

# Adaptive Fuzzy Throttle Control for an All Terrain Vehicle

Ashitey Trebi-Ollennu, John M. Dolan, and Pradeep Khosla  
Carnegie Mellon University, Institute for Complex Engineered Systems  
5000 Forbes Avenue, Pittsburgh, PA, 15213, USA  
[ashitey@cs.cmu.edu](mailto:ashitey@cs.cmu.edu)

## 1 Abstract

This paper describes an adaptive fuzzy throttle control for an All Terrain Vehicle (ATV) powered by an 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 2MPH to 30MPH speed range. 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 2.74MPH (1.2m/s).

**Keywords:** *Fuzzy Control, Adaptive Control, Robotics and Mechatronics*

## 2 Introduction

In the CyberScout project at Carnegie Mellon University's Institute for Complex Engineered Systems, we are developing 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. Autonomous operation of mobile robots requires effective speed control over a range of speeds. In this paper, we present an adaptive fuzzy speed control design and implementation for a throttle-regulated internal combustion engine on an All Terrain Vehicle (ATV), one of the platforms used within the CyberScout project. This is a difficult problem due to significant nonlinearities in the engine dynamics and throttle control.

In the literature several authors have developed automobile speed control systems (cruise control). In [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 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 [2] an automatic speed control system employing self-tuning fuzzy logic rules is outlined. The scheme uses fuzzy logic to tune the speed control characteristics of a vehicle to match individual drivers' preferences. [3] presented a robust stabilizing controller for an internal combustion engine with throttle driven by a DC motor. The control structure consists of two loops, the drive

loop and engine loop. 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. [4] 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 in reducing output chattering in experimental results presented. [5] also presented a switching control scheme for a pneumatic throttle actuator. The sliding surface is defined in terms of throttle plate angle error, since this 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 carburetor, unlike most production vehicles, which have microprocessor-based engine management systems which guarantee maximum engine efficiency and horsepower. Second, the ATV carburetor clearances make 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, the automatic speed control (cruise control) of modern automobiles is generally recommended for use at speeds greater than 30MPH. At speeds below 30MPH most internal combustion engines exhibit considerable torque

fluctuations, a highly nonlinear 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 30MPH. Finally, the ATV throttle is actuated via R/C servo instead of a pneumatic actuator, the preferred actuator in most production vehicles. Although the R/C servo setup has the potential to provide faster and more accurate throttle plate control, it provides no explicit feedback of the servo's angular position.

We propose an adaptive fuzzy throttle control scheme in which 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 3 an overview of the ATV's throttle and power train systems is presented. The engine mathematical model is presented in Section 4. Section 5 outlines the design objectives, Section 6 presents the control law formulation and results, and Section 7 gives conclusions.

### 3 Overview of ATV Throttle Actuation and Power Train System

The ATV is a Polaris Sportsman 500 equipped with a 4-stroke, liquid-cooled engine with a 34mm Mikuni carburetor. The primary input for controlling the speed for an internal combustion engine vehicle is the closing and opening of the throttle plate. As depicted in Figure 1, an R/C servomotor has been introduced in the cable connecting the throttle lever to the throttle plate. This preserves a rider's ability to manually control the throttle using the lever, while allowing autonomous control via the R/C servo. The choice of 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. Vehicle velocity feedback is obtained via a tach generator mounted in the gearbox.

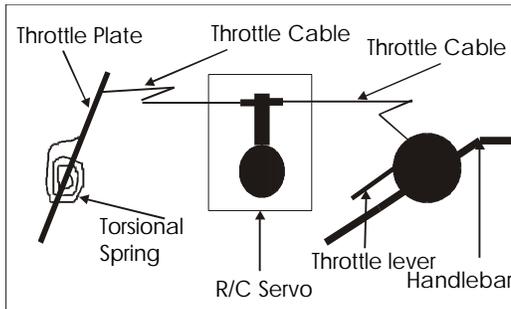


Figure 1 Modified Throttle System including throttle actuator, ATV handlebar and throttle plate

The ATV has an automatic transmission system called the Polaris Variable Transmission (PVT). The PVT changes engine-load requirements by automatically up-shifting or down-shifting and consists of three components: 1) drive clutch, 2) drive belt and 3) 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 an RPM 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 RPM in the face of varying engine loads [6].

