Fuzzy-GSA Based Control Approach for Developing Adaptive Cruise Control

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Abstract: Adaptive Cruise Control (ACC) controls vehicle speed and its distance to the proceeding vehicle in the same lane. In this paper a two-level control architecture is proposed to control both velocity and distance to the leading vehicle by taking advantage of fuzzy logic control (FLC) approach. Then the control parameters were tuned by Gravitational Search Algorithm (GSA) to ensure achieving the fastest and most accurate control response. To evaluate performance of the proposed scheme, a speed profile was developed in simulation based test platform to measure performance of the proposed ACC in different maneuvers including some velocity tests and a distance control maneuver. The results revealed that the proposed approach had a stable and fast response which satisfied the requirements of an ACC.

Keywords: Adaptive cruise control, Distance control, Fuzzy logic control, Velocity control

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1 INTRODUCTION

Advanced Driving Assistant System (ADAS) is a mechatronics based structures that provide drivers with a safe and efficient driving. Many researches have been dedicated to develop ADAS under variety of study fields [1-8]. Cruise control is one of the most prominent ADAS systems that tries to control vehicle's longitudinal dynamics. The system is linked to vehicle longitudinal control which has been studied for more than 40 years [9-16]. Since cruise control has been commercialized, Toyota, Nissan, BMW, Lexus, and Mercedes companies have offered cruise control with their luxury models.

The cruise control systems are classified into Conventional Cruise Control (CCC), and Adaptive Cruise control (ACC). The CCC architecture receives a reference speed defined by the driver and tries to keep the vehicle's speed at predefined speed. To this end, the control system receives the vehicle's actual speed as an input; then accord to speed error, which is defined as the difference between reference speed and actual speed, the throttle and brake actuators are regulated in such way that reference speed would be achieved.

Due to increasing traffic density, the CCC modules have been less and less practical, because driving at a predefined speed may lead to front end collisions. Hence, ACC is introduced as a solution to this shortcoming. The ACC operates in same manner as CCC; however, the new module keeps a safe headway between the cars moving on the same lane. This goal is met by taking advantages of radar based sensors and signal processing unit.

Note that, the paper has addressed the ACC-equipped, and radar detected vehicles as host and target vehicle respectively. During operation, when distance to the target vehicle or fixed obstacle is reduced to unsafe value, the control unit actuates the braking unit and/or engine to reduce speed and consequently keep the safe gap with the target vehicle. Since the target vehicle starts accelerating, the control unit regulates the throttle actuator and reaccelerates to resume the reference speed. Such a system not only removes the routine and tedious tasks of driver but also improves the driving safety by keeping the safe gap between target and host. Fig. 1 shows schematic of ACC operation.

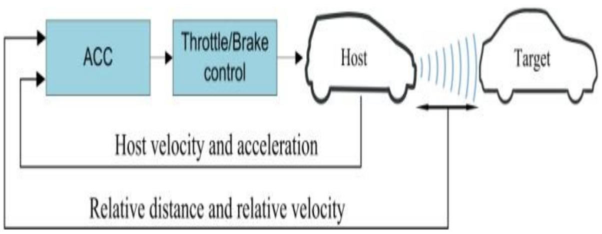


Fig. 1 Schematic of ACC operation

Studies show that ACC can enhance traffic flow by increasing traffic density. Moreover, the ACC can result in pollution reduction and improvement in energy consumption through automation [17-21]. Although many ACC are developed based on pure mathematical models [22-28], the control object, which is the vehicle's power train system, is a highly nonlinear element and precise mathematical representation of the system is not a feasible task [20], [21]. Hence, the alternative is adopting artificial intelligence based techniques such as artificial neural networks and fuzzy logic [16], [20], [21], [29-35].

Fuzzy logic is a powerful popular solution that is categorized in artificial intelligence class. The method first was presented by L. A. Zadeh [36]. E. H. Mamdani [37] was the first one who used fuzzy logic in a real control application. The basic idea behind fuzzy logic comes from formulating human reasoning and intelligence into simple if-then rules. So it offers a qualitative description of system rather than mathematical-numerical representation. Unlike model based controllers, FLC can handle measurement inaccuracies and also errors. The FLC has a long history and has been used to control air vehicles [38-40], railways [41], [42], and cars [43], [44].

The paper proposed using a FLC as control scheme of ACC. Since the FLC is decided to be used as the controller, the parameters of FLC should be determined firstly. Although parameters of FLC are usually determined accord to expert knowledge, the design process can be considered as an optimization problem to ensure achieving the best results [29], [40], [44]. The optimization process tries to determine the rules and/or optimal geometric shape of fuzzy sets [44].

Since the objective function is complicated and highly nonlinear that contains several local optimums, the optimization algorithm may fail to discover the global solution by getting stocked in local optimums. To ensure achieving the best solution, using a viable optimization algorithm is essential.

Over the last decade there has been an increasing demand for applying search algorithms based on behavior of natural phenomena. A novel optimization algorithm is proposed by E. Rashedi [45] which is introduced as Gravitational Search Algorithm (GSA). The main idea behind GSA is law of gravity; it is inspired by attraction among physical objects and it has proved to have a good performance in solving wide variety of problems [46].

Since the GSA is proved to be a powerful approach compared to other search algorithms [45], the paper has chosen this search algorithm as optimization approach to explore the best parameters of FLC. So, a Fuzzy-GSA approach is proposed as control unit of ACC. To this end, a simulated vehicle model is considered as test platform and the proposed control approach is implemented into the model. Then, simulations were accomplished to evaluate the effectiveness of proposed approach.

The rest of the paper is organized as follow. The control objectives and control strategies implemented in ACC are described in section two. The structure of controller is introduced in section three. Details around design of velocity and distance FLCs are given in section four. Section five is dedicated to optimization process, and finally simulation results are provided in section six.

