AN OPTIMAL CONTROL FOR MULTIPLE UNMANNED UNDERWATER CRAWLING VEHICLES

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ABSTRACT

This paper presents a methodology to generate a group behavior for Unmanned Underwater Crawling Vehicles (UUCV) having track-style wheels. The methodology with Leader-Follower formation is developed to maximize the search efficiency of targets on three-dimensional mission field by using Fuzzy Logic. The motion of UUCV is constrained by environmental uncertainties which are represented by unknown friction coefficients between the tracks and ground surface, and an unknown topography of the operating field.

The Leader-Follower formation is designed under two trajectory generation modes, centralized and decentralized. The commands of all UUCV of the group in centralized mode are assigned by the central command control board or a designated group leader. In the decentralized mode, each vehicle of the group can be a leader and follower except a designated group leader and the two outmost vehicles. As a follower in this mode, each vehicle generates its own commands autonomously to maintain a constraint mutual distance and a velocity between its leader.

The controller used in each UUCV, a combination of conventional Proportional-Integral-Derivative (PID) and Adaptive Neural Network Fuzzy Logic (ANNFL), is designed by using multi-objective optimization techniques from which the fixed control gains of PID controller and the adjustable control gains of ANNFL are obtained.

In the simulation to implement the formation control of group vehicles, two three-dimensional spline surfaces are used for the topography of the mission area, and the friction coefficient distribution that is taken at random. When the desired command trajectory of a heading with a constant velocity and a constraining mutual distance are given, the behavior of a group of vehicles shows satisfactory results.

KEYWORD: Formation Control; Adaptive control; Fuzzy Logic.

1. INTRODUCTION

It has long been recognized that there are several tasks that can be performed more efficiently and robustly using multiple robots (Donald, Gariepy, and Rus, 2000; Khatib, Yokoi, Chang, 1996; Park , 2000; Rus, Donald, and Jennings, 1995; Desai, Ostrowski, and Kumar, 1998). In this paper, a methodology for generating a group behavior of UUCV for the task of maximizing the search efficiency of targets is presented. UUCV having track-style wheels is used for performing reconnaissance missions in the very shallow water (VSW) and surf zone (SZ). SZ can be referred to as the underwater region between 0 and 10 feet in depth, VSW is between 10 and 40 feet. The UUCV also can be applied to explore and map the sea bottom at low cost. Furthermore, it can replace divers by performing a variety of hazardous missions in the coastal waters.

The formation control of mobile robots operated in an indoor simple plane were described in (Fierro, Das, Kumar, and Ostrowski , 2001). They approached controlling a group of n robots by adopting a simple kinematical model for a nonholonomic robot in the two dimension field, and used three distinct controllers such as Separation-Bearing Control, Separation-Separation Control, and Separation Distance-To-Obstacle Control. These controllers are composed properly to make a formation of a group of robots in the manner of leader-follower to accomplish a given cooperative task. It is difficult and insufficient to adapt this type of formation control for an underwater mission field having unknown 3D topography and uncertainty.

The approach for this study with the Leader-Follower formation is to answer these questions by combining conventional model-based control and the so called "Intelligent Technology" Fuzzy Logic for adaptive behavior control. The Leader-Follower formation is designed under the assumption that there exists a communication system between a vehicle and the next closest vehicle starting from the leader as well as between the central command control board and a designated leader of a group of UUCVs.

Each vehicle in the group can be a leader and follower except the group leader and the two outmost vehicles. As a follower, each vehicle generates its own commands autonomously to maintain a given constraint of mutual distance and a velocity relative to its leader.

The contributions of this paper are (1) modeling of the dynamic behavior of crawler vehicle in a three dimensional environment of a mission field having a random distribution friction coefficient between the tracks and the field, and (2) a newly developed Leader-Follower formation to generate self-commands based on fuzzy-logic and the adaptive controller of each vehicle described in (Lee K. H., 2001).

The controller used in each UUCV was developed by K. H. Lee in to control a UUCV in an uncertain environment adaptively. The adaptive controller was modeled by combining a conventional PID controller and ANNFL to provide an adaptability and a robustness for the integrated controller and make it possible to control a system in real time.

This paper is organized as follows: In section 2, the modeling of contact dynamics of a UUCV on a three dimensional mission field is described. In section 3, a trajectory generation algorithm in centralized and decentralized modes are developed with fuzzy expert systems. The simulation results from the implementation of the developed group formation control strategy are presented in section 4.

2. MODELING OF CONTACT DYNAMICS ON 3-D TOPOGRAPHY

In this section, we derive the contact dynamics of a UUCV on a mission field having three dimensional topography, which create a nonholonomic constraint on the vehicle motion.