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 (5MPH and lower) also tends to induce slippage.

### 4 Engine Mathematical Model

The rotational dynamics of the engine can be modeled as [3]:

$$J_e \dot{N} = T_I - T_f - T_L \quad (1)$$

where  $N$  is engine speed (RPM),  $J_e$  is engine moment of inertia,  $T_I$  is indicated torque,  $T_f$  is the friction torque,  $T_L$  is external load torque (assumed to be constant or slowly varying in comparison with the other variables). Friction torque can be expressed in terms of engine speed as follows

$$T_f = d_1 N + d_2 \quad (2)$$

where  $d_1$  and  $d_2$  are constants. 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. Indicated torque is defined as

$$T_I = c_t \frac{\dot{m}_{ao}}{N}, \text{ where } c_t = \frac{h_e Q_c}{A/F} \quad (3)$$

where  $h_e$  is engine efficiency,  $Q_c$  is combustion heat, and  $A/F$  is air-to-fuel ratio. By substituting equations (3)

and (2) into equation (1) it can be shown that

$$\dot{N} = \frac{-d_1}{J_e} N + \frac{c_t c_e h_{vol}}{J_e} m_a - \left( \frac{d_2}{J_e} - T_L \right) \quad (4)$$

Computing the time derivative of  $\dot{N}$  and substituting for  $\dot{m}_a$  gives, after some manipulation:

$$\begin{bmatrix} \dot{\dot{N}} \\ \dot{N} \end{bmatrix} = \begin{bmatrix} \frac{-d_1}{J_e} & 0 \\ -\frac{c_t c_e h_{vol}^2 m_a}{J_e} & \frac{-d_1}{J_e} \end{bmatrix} \begin{bmatrix} \dot{N} \\ N \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{c_t c_e h_{vol} D_1}{J_e} \end{bmatrix} \mathbf{a} + \hat{E} \quad (5)$$

where higher-order and cross-coupling terms and load torque have been lumped into  $\hat{E}$ .

## 5 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 2MPH to 30 MPH speed range. Additionally, the number of control calibrations for different vehicle applications should be minimal.

## 6 Speed Control Design and Results

The two main challenges in designing an effective speed controller for the ATV are 1) the lack of a complete mathematical model for the engine, and 2) the highly nonlinear nature of the engine dynamics, especially for the targeted low speed range of 3-30MPH. Both of these factors make the use of classical control strategies, such as PID control, ineffective.

One of the main reasons for these challenges is the ATV's carburetor. Carburetors are general calibrated for a fixed range of altitudes and ambient temperatures. Since maximum engine efficiency and horsepower are directly related to proper carburetor setting, any significant changes in altitude and ambient temperatures require recalibration of the carburetor, 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 setup shown in Figure 1. Experiments conducted on level terrain showed that even humans could not easily drive the ATV at constant speeds below 10MPH, shedding light on the nonlinear 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 nonlinearities, including delay, involved with the carburetor control action and the PVT, hunting and overshoot with respect to 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, so 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 carburetor nonlinear characteristics. Nevertheless, a PI controller can be used for higher speeds where the carburetor operation is fairly linear, i.e., throttle openings above one-half and speeds above 15MPH, 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 lookup 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 which we were unable to obtain from the manufacturer. An alternative control approach is fuzzy logic control, 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 ( 5 ).

### 6.1 Fuzzy Logic Speed Control

Fuzzy logic control (FLC) has been demonstrated to solve some practical problems that have been beyond the reach of conventional control techniques. Fuzzy logic control 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 generate control surfaces whose shape can be individually manipulated for different regions of the state space with virtually no effects on neighboring regions.

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

$$\text{Speed Error} = \text{Desired Speed} - \text{Actual Speed} \quad ( 6 )$$

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

$$CTO = \text{Control Input}_{(k-1)T} - \text{Control Input}_{(k-2)T} \quad (7)$$

Discrete time  $t = kT$ , where  $k = 0, 1, 2, \dots, n$ , and  $T$  = the sampling and control update period.

A block diagram of the control structure is shown in Figure 2. Five triangular membership functions were defined for speed error: Negative Large (NL), Negative Small (NS), Zero, Positive Small (PS), and Positive Large (PL). Similarly, three triangular membership functions were defined for CTO: Negative Small (NS), Zero, and Positive Small (PS). Five triangular membership functions were defined for throttle opening: Zero, Small, Medium, Large and Very Large. The ranges of these variables were determined by experimentation and the physical constraints of the sensors employed, e.g., the R/C servomotor input command range is 1ms to 2ms.

