A Fuzzy Logic Intelligent Control System Architecture for an Autonomous Leader-Following Vehicle

K.C. Cheok, G.E. Smid,
K. Kobayashi
Dept. of Electrical and Systems Engineering
Oakland University, Rochester, MI 48309-4401

J.L. Overholt (Simulation Group),
P. Lescoe (Robotics Office)
US Army Tank-Automotive Armament Command, Warren, MI
49397-5000, USA

Abstract

A hierarchical intelligent control system paradigm for a vision-based autonomous driving scheme is presented for a leader-Following HMMWV. The paper shows how fuzzy logic is employed to represent knowledge at the organizational level, resolve conflicting preceived information and plan the best path for the vehicle. After introducing the methodology, simulation and experimental aspects for realizing and testing the scheme are discussed.

Keywords : Intelligence Control, Fuzzy Logic, Leader-Follower, Unmanned Robotics.

1. Introduction

The US Army Tank-Automotive Armaments Command (TACOM) in Warren, Michigan has conducted R&D studies in the concept of a LF convoy for the High Mobility Multipurpose Wheeled Vehicles (HMMWV's). Successful individual experiments of Non-Line-Of-Sight (NLOS) and In-Line-Of-Sight (ILOS) leader/follower convoy schemes have been demonstrated at a TACOM test track and recorded on video tapes. Figure 1 shows an experiment in which an autonomous follower HMMWV trails a leader CUCV (Commercial Utility Cargo Vehicle).

Figure 1: Autonomous Vision-based Following.

In this paper, we will present an ILOS fuzzy logic vision based autonomous driving strategy. The follower must drive safely as it trails the leader by resolving conflicting vision information and control behaviour. We show how different types of fuzzy inference systems can be used to realize a hierarchical intelligent control paradigm that imitate the way a person would drive a vehicle.

Equipment Onboard **Follower**
VX-Works Computer System
Global Positioning System
Inertial Measurement Unit
Telemetry Tx/Rx
IR Receiver
Computer Vision
Night Vision
Laser Radar, Sonars
Robotized Driving Mechanisms

Equipment Onboard **Leader**
VX-Works Computer System
Global Positioning System
Inertial Measurement Unit
Telemetry Tx/Rx
Beacons/IR Tx
Night Vision
Laser Radar, Sonars
Head-Up Display

Figure 2: Equipment onboard the LF vehicles

The meaning of *Intelligence* in this paper will be interpreted in the sense of a fixed descriptive knowledge base. "Intelligent Control (IC) in its simplest form can be viewed as a knowledge processing scheme: The inputs consist of data and goals, while the output consists of some control action" [Ste87]. IC also uses human/animal/biologically motivated techniques and procedures (representation and/or decision making) to develop and implement a controller for a system [Pas93]. The ILOS LF scheme in this paper employs the hierarchical intelligent control paradigm of [Sar87] [Mey87] with the help of fuzzy logic.

2. Systems Setup

Figure 2 lists the main equipment onboard the follower and leader HMMWV's that have been installed for conducting LF convoying operations. Note that different sets of hardware can be selected and integrated through software to perform either ILOS or NLOS or combined ILOS/NLOS LF experiments. Most of the equipment was installed and configured by RedZone Robotics, Inc [RR95].

3. Objective

The scope of this paper is concerned with the design, simulation and experiments of a fuzzy logic vision-based autonomous ILOS LF driving scheme. The proposed scheme is built on the paradigm of an Intelligent Control System (ICS) as shown