The dynamic equation of motion of a UUCV in 3 degrees of freedom (DOF) (Littlejohn, 2001) is expressed as:

$$\mathbf{M}\, d^2q_i/dt^2 + H_i(q_i,dq_i/dt) = \mathbf{B}\, U_i - F_{Ni} + F_{G_i} \tag{2.1}$$

where $q_i \in \Re^3$ the generalized coordinates ,d /dt, d^2/dt^2 represent to the first and the second order time derivatives, respectively. **M** is a 3 x 3 positive-definite symmetric inertia matrix, $H_i(q_i,dq_i/dt)$ is a nonlinear inertial force, **B** is a 3 x 2 input transformation matrix, F_{Gi} is gravitational force, and U_i is the applied external force and torque. F_{Ni} is the constraint force acting negatively against a forward moving direction due to the nonholonomic constraint in Eq. 2.2.

A constraint condition according to the normal direction, $\underline{N}$ of three dimensional topography Eq. 2.4, is given by

$$dq_i/dt \cdot \underline{N} = 0 \tag{2.2}$$

$$d^2q_i/dt^2 \cdot \underline{N} + dq_i/dt \cdot d\underline{N}/dt = 0 \tag{2.3}$$

$$f(X,Y,Z) = 0 \tag{2.4}$$

where the symbol, "$\cdot$" represents vector dot product, and the normal directional vector , $\underline{N}$ is obtained from the following equations.

$$\underline{N} = N_X e_1 + N_Y e_2 + N_Z e_3, \tag{2.5}$$

$$n_X = \partial f/\partial_X,\ n_Y = \partial f/\partial_Y,\ n_Z = \partial f/\partial_Z \tag{2.6}$$

$$|\underline{n}| = (n_X^2 + n_Y^2 + n_Z^2)^{½} \tag{2.7}$$

$$N_X = n_X/|\underline{n}|,\ N_Y = n_Y/|\underline{n}|,\ N_Z = n_Z/|\underline{n}|. \tag{2.8}$$

where $e_i \in \Re^3$ is the unit vector.

From Eq. 2.1 and Eq. 2.3, there are four unknown variables to be solved, which are three state variables in body frame and one normal constraint force, N_f. They are obtained by a numerical integration method such as the Euler method. Each component of F_{Ni} is obtained from N_f multiplied by the three friction coefficients (μ_X, μ_Y, μ_φ). The μ_X, μ_Y and μ_φ are the friction coefficients between the track and ground surface and are obtained from a three dimensional distribution generated in terms of a cubic spline surface at random. We assume that the values of these coefficients are unknown to the controller but the upper and lower bounds are known because they are determined by the maximum driving force of the vehicle. In the model of the uncertainties, all possible factors such as the geometry of mission field and bottom conditions are represented in terms of the variation of these coefficients.

The kinematics in the transformation of the body system values to the fixed system are given as :

$$\begin{Bmatrix} I \\ J \\ K \end{Bmatrix} = \begin{bmatrix} C_2C_3 & -S_3C_2 & S_2 \\ S_1S_2C_3 + S_3C_1 & -S_1S_2S_3 + C_3C_1 & -S_1C_2 \\ -C_1S_2C_3 + S_3S_1 & C_1S_2S_3 + C_3S_1 & C_1C_2 \end{bmatrix} \begin{Bmatrix} e_1 \\ e_2 \\ e_3 \end{Bmatrix} \tag{2.9}$$

$$\begin{Bmatrix} I \\ J \\ K \end{Bmatrix} = [\mathbf{R}] \begin{Bmatrix} e_1 \\ e_2 \\ e_3 \end{Bmatrix} \tag{2.10}$$

The rotation sequence of roll (θ_1), pitch (θ_2), and yaw (θ_3) are applied to get this transformation matrix, **R**, where $C_1 = Cos(\theta_1)$, $C_2 = Cos(\theta_2)$, $C_3 = Cos(\theta_3)$, $S_1 = Sin(\theta_1)$, $S_2 = Sin(\theta_2)$, $S_3 = Sin(\theta_3)$, and *I, J, K* in Figure 2.1 represent the unit vector in the fixed coordinates. The **R** is being used to get a global coordinate of each vehicle as well as to get mutual distance between a two vehicles by using the transposed matrix, $\mathbf{R}^T$.