2 DRIVING STRATEGY OF ACC

Adaptive cruise control which is also known as Autonomous Cruise Control too, can control vehicle velocity, and its distance to the target vehicle. This goal is achieved by regulating two actuators. Since the first is throttle valve, which controls the air pressure of the engine, the second is brake hydraulic regulator which is responsible for deceleration. Regulating the actuators, results in three following modes. The first mode is acceleration which is resulted by opening the throttle valve. The second is light deceleration achieved by closing the throttle valve, and the last scenario is severe deceleration which is achieved by actuating brake hydraulics system.

For developing ACC, the following strategies have been taken into account. As long as radar based sensor detects no target vehicle, the ACC operates in velocity control domain in which the ACC tries to set vehicle velocity at reference speed just like a CCC. As soon as a slower target appears in radar coverage zone, ACC starts operating in distance control domain and keeps a safe distance with the target vehicle. In distance control mode, if the target velocity exceeds the reference speed and/or the target is disappeared from radar coverage range, then the ACC will switch to velocity control mode again. In case the slower target accelerates but its velocity is still lower than reference speed, then the ACC will reaccelerate while considering safe gap criteria at the same time; it should be noted that the ACC is still operating in distance control mode. If the target reduces speed, the ACC will also reduce speed in such way that safe gap regulations would be met. In addition, when the safe gap is decreased below critical limit, the driver is warned by an alarm.

3 CONTROLLER ARCHITECTURE

The proposed ACC is composed of two basic controllers including a velocity controller and a distance controller both of which are working together. Since, two controllers are working independently in a parallel manner there must be an upper level control unit to make appropriate connection between the two. To this end, a two level hierarchical control structure is proposed. Fig. 2 illustrates hierarchical structure of controller.

With the proposed hierarchical structure, as long as the first level is deciding over long-term control strategies, which are velocity control domain and distance control domain, the lower level is responsible for short-term control strategies which are accelerating and braking. The lower level is composed of two different subsystems. The first is velocity control unit which is responsible for stabilizing vehicle velocity to reference speed. The performance of velocity control unit is the same as CCC's. The later is distance control unit that its goal is to keep a safe gap between two vehicles in case of detecting target vehicle.

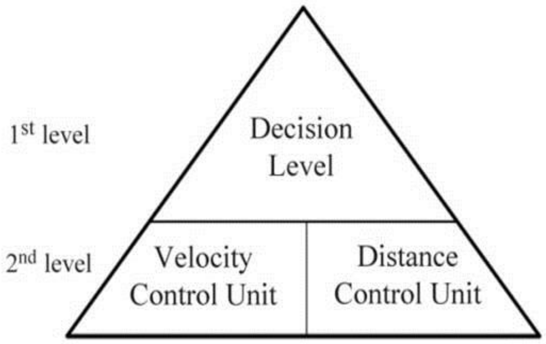


Fig. 2 Hierarchical structure of ACC

4 DESIGN OF FUZZY LOGIC CONTROLLER

Since the structure of controller is determined, the next step is developing velocity and distance controllers.

4.1. Developing velocity controller

The velocity controller task is to follow the reference speed. It is assumed the vehicle is equipped with speed sensor that measures the speed of the host, and also a radar sensor that detects the relative distance of target vehicle. The reference speed is a fixed speed determined by the user. Since the reference speed is given, the velocity of host is achieved through speed sensor. Fuzzy controller receives velocity error and error derivative as input. According to Eq. (1), the velocity error is defined as difference of vehicle velocity and reference speed.

$$e_v(t) = V_h(t) - V_{ref} \tag{1}$$

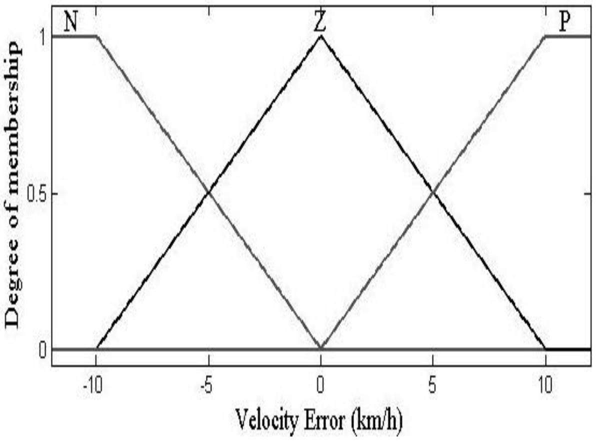
where $e_v(t)$ denotes velocity error related to host vehicle, t is time, and V_{ref} and V_h stand for reference speed, and velocity of host respectively. The other input that controller receive is derivative of velocity error (e'_v) which is acceleration.

$$e'_v = \frac{dV_h(t)}{dt} \tag{2}$$

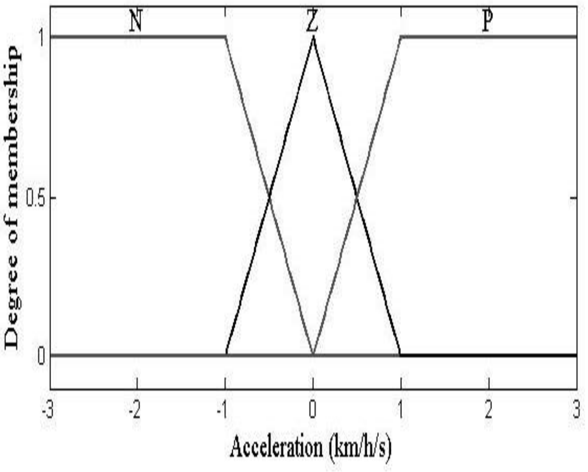
In this paper, Mamdani type fuzzy model is used to develop velocity, and distance controllers. The velocity controller regulates the throttle and brake systems based on error, and error derivative.

