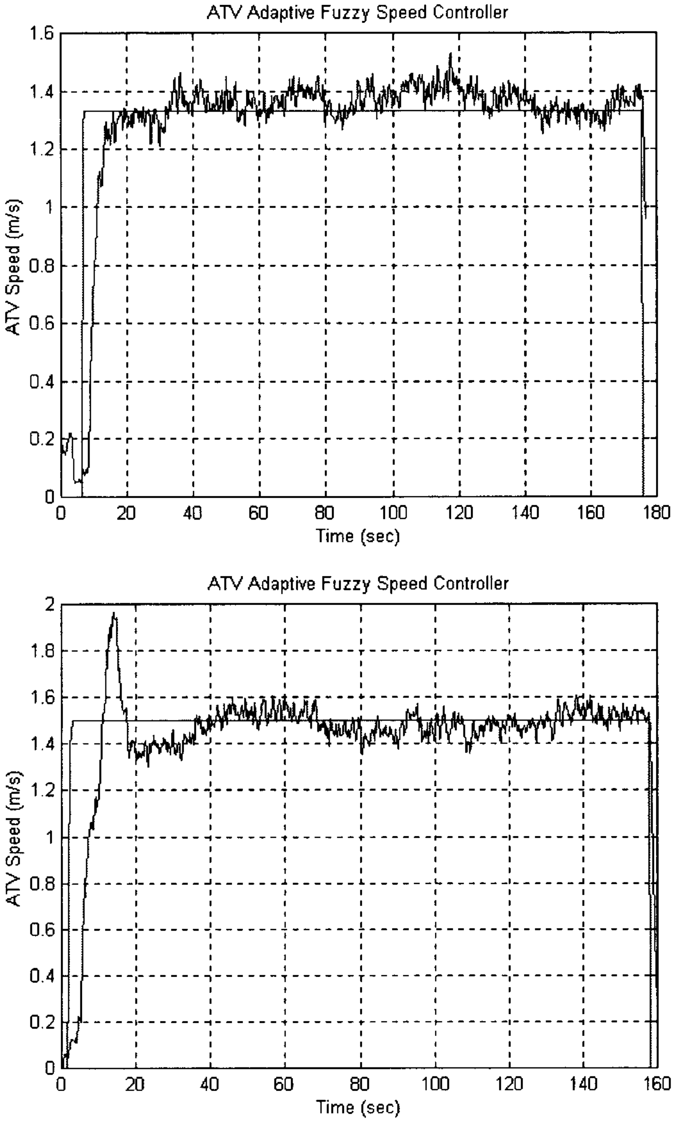

Fig. 11 ATV speed responses for adaptive fuzzy throttle controller for 2.97 mile/h (1.3 m/s) and 3.4 mile/h (1.5 m/s) speed commands

5 CONCLUSIONS

An adaptive fuzzy speed controller for a throttle-regulated internal combustion engine on an ATV was described. The experimental results presented showed the following desirable properties: smooth throttle movement, robustness with respect to varying terrain and commanded speeds in the range 2–30 mile/h. The adaptive fuzzy throttle control algorithm presented here has been implemented on two other ATVs with very little recalibration of the control parameters. The formulation of the fuzzy rules here may be relevant to other practical

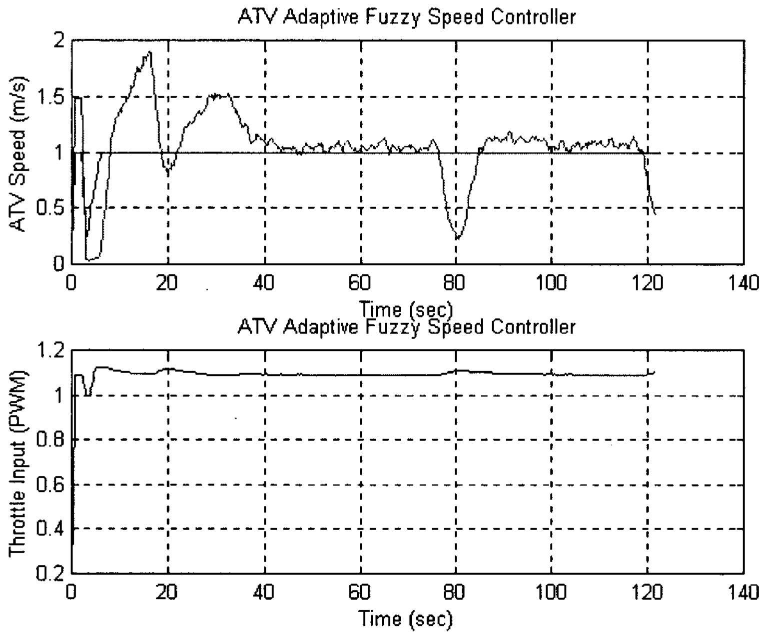

Fig. 12 ATV speed response for an adaptive fuzzy throttle controller for 1.0 m/s speed command

applications where a complete mathematical model is not available.

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REFERENCES

1 **Liubakka, M. K., Rhodes, D. S., Winkelman, J. R.** and **Kokotovic, P. V.** Adaptive automotive speed control. *IEEE Trans. Autom. Control*, 1993, **38**(7), 1011–1020.
2 **Loukianov, A. G., Dodds, S. J., Hosny, W.** and **Vittek, J.** A robust automotive controller design. In Proceedings of the IEEE International Conference on *Control Applications*, Hartford, Connecticut, 1997, pp. 806–811 (IEEE, New York).
3 **Lee, B.-J., Kim, Y.-W.** and **Cho, D.-I.** Engine throttle control using anticipatory band in the sliding phase plane. *IEEE Trans. Control Systems Technol.*, **1**(4), 280–284.
4 **Sommerville, M., Hatipoglu, C.** and **Ozguner, U.** Switching control of a pneumatic throttle actuator. *IEEE Control Systems*, 1998, **18**(4), 81–87.
5 **Manual, P.** *Service Publications, 1995–1996 Magnum and 1996 Sportsman 500*, 1995 (Polaris, Roseau, Minnesota).
6 **Vachtsevanos, G., Farinwata, S. S.** and **Kang, H.** A systematic design method for fuzzy logic control with application to automotive idle speed control. In Proceedings of the 31st IEEE Conference on *Decision and Control*, Tucson, Arizona, 1992, Vol. 3, pp. 2547–2548 (IEEE, New York).
7 **Trebi-Ollennu, A.** Robust nonlinear control designs using adaptive fuzzy systems. PhD thesis, Department of Aerospace and Guidance Systems, School of Engineering and Applied Science, Royal Military College of Science, Shrivenham, Cranfield University, 1996.
8 **Li-Xin, W.** *Adaptive Fuzzy Systems and Control Design and Stability Analysis*, 1994 (Prentice-Hall, Englewood Cliffs, New Jersey).
9 **Trebi-Ollennu, A.** and **White, B. A.** Robust output tracking for MIMO nonlinear systems: an adaptive fuzzy systems approach. *IEE Proc. Control Theory and Applic., Part D*, 1997, **144**(6), 537–544.