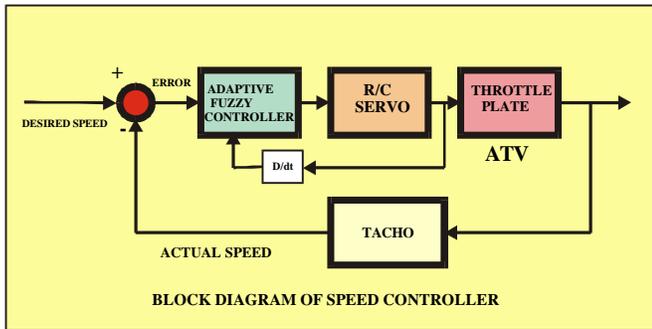


Figure 2 Block diagram of the fuzzy logic control scheme

The complete fuzzy rules are shown in Table 1. The 8th rule is given as an example.

**Rule 8:** *If Speed Error is PL AND CTO is Zero THEN Throttle Opening is Large.*

This rule is fairly intuitive, since if there is a large positive speed error one should open the throttle wider, especially if the throttle opening has changed very little or remained the same from the previous opening, as implied by CTO being 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 was implemented using product inference and a center-average defuzzifier.

Figure 3 depicts the speed response of the ATV using the above fuzzy logic control scheme. There was a fairly large steady state error, but the ATV response was very smooth. Nevertheless, for substantial changes in the terrain (up and down hill) the steady state error was found to increase to an unsatisfactory degree. Several attempts to tune the member functions for fuzzy variables did not significantly reduce the

steady state error, suggesting the need for adaptivity. However, in general, most adaptive control schemes require a fairly good parametric model of the plant to be controlled.

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

Table 1 Fuzzy Rule Table for ATV Speed Controller

Since this was not available, adaptive control schemes that do not require a very accurate model of the plant were considered. Since the fuzzy logic control 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.

## 6.2 Adaptive Fuzzy Speed Control

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

$$R^{(j)} : \text{IF } x_1 \text{ is } A_1^j \text{ and } \dots \text{ and } x_n \text{ is } A_n^j \text{ THEN } y_j \text{ is } C^j \quad (8)$$

where  $\underline{x} = (x_1 \dots x_n) \in N$ ,  $y$  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  $x$  and  $y$  in the universes of discourse  $N$  and  $S$ , respectively, with  $j = 1, 2 \dots Q_R$  (number of rules).

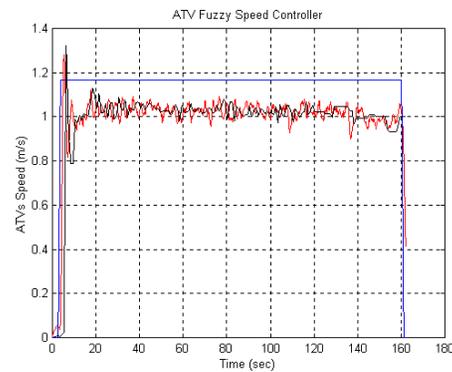


Figure 3 ATV speed response to fuzzy controller, commanded speed 2.3MPH (1.0m/s)

A fuzzy system consisting of a singleton fuzzifier, product inference, center-average defuzzifier and triangular membership functions can be written as [8]

$$f(x) = \frac{\sum_{j=1}^{Q_R} \bar{y}^j \left( \prod_{i=1}^n m_{A_i^j}(x_i) \right)}{\sum_{j=1}^{Q_R} \left( \prod_{i=1}^n m_{A_i^j}(x_i) \right)} \quad (9)$$

where  $f : N \subset \mathfrak{R}^n \rightarrow \mathfrak{R}$ ,  $x = (x_1 \dots x_n)^T \in N$  and  $m_{A_i^j}(x_i)$  is a triangular membership function and  $\bar{y}^j$  is the point in  $S$  where  $m_{c_j}$  is maximum or equal to 1. If the  $m_{A_i^j}(x_i)$ 's and  $\bar{y}^j$ 's are free (adjustable) parameters, then equation (9) can be written as