According to Fig. 3-a, the velocity error is fuzzified with three Membership Functions (MFs). Membership function N represents negative amount of velocity error that regards where vehicle velocity is smaller than reference speed; in other word, N is responsible for condition that vehicle velocity has not reached reference speed yet. In the same manner, the P represents positive amount of velocity error. The membership function Z fuzzifies zero velocity error which shows condition where vehicle velocity is around reference speed. In order to improve efficiency of the controller, the velocity error range is limited to [-12*km/h*, +12*km/h*].

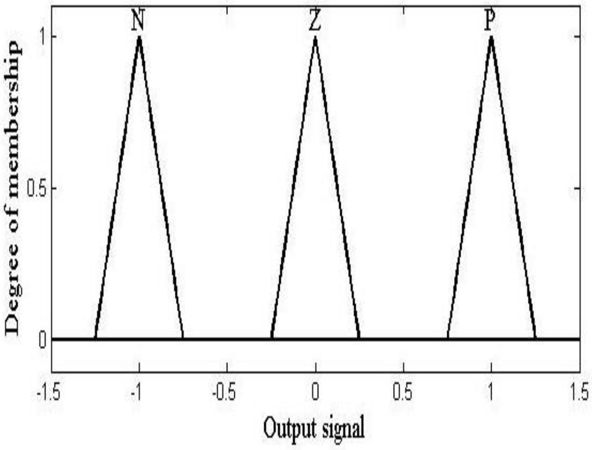
Fig. 3-b depicts MFs of error derivative. Although measurement units do not affect the control task, for easy understanding of acceleration value, the paper used km/h*s instead of typical m/s^2. The P is responsible for acceleration which is achieved through opening the throttle valve; and N reflects deceleration that is resulted by closing the throttle valve and/or regulating the brake system. Finally, Z refers to zero acceleration condition. Fig. 3-c demonstrates fuzzy output MFs. While Z corresponds to no regulation in throttle valve and brake actuator, P and N result in acceleration and deceleration respectively.



(a)



(b)



(c)

Fig. 3 MFs of velocity controller, (a): velocity error, (b): acceleration and (c): fuzzy output

Fuzzy rules are represented in Table 1. As an example, if velocity error is negative and error derivative is negative, then the output would be P which results in wide opening of throttle valve.

Table 1 Fuzzy rules related to velocity controller.

		Velocity error		
		N	Z	P
Error derivative	N	P	—	N
	Z	P	Z	N
	P	P	—	N

Applying the aforementioned setting, the following fuzzy decision surface would be achieved.

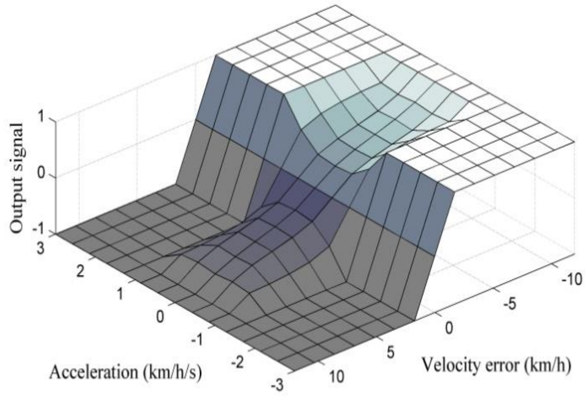


Fig. 4 Fuzzy decision surface.

4.1. Developing the distance controller

Behavior of human driver for keeping safe distance is most affected by relative distance and relative velocity between host and target vehicles. The relative distance is defined in the following equation.

$$d_{rel}(t) = x_t(t) - x_h(t) \quad (3)$$

where d_{rel} is relative distance between two vehicles, x_t, and x_h are target, and host positions respectively. Let V_{rel} to be relative velocity between host and target, then Eq. (4) describes the relative velocity between host and target.

$$V_{rel}(t) = V_h(t) - V_t(t) \quad (4)$$

where V_t denotes velocity of target. Since the radar sensor gives the relative distance, the relative velocity can be obtained from Eq. (5) too.

$$V_{rel}(t) = -\frac{dx_{rel}(t)}{dt} \quad (5)$$

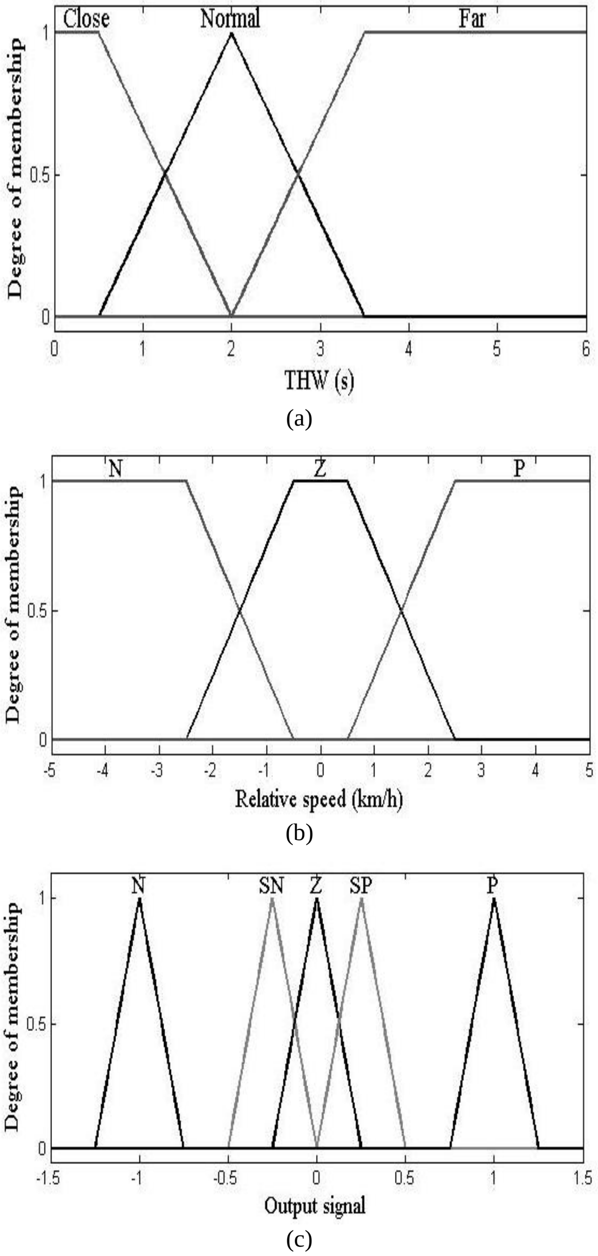
Safe distance is a variable rather than being a constant parameter; and its value depends on value of relative velocity. In order to have a constant parameter instead of a velocity-dependent parameter, the paper has adopted Time Headway (THW) idea instead of safe distance; THW represents time gap between two vehicles. There are three parameters taken into account of THW including Time to Collision (TTC), braking time, and driver's response delay. Using TTC parameter, distance headway can be translated to time headway between two vehicles. The TTC parameter is expressed in the following equation.