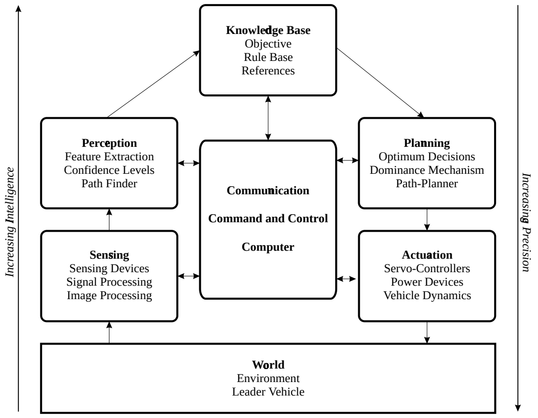

Figure 3: A paradigm for Intelligent Control System (ICS)

in Figure 3. The idea is to develop an intelligent autonomous robotic follower for trailing the leader vehicle at a safe separation distance, stay on the road. We focus on the theoretical and practical aspects of designing a fuzzy logic based hierarchical intelligent control strategy for performing the task of autonomous Leader Following. The following issues will be addressed: 1) Vision, 2) Perception, 3) Planning, 4) Actuation, 5) Computer Study, 6) Experiments.

4. Intelligent Control System Paradigm

An Intelligent Control System (ICS) Paradigm has been formulated as a multi-level hierarchical structure obeying the Principle of Increasing Precision with Decreasing Intelligence [Sar87], [Mey87]. In what follows, we adopt the philosophy of this paradigm in the LF-based ILOS scheme using fuzzy logic.

The ICS paradigm for a general autonomous mobile robot is shown in Figure 3. Figure 4 shows the more specific adoption of this paradigm for the vision-based ILOS LF scheme. The hierarchical structure for the scheme can be divided into the following levels.

Organizational level. This highest level in the hierarchy deals with the knowledge base for intelligent decisions. In the ILOS LF scheme, the knowledge is represented by fuzzy logic rule base (linguistic logic statements) and data base (membership functions) for road following, lead vehicle tracking, fusing various information, defusing conflicts and optimizing decisions.

Coordinational level. This level deals with perception and planning decision. The perception involves feature extraction of road, lane and obstacle models, and leader position and motion, determination of confidence levels or uncertainties in these perceptive information. The planning stage evaluates the perceived information and plans the best path for the follower vehicle, based on the knowledge defined in the organizational level.

Execution level. The lowest level in the hierarchy executes numerically precise functions for the sensors and controllers. The vision system acquires information on road edges, and the position of the leader vehicle inputs. The controller drives the vehicle according to the path that was planned by the organizational and coordinational level.

These three basic hierarchical levels for the ICS paradigm are to be implemented using the real-time computers outlined in Section 2. More specifically, the knowledge base (see Figure 3) for the ILOS LF scheme (see Figure 4) consists of: 1) Pathfinder Logic, 2) Confidence Logic, 3) Dominance Logic, 4) Driving Logic.

It turns out that various methods of fuzzy inference mechanisms can be appropriately employed: The Pathfinder and Confidence Logic, for example, utilizes a Mamdani-style inference technique, the Dominance Logic employs Sugeno-style inference and the Driving Logic uses a ANFIS mechanism.

5. Vision based Autonomous Follower Driving Scheme

At the implementation schematic level, the structure can be sectioned into the following subsystems: Computer Vision, Perception (Perceived Visual Cues / Pathfinder / Reconnoiterer), Planning (Fused Visual Information / Navigator), Actuation (Controller) and Vehicle Dynamics.

5.1. Computer Vision System

The computer vision onboard the follower provides vital information of the lane markers and leader position/motion for the ILOS LF scheme. The vision pattern recognition processes the digitized images and computes the following information:

- *Identified dimension and RGB color composition of the leader vehicle.*
- *Trailing distances and heading angle between the leader and follower; and*
- *Lane marker model for representing the offset, heading and curvature of the right and left road edges.*

5.1.1 Acquisition of leader Position and Motion The separation or trailing distance R and the heading difference ϕ are used to define the relative position of the leader with respect to the follower. The distance R is deduced from the size of the rectangular rear gate of the leader vehicle, and the angle ϕ from the lateral displacement of the leader in the image.

5.1.2 Road Lane/Edge Marker Model The vision system detects the lane markers of a road using the lane marker models. The image processing and detection algorithms for the model are described in detail in [SN94]. From the images of road scenes, the right edge of the road can be approximated by polynomial function $x_R = a_0 + a_1 y + a_2 y^2$, where x and y are lateral and longitudinal coordinates in the camera view. The parameters, a_0, a_1 and a_2 are estimates of offset, heading and curvature of the road.