$$f(x) = \underline{J}^T \underline{\Psi}(x) \quad (10)$$

where  $\underline{J} = (\bar{y}^1, \dots, \bar{y}^{Q_R})$  is a parameter vector and  $\underline{\Psi}(x) = (\bar{y}^1(x), \dots, \bar{y}^{Q_R}(x))^T$  is a regression vector. Equation (10) 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. First, it has been proved in [8] that they are universal function approximators. Second, all the parameters in  $\underline{\Psi}(x)$  can be fixed at the beginning of the adaptive fuzzy system expansion design procedure, so that the only free design parameters are  $\underline{J}$ . 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 analyze and synthesize the performance and robustness of adaptive fuzzy systems.

### 6.2.1 Adaptive Law Synthesis

The engine mathematical model given by equation (5) can be expressed as ;

$$\dot{z} = Az + Bu + E(z) \quad (11)$$

where A is Hurwitz. Therefore there exists a unique positive definite matrix P that satisfies the Lyapunov equation.

$$A^T P + PA = -Q \quad (12)$$

If the control input,  $u$ , is expressed as an adaptive fuzzy system then equation (11) becomes

$$\dot{z} = Az + B\mathbf{J}^T \mathbf{y}(z) + E(z) \quad (13)$$

Let [9], [7],

$$\dot{\hat{z}} = A\hat{z} + B\mathbf{J}^{*T} \mathbf{y}(\hat{z}) \quad (14)$$

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

$$\mathbf{J}^* \equiv \arg \min_{\|\mathbf{J}\| \leq M} \left[ \sup_{z \in \Omega} |u(z | \mathbf{J}^*) - u(z | \mathbf{J})| \right] \quad (15)$$

Then

$$\dot{\mathbf{e}} = A\mathbf{e} + B\mathbf{f}^T \mathbf{y}(\mathbf{e}) + \hat{\mathbf{E}} \quad (16)$$

where  $\mathbf{f} = \mathbf{J} - \mathbf{J}^*$ . To derive a control law that ensures that  $\mathbf{e} \rightarrow 0$  as  $t \rightarrow \infty$ , a candidate Lyapunov function is defined as [7, 8];

$$V = \frac{1}{2} \left( \mathbf{e}^T P \mathbf{e} + \frac{\mathbf{f}^T \mathbf{f}}{\mathbf{g} \|\hat{\mathbf{E}}\|} \right) \quad (17)$$

where  $\mathbf{g} > 0$  is a design parameter. The time derivative of V is

$$\dot{V} = -\mathbf{e}^T Q \mathbf{e} + \mathbf{e}^T P B (\hat{\mathbf{E}} + \mathbf{f}^T \mathbf{y}(\mathbf{e})) + \frac{\mathbf{f}^T \dot{\mathbf{f}}}{\mathbf{g} \|\hat{\mathbf{E}}\|} \quad (18)$$

Now choosing the adaptive law (recalling that  $\dot{\mathbf{f}} = \dot{\mathbf{J}}$ )

$$\dot{\mathbf{J}} = -\mathbf{g} \|\hat{\mathbf{E}}\| \mathbf{e}^T P B \mathbf{y}(\mathbf{e}) \quad (19)$$

It can be shown that if  $\|\hat{\mathbf{E}}\|$  is selected such that

$$\|\hat{\mathbf{E}}\| \geq \frac{\mathbf{I}_{\min}(Q) \|\mathbf{e}\|^2 - \mathbf{a} \|\mathbf{e}\|}{\|\mathbf{e} P B\|} \quad (20)$$

where  $\mathbf{a} > 0$ , substituting for  $\hat{\mathbf{E}}$  in equation (20) gives

$$\dot{V} \leq -\mathbf{a} \|\mathbf{e}\| \quad (21)$$

Therefore the control law of equation (19) will ensure that the state  $\mathbf{e}$  converges.