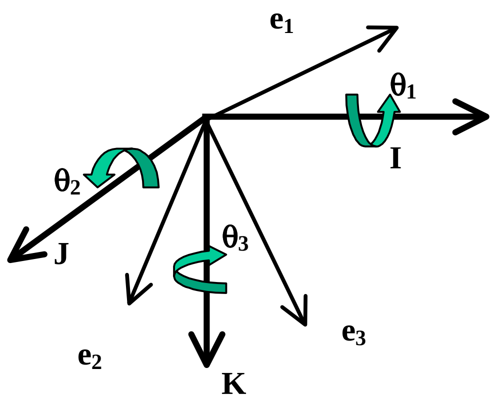

Fig. 2.1 The Representation of the Body Frame in the Fixed Coordinates

The global state variables, X,Y, Z, roll (θ_1), pitch (θ_2), and yaw (θ_3) are obtained from the following kinematical differential equation using the state variables, dq_i/dt, i = 1,2,3. We define the dq_1/dt and dq_2/dt as the linear velocities and dq_3/dt as the angular velocity along the e_3 unit vector in body frame.

$$dX/dt = dq_1/dt\, C_2C_3 - dq_2/dt\, C_2S_3 \quad (2.12)$$

$$dY/dt = dq_1/dt\,(S_1C_2S_3+C_1S_3) + dq_2/dt(C_1C_3-S_1S_2S_3) \quad (2.13)$$

$$Z = f\,(X,Y) \quad (2.14)$$

$$d\theta_1/dt = dN_x dt / C_2 \quad (2.15)$$

$$d\theta_2/dt = (S_1S_2\, d\theta_2/dt - dN_y/dt)/(C_1C_2) \quad (2.16)$$

$$d\theta_3/dt = dq_3/dt \quad (2.17)$$

The time derivative of Euler angles, θ_1 and θ_2 in Eq. 2.15 and Eq. 2.16 can be obtained by using the components of the unit normal vector in fixed space, the unit normal in body space, and the rotation matrix given in Eq. 2.9. The relationship between the components in fixed space of the unit normal and Euler angles, θ_1 and θ_2 are

$$N_X = \mathrm{Sin}(\theta_1) \quad (2.18)$$

$$N_Y = -\,\mathrm{Sin}(\theta_1)\,\mathrm{Cos}(\theta_2) \quad (2.19)$$

To obtain the yaw value a rotating coordinate system and a fixed system concept is used [2]. The angular velocity vector in terms of the Euler angles and their time derivatives is used to obtain the relationships between the body and fixed angular velocity components. Using a pitch, roll, yaw sequence, the relationship is given as:

$$d\theta_3/dt = dq_3/dt + (w_2\mathrm{Sin}(\theta_3) - w_1\mathrm{Cos}(\theta_3)\mathrm{Sin}(\theta_2))/\mathrm{Cos}(\theta_2) \quad (2.20)$$

For planar motion, w_1 and w_2 equal zero, therefore Eq. 2.20 reduces to Eq. 2.17. Equation Eq. 2.17 shows that for the rotation sequence of pitch, roll, and yaw, the body and fixed yaw rates are the same.

3. FORMATION CONTROL

In this section, we consider the group behavior of UUCVs which are constrained nonholonomically by a 3D topography and the uncertainties of the mission field, and describe the command generation to maintain a given constraint distance between each vehicle and its neighbor to achieve the optimal search efficiency in an obstacle free field.

The controller used in each UUCV had been developed by K. H. Lee to control the UUCV in an uncertain environment adaptively. The adaptive controller uses conventional Proportional-Integral-Derivative (PID) and Adaptive Neural Network Fuzzy Logic (ANNFL) through the process of the computer aided design with multi-objective optimization (Fleming, and Pashkevich, 1985). The PID controller is designed at a nominal operating point and establishes a desired system response pattern of feedback (closed loop) control. The ANNFL deals with the system uncertainties to compensate the PID controller by reducing the "command following error".

This error is reduced by tuning an additional gain feedback from the system output besides the fixed gain of the PID controller.

The ANNFL provides adaptability and robustness for the PID controller, and makes it possible to control a system in real time. ANNFL is a functional relationship formulated in terms of the gain domain which is obtained through an optimization process to get the desired system response for the given possible known uncertainties within the bounded domains. The optimization technique (used to obtain not only the adjustable gains of ANNFL but also the gains of the PID controller) is the multi-objective optimization using a Sequential Quadratic Program (SQP) method.

We approach the development of formation control, a sort of Leader-Follower method, for generating a trajectory, a constraint, and a command in each UUCV by using Fuzzy Logic (FL) to maintain the mutual distance between each UUCV which is needed to maximize search efficiency. In support of this formation control, the modeling of environment described in section 2 and the adaptive controller of each UUCV are working implicitly.

It is well known that FL has been used to model the experience or a skill of a human expert and is needed to represent knowledge in a manner that is both faithful to the human style of processing information as well as a form amenable to computer manipulation. By taking advantage of this characteristic of FL, we develop the behavior of a group of UUCVs.