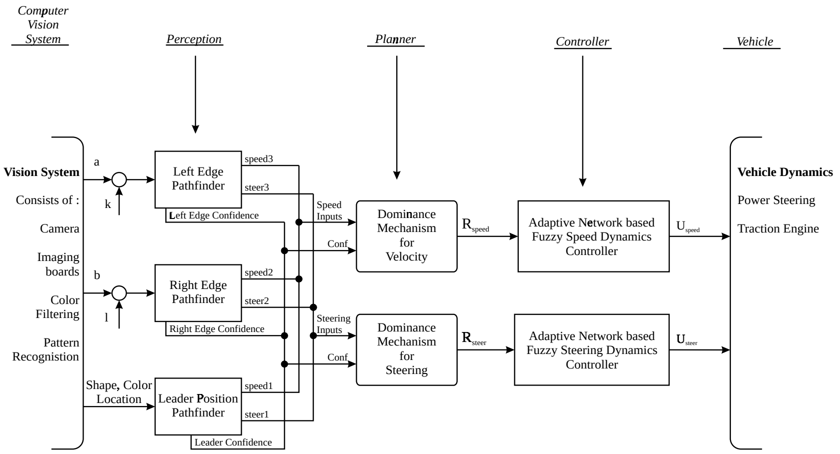

Figure 4: Vision-based hierarchical intelligent control strategy for ILOS LF HMMWV.

Similarly, the left edge of the road can be approximated as $x_L = b_0 + b_1 y + b_2 y^2$. To utilize the lane model parameters in steering logic, we define the right and left edges of **straight roadways** as $x_{RS} = k_0 + k_1 y + k_2 y^2$ and $x_{LS} = l_0 + l_1 y + l_2 y^2$, to represent the neutral reference direction for steering the vehicle. The *error lane marker models* can then be defined as

$$x_R - x_{RS} = (a_0 - k_0) + (a_1 - k_1)y + (a_2 - k_2)y^2 \quad (1)$$

$$x_L - x_{LS} = (b_0 - l_0) + (b_1 - l_1)y + (b_2 - l_2)y^2 \quad (2)$$

These error offsets, heading and curvatures can be used to differentiate curve or cross road edges from simple straightways. Steering commands can be based on the errors in coefficients $(a_i - k_i)$ and $(b_i - l_i)$ with i = 0, 1, and 2.

5.2. Perception

5.2.1 Rule Base for Direct Tracking of Leader Vehicle (Leader logic) Driving commands for the follower to directly track the leader are based on the trailing distance R and direction ϕ. A sample of the Mamdani-style fuzzy logic rule base for tracking the leader vehicle is as follows (**Leader** logic).

```
1. If (distance is close) and (direction is left)
   then (steer3 is left)(speed3 is slow) (1)
2. If (distance is close) and (direction is straight)
   then (steer3 is straight)(speed3 is slow) (1)
......
9. If (distance is far) and (direction is right)
   then (steer3 is right)(speed3 is normal) (1)
```

5.2.2 Rule Base for Confidence in Acquired Leader Position (Confidence logic 1) Two tests can be performed on the image, to check the confidence of the aquired leader position.

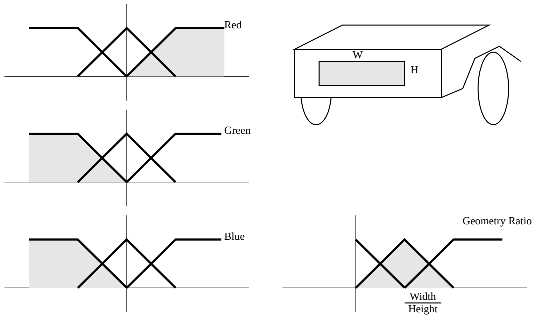

Figure 5: Fuzzy membership functions for confidence factors for the leader vehicle