$$TTC = \frac{d_{rel}}{V_h} \quad (6)$$

The next parameter considered in THW includes braking time which is defined as the time spent to reduce the host velocity to target velocity.

$$t_{brk} = \frac{(V_h^2(t) - V_t^2(t))}{2.\mu.g.V_{rel}} \quad (7)$$

In which, t_{brk} is braking time, μ refers to tire-road friction coefficient and g is gravitational acceleration.



(a)

(b)

(c)

Fig. 5 Fuzzy sets related to distance controller, (a): THW, (b): relative velocity and (c): fuzzy output.

The last parameter included in THW is human response behavior; considering the fact response of human driver is tied to delay, thus delay time (T_{dl}) is inserted into equation. Delay time is defined as time between realization and manipulation. Hence, the THW parameter can be expressed as follow.

$$THW = \frac{d_{rel}}{V_h} - \frac{V_h^2(t) - V_t^2(t)}{2.\mu.g.V_{rel}} - T_{dl} \qquad (8)$$

THW is a control parameter that can take a value from 1.0 to 2.0 sec. The paper considered 2.0 sec as safe value. By using the last formula, THW is not only related to TTC but also is sensitive to driver response delay and also relative velocity between host and target. Considering THW as a constant, according to Eq. (8), the greater relative velocity results in bigger relative distance; and this fact is totally in agreement with normal behaviour of human drivers.

To arrange distance controller, the THW and relative velocity are received as input to the controller. MFs of THW are depicted in Fig. 5-a. Z fuzzifies values of THW which are around predefined 2.0 sec limit. Close, and Far are responsible for cases where THW is reduced below, and increased above specified limit. The other input, which is relative velocity, is fuzzified according to Fig. 5-b. The N, P, and Z are responsible for relative speed when the value is negative, positive, and zero respectively. Fuzzy rules are also available in table 2; and Fig. 6 depicts the fuzzy decision surface.

Table 2 Fuzzy rules related to distance controller.

		THW		
		close	Normal	Far
Relative veolcity	N	N	SP	P
	Z	N	Z	P
	P	N	SN	P

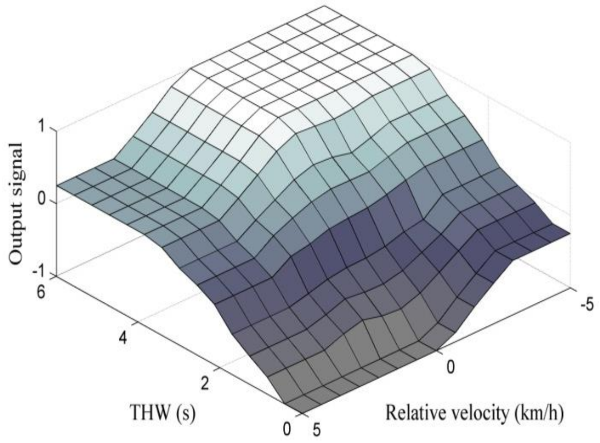


Fig. 6 Fuzzy decision surface

5 OPTIMIZATION OF FUZZY CONTROLLER

The FLC described in former section was developed based on expert knowledge. Since the nature of problem is nonlinear and complicated, the developed controller is not optimal essentially. To tackle this fact, an optimization process is required to optimize controller parameters. Considering nonlinear nature of the problem, the paper has adopted Gravitational Search Algorithm (GSA), which is a viable search algorithm for solving complex problems, to quest the best parameters of controller. To this end, as illustrated in Fig. 7, the controller parameters first tuned offline by GSA; then, according to Fig. 8, the optimized controller would be adopted to perform task of control.

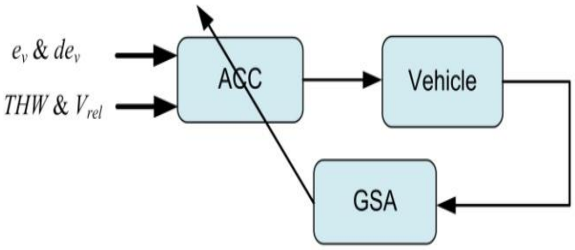


Fig. 7 Offline tuning of controller parameters

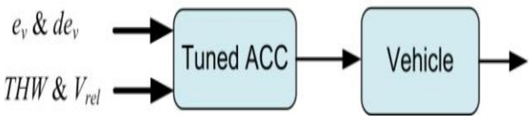


Fig. 8 Using optimized parameters for ACC

5.1. Coding

In order to achieve an optimal FLC, all defining parameters should be coded into a string. Handling the greater number of parameters by optimization algorithm will increase chance of achieving global best solution. However, increasing length of string will result in some bad outcomes. The longer string requires more number of search agents and generations, which results in longer computational time. Besides, since many fuzzy rules are of conflicting nature with each other, expert knowledge may cannot interpret the optimized FLC. Taking into account the aforementioned drawbacks, some FLC parameters are handled by expert person instead of being handled by optimization algorithm.