The Leader-Follower formation control based on FL has two trajectory generation modes, centralized and decentralized. The centralized mode is used to deploy the multiple UUCVs to reach a formation which is equitably distributed with the mutual distances designated by the central control system. In the beginning of mission assignment, the central control system calculates and produces a desire heading and a velocity for each vehicle to reach the formation. When the mutual distances of the vehicles reach the control range of each vehicles FL, the central control system switches the control mode from centralized to decentralized.

a. Centralized Trajectory Generation Mode.

In the centralized mode, the commanded headings and the velocities in a group as can be seen in Figure 3.1 are calculated and assigned as in the following algorithm.

$$L_k(t_i) = {}^kY(t_i) - {}^{k-1}Y(t_i), \quad {}^kSL(t_i) = \sum_{j=1}^{k} L_j(t_i) \qquad (3.1a)\ (3.1b)$$

$$ {}^kdL_{si} = {}^kSL(t_f) - {}^kSL(t_i) \qquad (3.2)$$

$$Lh_k = [{}^kdL_{si}{}^2 + Lh_0{}^2]^{1/2} \qquad (3.3)$$

$$Lh_k / Lh_n = V_k / V_{max}, \quad k = 1 \ldots n \qquad (3.4)$$

$$Lh_k \operatorname{Sin}(\theta c_k) = {}^kdL_{s0} \qquad (3.5)$$

where ${}^kY(t_i)$ represents Y value in fixed coordinate for the k^{th} vehicle in the group at time t_i, t_f is a time when the centralized mode is switched into the decentralized and V_{max} and V_{min} are the maximum and the minimum linear velocities which a vehicle can reach ($V_{max} > V_k > V_{min} > 0$).

Step 1. Initialize the values of Lh_0, $L_k(t_i)$, dt and $L_k(t_i)$, where Lh_0 is V_{max} dt and dt is a time step.

Step 2. Set the values V_k and θc_k of each vehicle from Eq. 3.4 and Eq. 3.5, respectively.

Step 3. After the time dt, evaluate Eq. 3.2.
If abs(${}^kdL_{si}$) of all the vehicles are less than (3 V_{nom} dt).
Then
Switch control mode into decentralized.
Otherwise
Continue to the Step 2 .

V_{nom} is a constant velocity used in the decentralized mode, abs(${}^kdL_{si}$) are the absolute values of ${}^kdL_{si}$.

b . Decentralized Trajectory Generation Mode.

In the decentralized mode of Leader-Follower formation, each UUCV generates a heading and a constant velocity, V_{nom} as its command for itself to satisfy a given constraint condition except for a designated leader of a group. The commands used in the leader can be assigned by the central command control board through the communication system. Depending upon the behavior of the group leader, the next closest vehicle starting from the leader generates its commands and becomes a follower as well as the leader of the next closest one. Each vehicle in group can be a leader and follower except the group leader and the outmost vehicles.

As an intelligent agent with a reasoning fuzzy expert system, each vehicle makes a decision of generating its own commands by reading and comparing its own navigational data and the neighbor vehicle's through its navigation sensor and communication device.

There is no learning system in our intelligent approach of formation control because we want to avoid the time consumed by the learning process, and to control the vehicles in real time by mapping the skill of human expert using fuzzy logic.

Considering the mission characteristic of maintaining the mutual distance between each UUCV, which is needed to maximize search efficiency, we need navigational data, X and Y values in terms of the fixed global coordinate system.

The global states are measured and evaluated in a relatively long time period when they are compared to the sampling time of general signal processing.

The parameters in Leader-Follower formation based on FL shown in Figure 3.2 are constructed and configured as follows:

$$ {}^kdY(t_i) = Lc(t_i) - L_k(t_i) \qquad (3.6)$$

$$ {}^kRt_Y(t_i) = {}^kdY(t_{i-1}) / {}^kdY(t_i) \qquad (3.7)$$

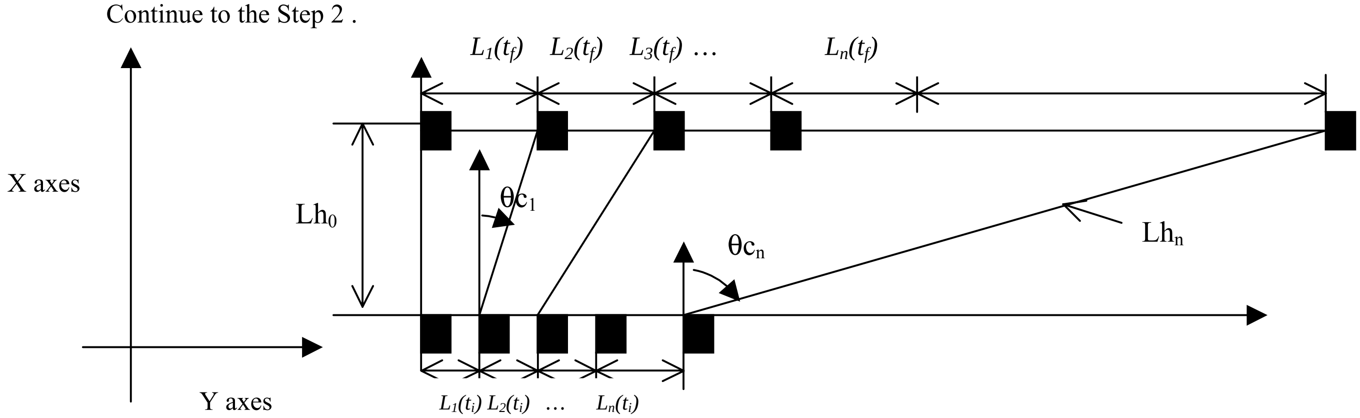

Fig. 3.1 Centralized Trajectory Generation Mode

The condition of switching from the centralized to the decentralized is that all the values in Eq. 3.6 should be less than three times $Lc(t_i)$.

As a mathematical mapping function, the fuzzy expert system generates θc_k of a follower according to two input values in Eq. 3.6 and Eq. 3.7.

The ${}^kdY(t_i)$ in Eq. 3.6 which is the difference between the desired constraint and an actual mutual distance in Eq. 3.1a represents the spatial nonlinearity effected on two vehicles in the mission field during a time step, t_i and t_i-dt.

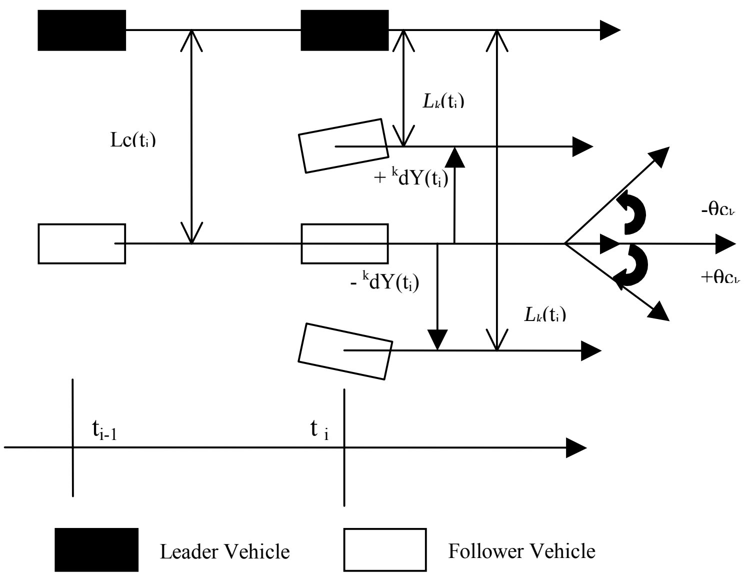

Fig. 3.2 The Parameters in Decentralized Trajectory Generation Mode

Each input and output variable of a fuzzy system has its linguistic fuzzy sets. For the first input, ${}^{k}dY(t_i)$ having triangular and trapezoidal membership functions, there are nine fuzzy sets which are { Negative Very Large (NVL), Negative (N) Large (NL), Negative Medium (NM), Negative Small (NS), Zero (Zr), Positive (P) Small (PS), Positive Medium (PM), Positive Large (PL), Positive Very Large (PVL) }.

Table 3.1 Fuzzy Rules Matrix

${}^{k}dY(t_i)$\ ${}^{k}Rt_Y(t_i)$	Vinc	Inc	Same	Dec	Vdec
NVL	ZrH	PVLH	PVLH	PLH	PMH
NL	ZrH	PVLH	PLH	PMH	PSH
NM	ZrH	PLH	PMH	PSH	ZrH
NS	ZrH	PMH	PSH	ZrH	ZrH
ZR	ZrH	ZrH	ZrH	ZrH	ZrH
PS	ZrH	NMH	NSH	ZrH	ZrH
PM	ZrH	NPLH	NMH	NSH	ZrH
PL	ZrH	NVLH	NLH	NMH	NSH
PVL	ZrH	NVLH	NVLH	NLH	
NMH					