The two features extracted are the geometry width / height (W/H) ratio and color (R,G,B) of the rectangle. The first indicator for confidence of geometry `cgeometry` is a simple fuzzy logic conclusion based on the membership function of W/H, as illustrated in Figure 5. The second indicator `ccolor` checks the composition of the RGB-components of the rectangle. Since a red rectangular beacon is used, the desired memberships are as shown in Figure 5; high values for red, and low values for green and blue. The identified dimensions and color of the leader vehicle from visual information therefore also yields a set of fuzzy confidence factors for the visual aquisition and recognition of the leader. The combined confidence factor for recognizing the leader vehicle is a combination of the confidence for color geometry.

5.2.3 Rule Base for Confidence in Acquired Lane Model (Behaviourist logic 2 and 3) Driving commands for road following are based on the error lane marker models. The applied Mamdani-style fuzzy logic rule base for following the right edge of the road is shown below (**RMarker** logic).

```
 1. If (a0-k0 is neg) and (a1-k1 is neg) and (a2-k2 is neg)
    then (steer2 is left)(speed2 is slow) (1)
 2. If (a0-k0 is neg) and (a1-k1 is neg) and (a2-k2 is small)
    then (steer2 is left)(speed2 is slow) (1)
......
27. If (a0-k0 is pos) and (a1-k1 is pos) and (a2-k2 is pos)
    then (steer2 is right)(speed2 is slow) (1)
```

Similar rules are used for issuing commands to follow the left road edge (**LMarker** logic).

5.2.4 Rule Base for Confidence in Acquired Lane Model (Confidence logic 2 and 3) The coefficients of the edge polynomials take on small values even for the sharpest turns on a

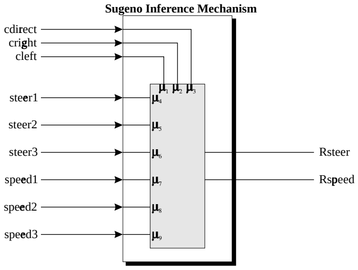

Figure 6: Sugeno style inferencing mechanism with inputs and outputs as used in this model.

normal roadway under normal driving condition. If there is no good fit for the edge polynomials, coefficients will be outside this region. Fuzzy logic for confidence levels, `cleft` and `cright`, in aquisition and recognition of the left and right roadedges were setup, based on the idea.

5.3. Planning

From the outputs of the above Fuzzy Logic, the planning hierarchy has to generate the overall command signals for the vehicle speed and steering. The command signals, denoted by R_{speed} and R_{steer}, will be determined as outputs of a Sugeno-style fuzzy inference system.

5.3.1 Dominance Mechanism for Steering The Sugeno-style fuzzy logic rule base for generating the overall R_{steer} is shown below. The objective is to use the different informations *wisely* to achieve the ILOS LF objective as was explained in Section 3. The rules intend to keep the follower vehicle on the rThe rules intend to keep the follower vehicle on the road as it trails the leader.

```
 1. If (cleft is good) and (cright is good)
    then (Rsteer is lmarker and rmarker) (1)
 2. If (cleft is good) and (cright is bad) and (cdirect is bad)
    then (Rsteer is lmarker) (1)
......
16. If (cleft is bad) and (cright is bad)
    then (Rsteer is leader) (1)
```

The consequence part of a Sugeno-style inference mechanism consists of functions which are represented as a linear combination of the inputs. This technique is implemented with the Sugeno style fuzzy inference system (FIS) [TM]. Table 1 shows the functions and parameters for the consequence. The Sugeno inference mechanism is graphically represented in Figure 6. In equation form this can be written as:

$$R_{steer} = \frac{\mu_1^1\mu_2^1 f_1 + \mu_1^2\mu_2^2\mu_3^2 f_2 + \mu_1^3\mu_2^3\mu_3^3\mu_4^3\mu_5^3 f_2 + \cdots}{\mu_1^1\mu_2^1 + \mu_1^2\mu_2^2\mu_3^2 + \mu_1^3\mu_2^3\mu_3^3\mu_4^3\mu_5^3 + \cdots} \quad (3)$$

From Table 1 it can be derived that $f_1 = 0.5(\texttt{steer1} + \texttt{steer2})$, and $f_2 = \texttt{steer1}$. The superscripts 1, 2, 3 in Equation 3 denoted that the μ_i's were evaluated using rules 1, 2, 3, and so on.