Basically two crucial degrees of freedom in designing a FLC are rule base and MFs. Since fuzzy rules are limited to maximum nine rules, the paper handled its parameters based on trial and error and perception of expert knowledge about the problem; consequently, in this paper the fuzzy rules are fixed and optimization algorithm just tunes the parameters of MFs.

The fuzzy inputs of velocity controller consist of trapezoidal and triangular MFs. In order to further reduce string length in optimization algorithm, the sides of triangular MF are aligned to those of adjacent trapezoidal MFs. Fig. 9 demonstrates this technique.

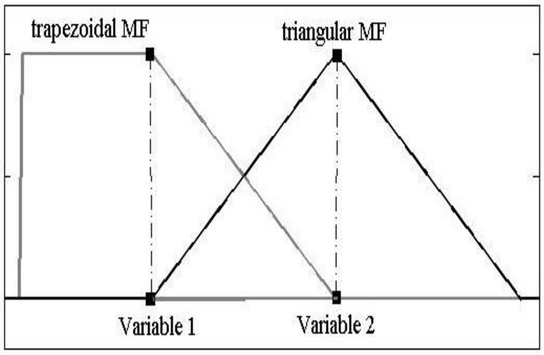


Fig. 9 Aligning triangle side, to side of adjacent trapezoid.

By using this technique, the number of string variables is decreased to half, so that a computationally more efficient optimization process can be achieved.

5.2. Problem formulation

At this stage, the FLC design problem should be turned into an optimization problem which can be handled by GSA. The goal of control action is to exactly follow the speed of drive cycle. The speed profile chosen to perform optimization is STEPS cycle which is presented in Fig. 10. The cycle contains a set of regularly increasing then decreasing steps which gives opportunity to evaluate performance of the controller at different speed levels.

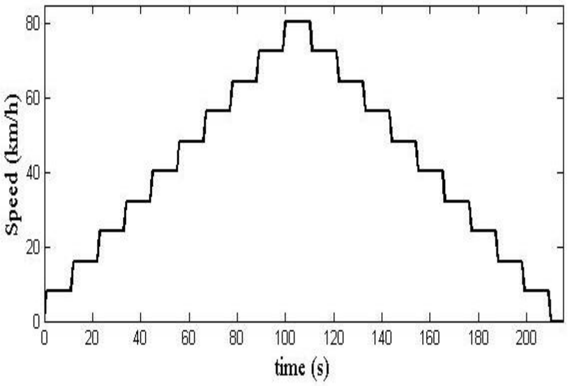


Fig. 10 Speed profile of STEPS cycle

In order to achieve the best solution, objective function is of crucial importance. Since the control response is susceptible to oscillation, the number of ripples at each step is included in objective function as a variable to be minimized. In addition, in order to take into account, the magnitude of the ripples, area of the ripples is another parameter considered as an objective to be reduced. Fig. 11 demonstrates two parameters considered as objectives.

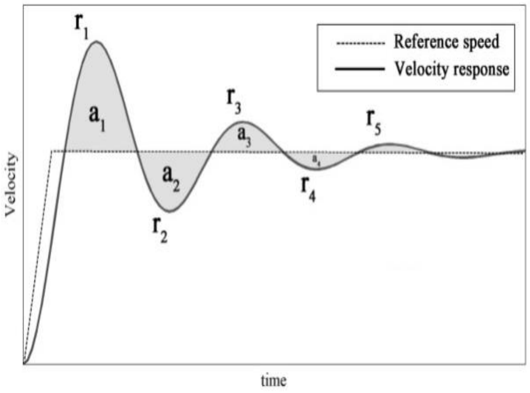


Fig. 11 Number of ripples (n) and ripples' area (a) in step response

Finally, for avoiding delayed response, area between velocity response and drive cycle velocity is taken into account of objective. Fig. 12 illustrates the area assigned to late response. At the end, the objective function is represented in Eq. (9).

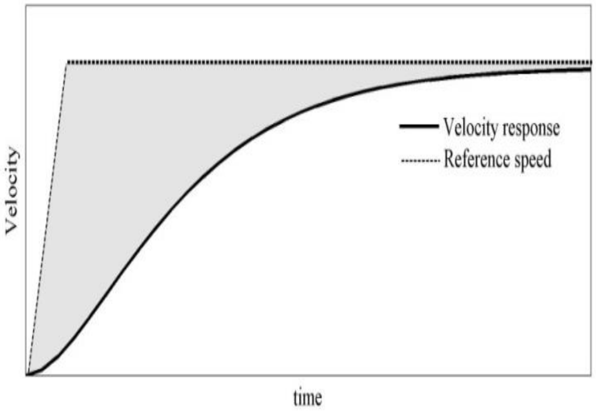


Fig. 12 Area considered in objective function for delayed response

$$obj(x) = w_1.n_{ripple} + w_2.\int_0^{T_{DC}} a_{ripple} + w_3.\int_0^{T_{DC}} \left(V_{cycle} - V_h\right) \tag{9}$$

In which, w1, w2, and w3 are weighting factors that are determined based on trial and error. n_{ripple} denotes number of ripples in entire cycle, a_{ripple} refers to cumulative area of ripples, and TDC is the driving cycle time. V_{cycle}, stands for the velocity of speed profile which is called reference speed.