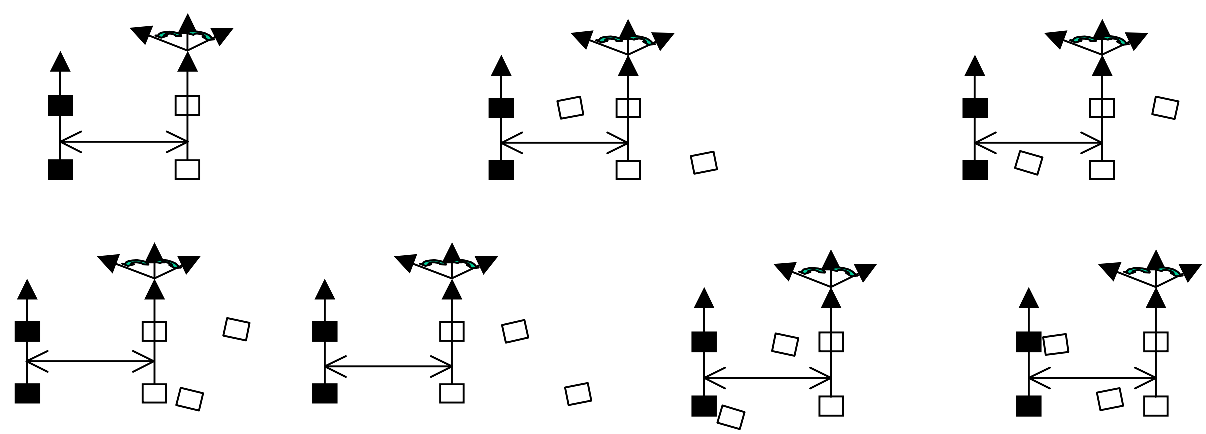

Fig. 3.3 The Pattern of Relative Behavior between Leader and Follower during a Time Step

${}^{k}Rt_Y(t_i)$ in Eq. 3.7, which is the rate of change of the value in Eq. 3.6, represents the temporal nonlinearity effected on two vehicles in the mission field during the time step. In an unknown and uncertain environment, based on these two factors, the pattern of possible relative coordinates between leader and follower in the time step can be classified as in Figure 3.3. The rules in the fuzzy inference engine are made from this pattern by using human's common driving skill.

The fuzzy expert system which has the type of Mamdani is implemented by the following sequence of reasoning process: 1) AND (Minimum) / OR (Maximum) method in applying fuzzy operator, 2) Minimum method in implication from the antecedent to the consequent, 3) Maximum method in aggregating all output, 4) The centroid calculation in defuzzification process of output fuzzy variable.

For the second input, ${}^{k}Rt_Y(t_i)$ having triangular and trapezoidal membership function, there are five fuzzy variables, {Very Increase (VInc), Increase (Inc), Same (S), Decrease (Dec), Very Decrease (Vdec) }, and the output variable, θc_k which has gaussian membership function has also nine fuzzy variables, {Negative Very Large Head (NVLH), Negative Large Head (NLH), Negative Medium Head (NMH), Negative Small Head (NSH), Zero Head (ZrH), Positive Small (PS), Head (PSH), Positive Medium Head (PMH), Positive Large Head (PLH), Positive Very Large Head (PVLH) }. The input domain range of input 1 is [-1.2 1.2] and [-1.35 3] for input 2. The output domain range is [-1 1] which are normalized values by $\pi/2$ in units of radian. The specification of each fuzzy set in input and output of the fuzzy inference system is shown in Figure 3.4.

The fuzzy rules having the form of " If ${}^{k}dY(t_i)$ is NVL *And* ${}^{k}Rt_Y(t_i)$ is Inc, *Then* θc_k is NVLH" can be expressed as in Table 3.1. Figure 3.5 shows the mathematical functional relationship of the fuzzy expert system.