Dominance Mechanism for Speed. The structure of the fuzzy logic dominance mechanism for R_{speed} is similar to that of the steering logic described above, although the rules were set to describe speed and trailing distance.

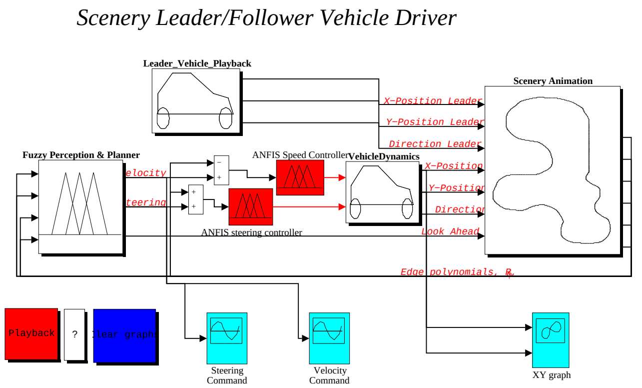

Figure 7: Main SIMULINK schematic for the leader-follower simulation

fcn	consequent	steer1	steer2	steer3
f_1	`lmarker and rmarker`	0.5	0.5	0
f_2	`lmarker`	1	0	0
f_3	`rmarker`	0	1	0
f_4	`lmarker and leader`	0.5	0	0.5
f_5	`rmarker and leader`	0	0.5	0.5
f_6	`leader`	0	0	1

Table 1: The output functions representing the consequence of the Sugeno fuzzy logic dominance mechanism.

5.4. Vehicle Actuation Systems

The vehicle actuation systems receive two commands, one for speed (R_{speed}) and one for steering (R_{steer}) from the planning stage. The actuators are responsible for tracking the planned commands or path, however, since driving a vehicle is a highly non-linear task, a simple PID-controller would not be able to satisfactorily drive the follower on its planned path. It was decided that an Artificial Network-based Inference System (ANFIS) [Jan93] could be applied to actuate the driving mechanism of the following vehicle according to the issued speed and steering commands. Actuation patterns of the human driver were measured and recorded together with the commands from the pathplanner as training sets for the ANFIS. When the ANFIS has been trained, it was programmed to take over the vehicle from the human driver and perform driving manouvres with the same skills under similar situations.

6. Simulation

A two-vehicle convoy simulation was developed using Matlab/Simulink to analyze the proposed fuzzy logic vision based autonomous leader following scheme, described in the previous section. The main simulation diagram, Figure 7, shows the two

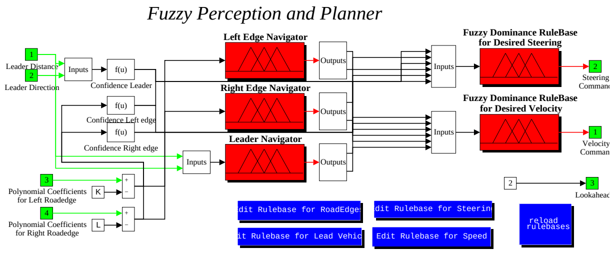

Figure 8: Fuzzy Navigator and Dominance Mechanism

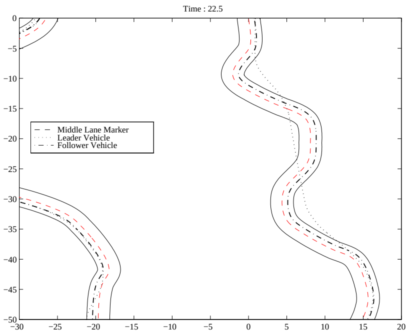

Figure 9: Part of the course is zoomed in to show the simulation result of the ILOS LF scheme.

vehicles, the scenery animation, and holds all the simulation algorithms for the vision. The fuzzy Perception and Planner block implements the autonomous driving scheme of the follower Vehicle. We briefly explain the implementation of the scheme for the simulation.