5.2. Gravitational Search Algorithm

GSA is a novel heuristic search algorithm that searches the solution based on Newtonian law of gravity, and also law of motion. According to law of gravity, there is an attraction force among every two objects which is represented as follow.

$$F = G.\frac{m_1.m_2}{R^2} \quad (10)$$

Where F is induced gravitational force, G denotes gravitational constant, and R refers to euclidean distance between two objects. m_1, and m_2 are corresponding mass of first and second objects respectively. In addition, the gravitational constant is a function of time. Decreasing of the gravitational constant with time is described as follow.

$$G(t) = G(t_0).({}^{t_0}\!/_{t})^{\beta} \quad (11)$$

Where β is a constant, $G(t)$ is gravitational constant at time t, and $G(t_0)$ refers to its initial value at time t_0. The GSA assumes the search agents as mass particles and the particle's fitness is related to its mass. According to Eq. (10), the bigger and closer particles tend to induce greater attraction force. Since the particle is exposed to attraction force, it will start accelerating toward other particles according to Newton's second law of motion as represented in Eq. (12). The acceleration achieved (a) is directly proportional to applied force (F) and inversely proportional to particle mass (m).

$$a = \frac{F}{m} \quad (12)$$

The GSA first generates initial particles randomly. As shown in Eq. (13), the particles' masses are calculated based on their fitness with respect to the best and the worst fitness in population.

$$m_i = \frac{fit_i(i) - fit(w)}{fit(b) - fit(w)} \quad (13)$$

Where, $fit(i)$, $fit(w)$, and $fit(b)$ are fitness of i-th, the worst, and the best particles, and mi denotes mass of i-th particle. At next stage, the gravitational interaction among particles is analyzed, and force applied on each particle is calculated. Then, by using law of motion, amount of acceleration for each particle would be achieved. Due to the resultant acceleration, the particles move to new positions. The next iteration continues by evaluating mass of rearranged particles. The iterations go on until stopping criteria is met. Eventually, the biggest particle would be reported as the best solution. Fig. 13 shows the operating principle of GSA.

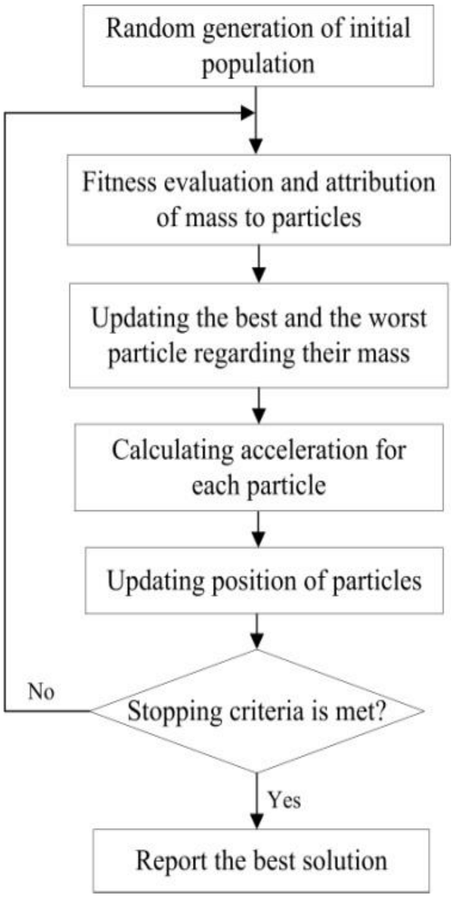


Fig. 13 Operating principle of GSA

6 RESULTS

In this section, the proposed controller is analyzed in a simulation platform. The controller is implemented in a vehicle control system in order to evaluate its performance. The simulated platform is composed of a conventional powertrain with an 82kw IC-engine and a 5-speed automatic transmission.

6.1. Performance of velocity controller before tuning

The velocity controller developed in section 4.1, was analyzed in simulation platform. It should be noted that the controller used at this part, has not been tuned by optimization algorithm yet. To evaluate performance of proposed controller, the steps speed cycle introduced in section 5.2, was modified to be adapted for test application of ACC scheme. The proposed speed profile, which is used as reference velocity to the ACC, is presented in Fig. 14. The characteristic parameters of proposed speed profile are available at table 3.

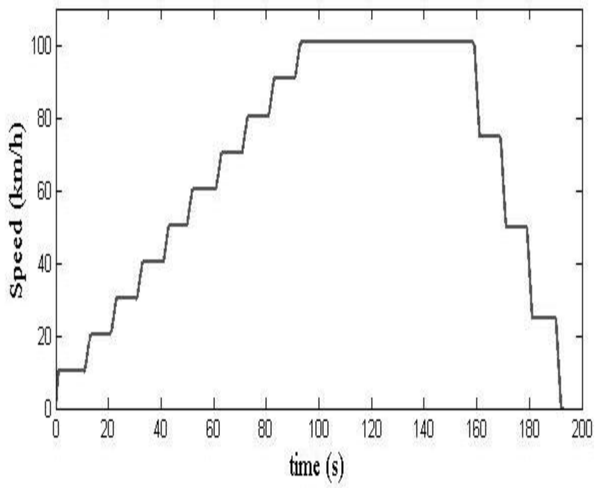


Fig. 14 The proposed speed profile for analyzing the ACC

Table 3 Characteristics parameters of the proposed speed profile

Parameter	Value
time	193 s
distance	3.59 km
max speed	100 km/h
avg. speed	65.5 km/h
max acceleration	2.8 m/s^2
max deceleration	-3.8 m/s^2

Using the explained speed cycle, the velocity controller was analyzed. Fig. 15 shows speed profile achieved by vehicle during simulation.