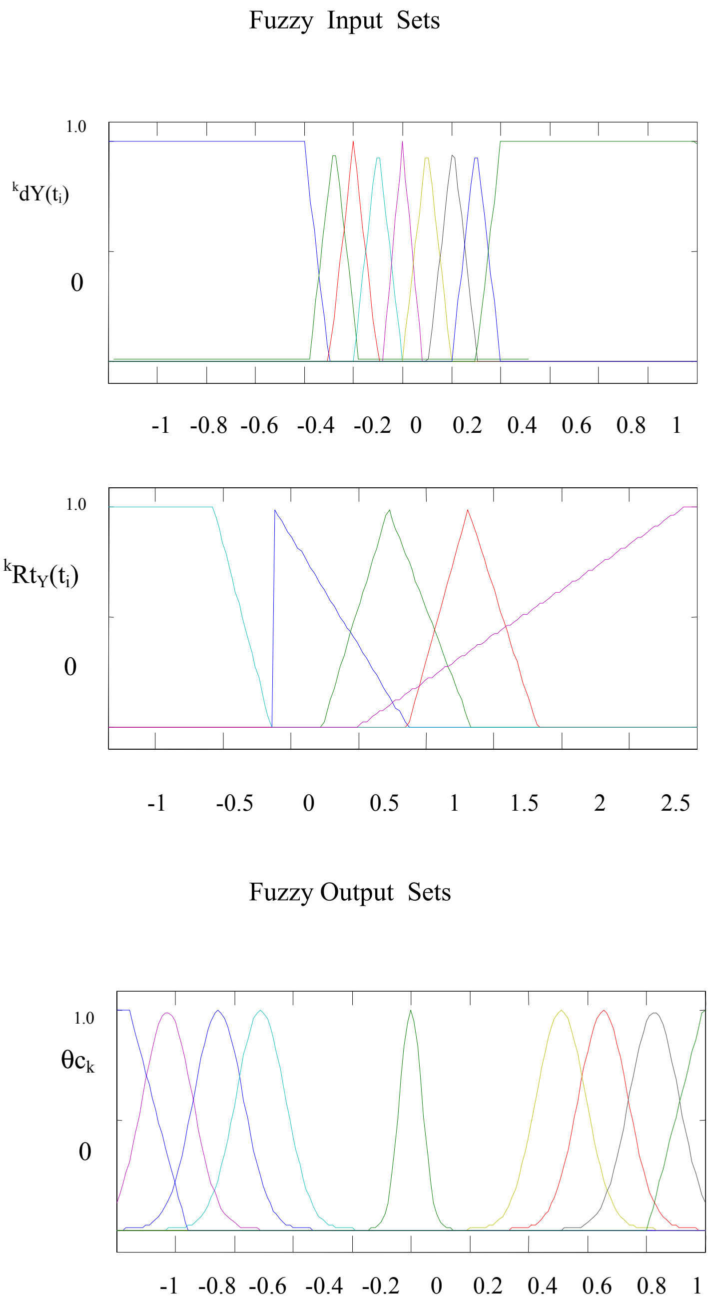

Fig. 3.4 Membership Functions of the Fuzzy Expert System of Fuzzy Sets.

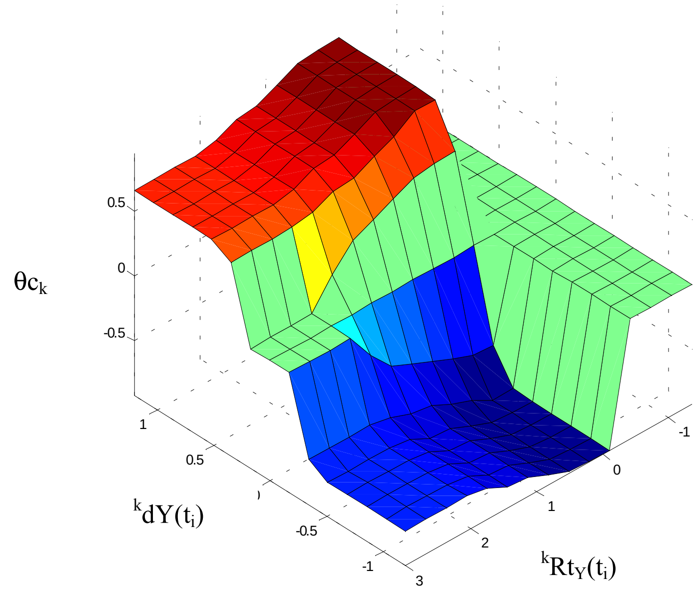

Fig. 3.5 Mathematical Function of Fuzzy Expert System

4. THE RESULTS OF SIMULATION

The dimensions of the vehicle used in simulation and in the design of the controller are weight (W) = 100 lb, length (L) = 2.3 ft, Width (B) = 2 ft and height = 1 ft.

A topography and a friction coefficient distribution are modeled in terms of two three dimensional cubic spline basis function surfaces to test the developed formation control. The topography shown in Figure 4.2, which is an obstacle free mission field has dimensions of 500 ft by 300 ft in the X and Y axes of the fixed coordinate system. The Z values which are generated at random, range between 0 and 30 ft. The friction distribution in between vehicle and ground is also generated randomly between 0.5 and 1.5.

The command trajectory of heading in Figure 4.1, which is assigned to a designated leader of decentralized mode, is generated in the 6^{th} order polynomial function of time, $\theta(t) = C_6 t^6 + C_5 t^5 + C_4 t^4 + C_3 t^3 + C_2 t^2 + C_1 t + C_0$, with the constant velocity of 1.5 ft/sec.

Figure 4.2 show the results of the simulation in which the developed formation control of Leader-Follower is applied to five UUCVs under centralized and decentralized modes. The plots in Figure 4.3 show the mutual distances between each UUCV in terms of X, Y, and Z directions.

The initial distances of all the vehicles are 24 ft and the desired mutual distances are set to 27 ft under the heading command trajectory of the leader UUCV.