Knowledge Base. In the simulation, the intelligence for the ILOS LF scheme was represented by knowledge base fuzzy rules, described in Section 5.

Simulation of the frame grabbing vision. The vision system is simulated by projecting a fixed prerecorded trackset of road edges, together with a wire frame model of the leader vehicle in a perspective onto a 2D-plane, as if it was a view from a true camera.

Perception and Planning. Mamdani style perception and Sugeno-style fuzzy logic based inference systems are used to evaluate and combine the various information from the navigators. Confidence factors are used as antecidents to weight the outputs of the navigators, the fuzzy logic is effectively a dominance mechanism for issuing speed and steering commands.

Actuation. We use an Adaptive Network-based Fuzzy Inference System (ANFIS) [Jan93] to learn and tune itself to control the vehicle, through human-in-the-loop simulation of the vehicle actuation and motion dynamics.

Simulation Results. Figure 9 shows the trajectories of a typical leader-follower simulation with the proposed fuzzy logic autonomous ILOS LF scheme. Figure 9 shows that the follower stays on the road even though the leader crosses the roadedges. Animation of the simulation results shows that the follower vehicle speeds up and slows down to stay on the road as it tries to keep up with the leader.

7. Experiments

Experimental tests of the ILOS LF driving scheme were succesfully conducted and recorded on video at the test track facility at the US Army TACOM, Warren, Michigan. A typical test run is shown in Figure 1. This work was done under the US Army Summer Faculty Research Engineering Program [COL95].

8. Conclusions

The leader-follower convoy is an excellent platform for testing the fuzzy logic based hierarchical intelligent control system paradigm. The fuzzy logic knowledge base was used to plan vehicle driving strategy by resolving conflicting perception. Computer simulation provides a means to analyze, design, and tune the proposed driving scheme. Actual experiments with specially equipped HMMWV's demonstrate encouraging success.

References

[COL95] Ka C. Cheok, J.L. Overholt, and P. Lescoe. Automated inline of sight leader/follower hmmwv's with rule-based preview control. Technical report, US Army Summer Faculty Research and Engineering Programs, TCN:95-223, October 1995.

[Jan93] J-S. R. Jang. Anfis: Adaptive-network-based fuzzy inference system. *IEEE Transactions on Systems, Man and Cybernatics*, Vol.23(No.3):–, May/June 1993.

[Mey87] A. Meystel. Intelligent control: Highlights and shadows. *IEEE International Symposium on Intelligent Controls*, pages 2–8, 1987.

[Pas93] Kevin M. Passino. Bridging the gap between conventional and intelligent control. *IEEE Control Systems*, pages 12–18, June 1993.

[RR95] Inc. RedZone Robotics. Operations manual non-line of sight leader/follower. Technical Report 9106-MAN-001, Vol. 1-6, 2425 Liberty Avenue, Pittsburg, PA 15222-4639 (412-765-3064), 1995. Contract Number: DAAE07-92-C-R036.

[Sar87] George N. Saridis, editor. *Knowledge Implementation: Structures of Intelligent Control Systems*, Dept. of ECSE; RPI Troy, New York 12180-3590, 1987.

[SN94] H. Schneiderman and M. Nashman. A discriminating feature tracker for vision based autonomous driving. *IEEE Transactions on Robotics and Automation*, Vol.10(No.6):769–775, December 1994.

[Ste87] H. Stephanou. Intelligent control: How it is understood by ai and systems scientists, and how to teach it to the graduate students. In *Panel Discussion During the IEEE International Symposium on Intelligent Control*, pages 511–512, 1987.

[TM] Inc. The MathWorks. Fuzzy logic toolbox.