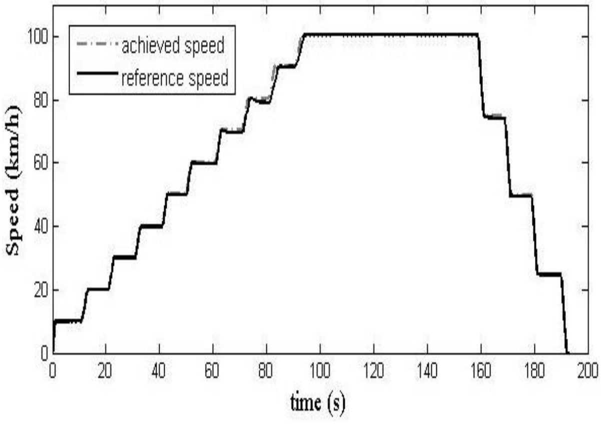


Fig. 15 Speed profile achieved by adopting velocity controller before optimization

The figure reveals that the reference speed profile is not exactly traced. For more detailed studying, missed trace parameter ($trace_{miss}$) is introduced in Eq. (14). This parameter refers to difference between reference speed (V_{ref}) and achieved speed (V_{actual}) respect with time. The missed trace resulted by velocity controller is depicted in Fig. 16.

$$trace_{miss}(t) = V_{ref}(t) - V_{actual}(t) \tag{14}$$

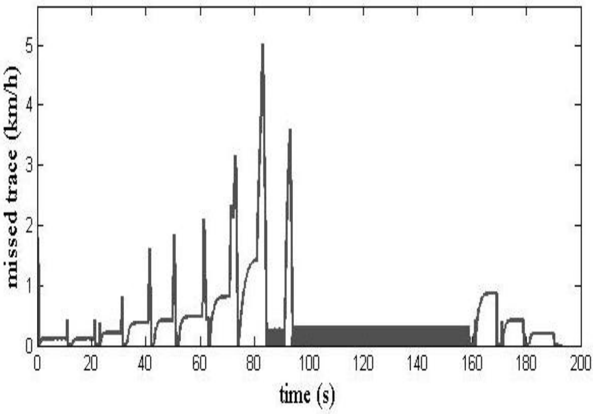


Fig. 16 Missed trace resulted by velocity controller

As figure shows, the missed trace profile contains ripples, instabilities and several picks. Basically, the picks have happened at steps edges of speed profile. Eventually, it can be concluded that the controller does not offer stability and smooth behavior.

6.2. Performance of velocity controller after optimization

The optimization process was carried out by taking number of particles and generations equal to 25, and 40 respectively. Fig. 17 depicts diagram of best fitness against generations in optimization process.

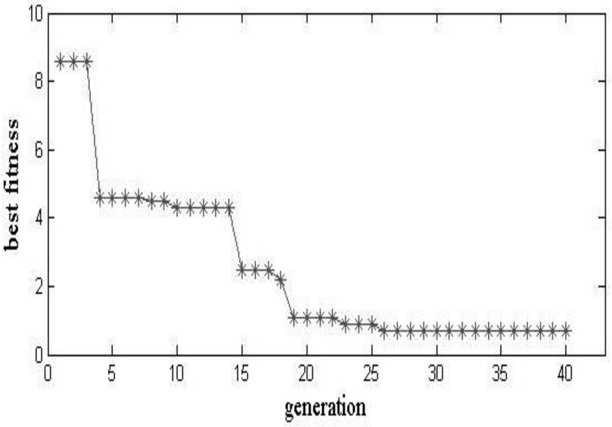
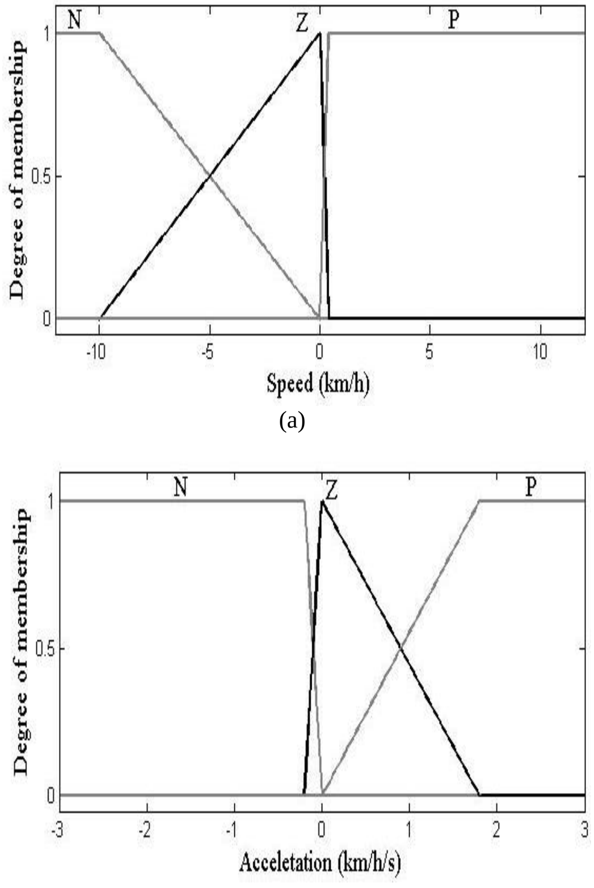


Fig. 17 Convergence diagram of objective function over 40 generations

Since the parameters of MFs was tuned, the shape of MFs and consequently the fuzzy control surface is changed. Figs. 18, and 19 represent updated MFs and fuzzy control surface of velocity controller after optimization.



(a)

(b)

Fig. 18 MFs of velocity controller after tuning, (a): velocity error MFs, (b): acceleration MFs

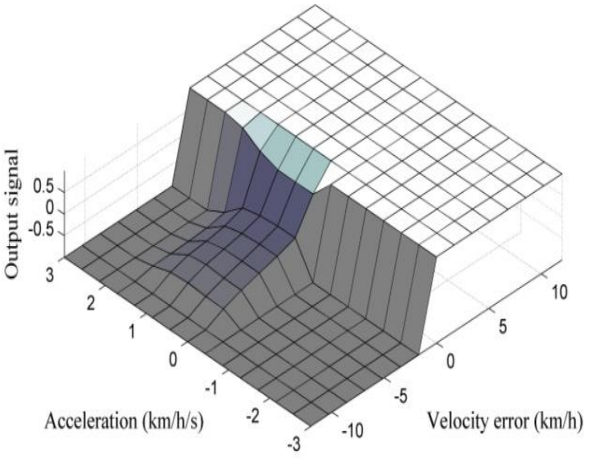


Fig. 19 Optimized Fuzzy control surface related to velocity controller

The optimized velocity controller is analyzed by using the speed profile presented in Fig. 14. The speed profile was given as input to the velocity controller and results are provided in figures 20, and 21.