To implement the above adaptive fuzzy control law, the fuzzy rule Table 1 was used and the insight gained from the non-adaptive fuzzy logic control was used to select the  $\underline{J}$  values to lie within the interval [1.0, 2.0]. The remaining control parameters were set as follows:  $Q = \text{diag}(3,3)$ ,

$$\hat{E} = 120, \underline{g} = 0.00025, e = \text{Desired Speed} - \text{Actual Speed}.$$

$\Psi(e)$  was formulated using the IF part of fuzzy rule Table 1. The adaptive fuzzy controller was also implemented on the ATV. Figure 4 depicts the ATV speed responses to selected speeds. Significant improvement can be observed with respect to steady state error and disturbance rejection (load and terrain). Figure 5 depicts the ATV's response to a speed command of 2.3MPH (1.0m/s), a very slow speed. As can be observed from the ATV's response, there is an overshoot, and it takes about 30 sec for the speed to settle. The ATV is back-heavy, so that when it is on a slight incline, considerable momentum is required to initiate motion. At about 80 sec (Figure 5) there is a considerable drop in the ATV's speed to well below the commanded speed of 1.0m/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.

## 7 Conclusions

We have developed an adaptive fuzzy speed controller for a throttle-regulated internal combustion engine on an ATV. Experimental results presented showed the following desirable properties: smooth throttle movement, robustness with respect to varying load and terrain, and good tracking of commanded speeds in the range 2MPH to 30MPH. 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 applications where a complete mathematical model is not available.

## 8 References

1. M. K. Liubakka, D.S.R., J. R. Winkelman and P. V. Kokotovic, *Adaptive Automotive Speed control*. IEEE Transactions on Automatic Control, 1993. **38**(7): p. 1011-1020.
2. Takahashi, H. *Automatic Speed Control Device Using Self-Tuning Fuzzy Logic*. in *IEEE*. 1988.
3. Alexander G. Loukianov, S.J.D., Wada Hosny and Jan Vittek. *A Robust Automotive Controller Design*. in *IEEE International Conference on Control Applications*. 1997. Hartford, CT, USA.
4. Byeong-Jo Lee, Y.-W.K.a.D.-I.C., *Engine throttle control Using Anticipatory Band in the Sliding Phase Plane*. IEEE Transactions on Control Systems Technology, 1993. **1**(4): p. 280-284.
5. Martin Sommerville, C.H.a.U.O., *Switching control of a*

*Pneumatic Throttle Actuator*. IEEE Control Systems, 1998. **18**(4).

6. Manual, P., *Service Publications, 1995 -1996 Magnum & 1996 Sportsman 500*. 1995: Polaris.

7. Trebi-Ollennu, A., *Robust nonlinear control design using adaptive fuzzy systems*, Ph.D Thesis, in Department of Aerospace & Guidance Systems, School of Engineering & Applied Science, Royal Military College of Science, Shrivvenham. 1996, Cranfield University.

8. Li-Xin, W., *Adaptive Fuzzy Systems and Control Design and Stability Analysis*. 1994: Prentice Hall.

9. Feng, G. *Improved Tracking Control for Robots Using Neural Networks*. in ACC. 1993.

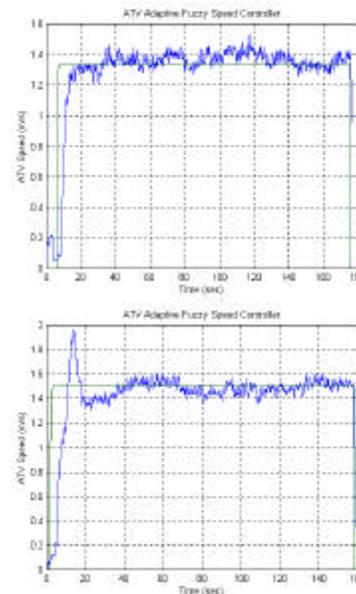


Figure 4 ATV speed responses for adaptive fuzzy throttle controller for 2.97MPH (1.3m/s) and 3.4MPH (1.5m/s) speed commands

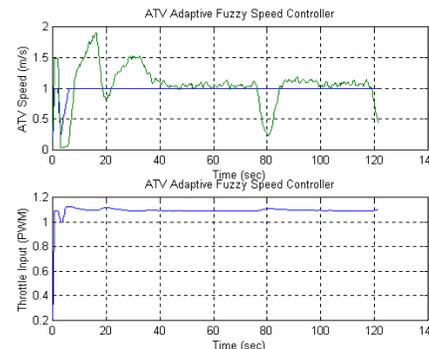


Figure 5 ATV Speed response for adaptive fuzzy throttle controller, 1.0m/s speed command