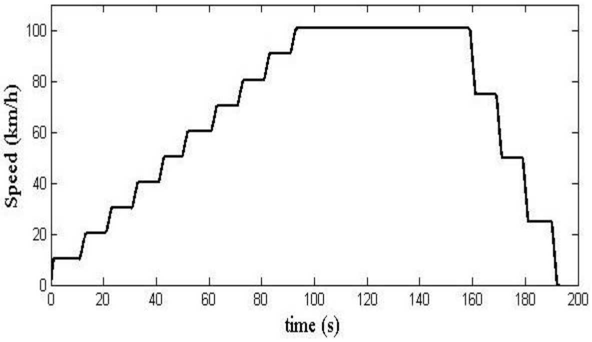


Fig. 20 Speed profile achieved by adopting optimized velocity controller

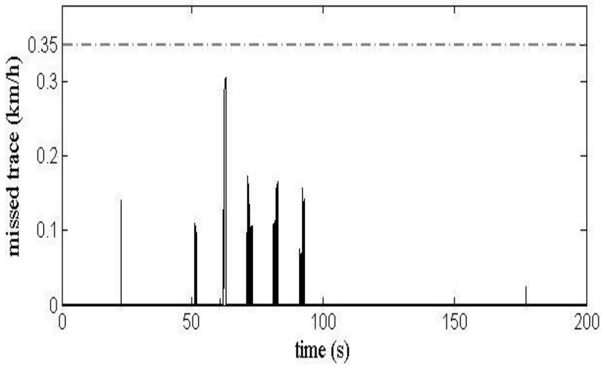


Fig. 21 Missed trace resulted by velocity controller after optimization

As shown in the figures the diagram represents a stable response. In addition, the maximum missed trace is smaller than 0.35 km/h. The missed trace took place at edges of drive cycle steps where the speed level changes at once, and the engine power is not enough to provide required acceleration.

6.3. Performance evaluation of ACC

In the last stage, the velocity and distance controllers are unified to make the ACC. For analyzing performance of the developed ACC, a comprehensive test procedure was carried out. The test procedure uses the developed speed profile to analyze velocity controller result. However, in order to evaluate performance of distance controller, another test scenario is considered in speed profile. The test scenario stars by appearing a target vehicle at time of 100 second respect with beginning of the speed profile. While velocity of host is 100 km/h, target drives at steady velocity equal to 60 km/h. Then, 40 seconds later the target disappears from radar coverage zone.

Since the target is detected, the host is supposed to reduce velocity to 60 km/h while satisfying THW requirements. Once the target is disappeared, the host should reaccelerate and resume to reference speed. Figures 22, and 23 demonstrate speed profile that is achieved by host, and THW respectively.

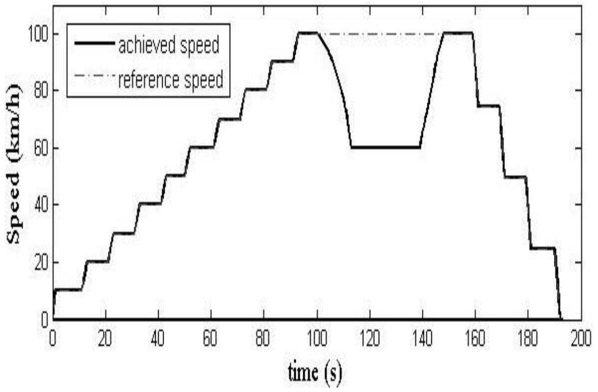


Fig. 22 Speed profile achieved by ACC in comprehensive test procedure

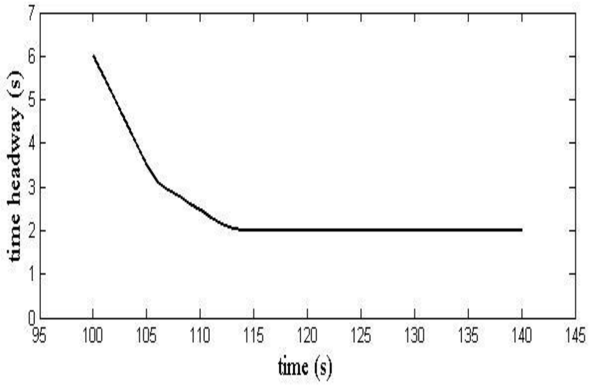


Fig. 23 THW diagram in a 40-second distance control maneuver

The figures show the host succeeded to switch to distance control mode and reduce velocity. The THW is also kept above the defined limit which is 2 seconds.

7 CONCLUSION

The paper described design of an ACC scheme that controls both vehicle velocity and its distance to the target vehicle. To this end, two fuzzy logic controllers were implemented in a two-level control structure. Since the control response was not satisfying, an optimization process was carried out. In this regard the GSA optimization algorithm was adopted to tune parameters of the controller. For simultaneous evaluation of velocity and distance control units, a new speed profile was developed and a distance control maneuver was included in the test procedure.

The results show the optimized controller succeeds to control velocity and distance at the same time. The vehicle velocity response was stable and smooth, but still sensitive to variation of reference speed and THW. The maximum amount of velocity error was less than 0.35 km/h. The results proved the proposed scheme which offered an ideal control behaviour.

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