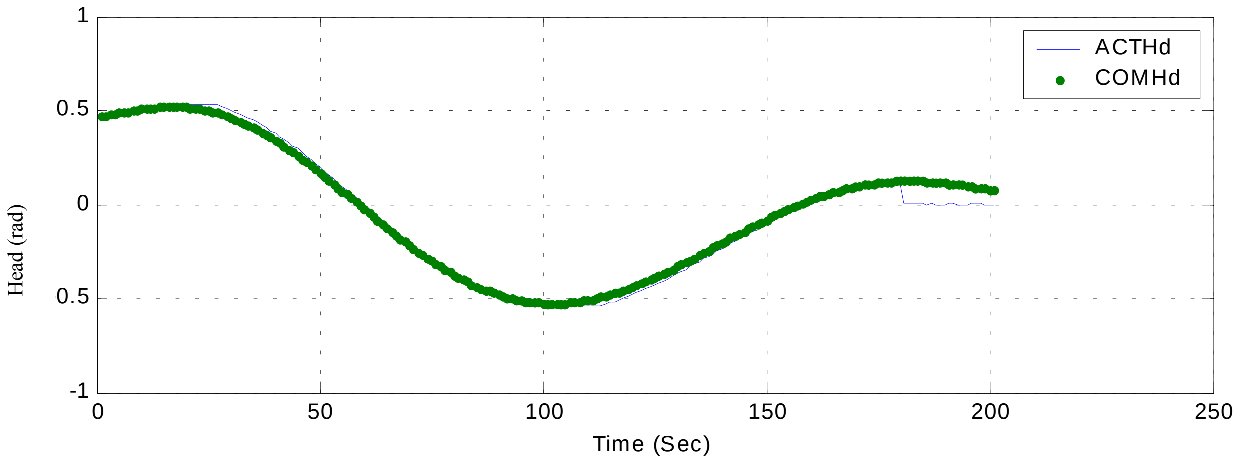

Fig. 4.1 The Commands and The Actual of Heading of Leader Vehicle

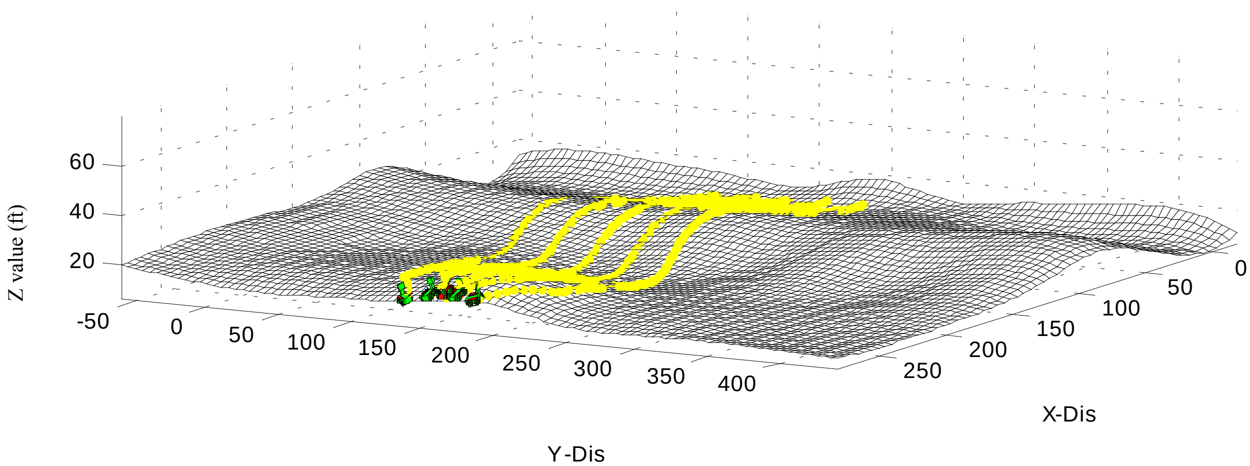

Fig. 4.2 Topography of Mission Field and Actual Trajectories of Multiple Vehicles

5. CONCLUSION AND FUTURE WORK

In this paper, we developed the formation control of UUCVs in the manner of Leader-Follower under centralized and decentralized trajectory generation modes.

This strategy was applied to an unknown and an uncertain mission field modeled by two three dimensional topography and friction distribution with the contact dynamics of vehicle. As the model of an intelligent agent, the fuzzy expert system in each individual vehicle showed its capability to maintain adaptively the mutual distance with a neighbor in the modeled environment.

The formation control of unmanned vehicle in the mission of search target is complicated and is required to achieve more intelligent behavior, particularly when there exist obstacles interrupting the moving vehicles. In future work we will adapt the Leader-Follower formation control to environments with obstacles, we will add a model to represent the sensor that detect obstacles, and we will develop method for planning UUCV's path to avoid them.

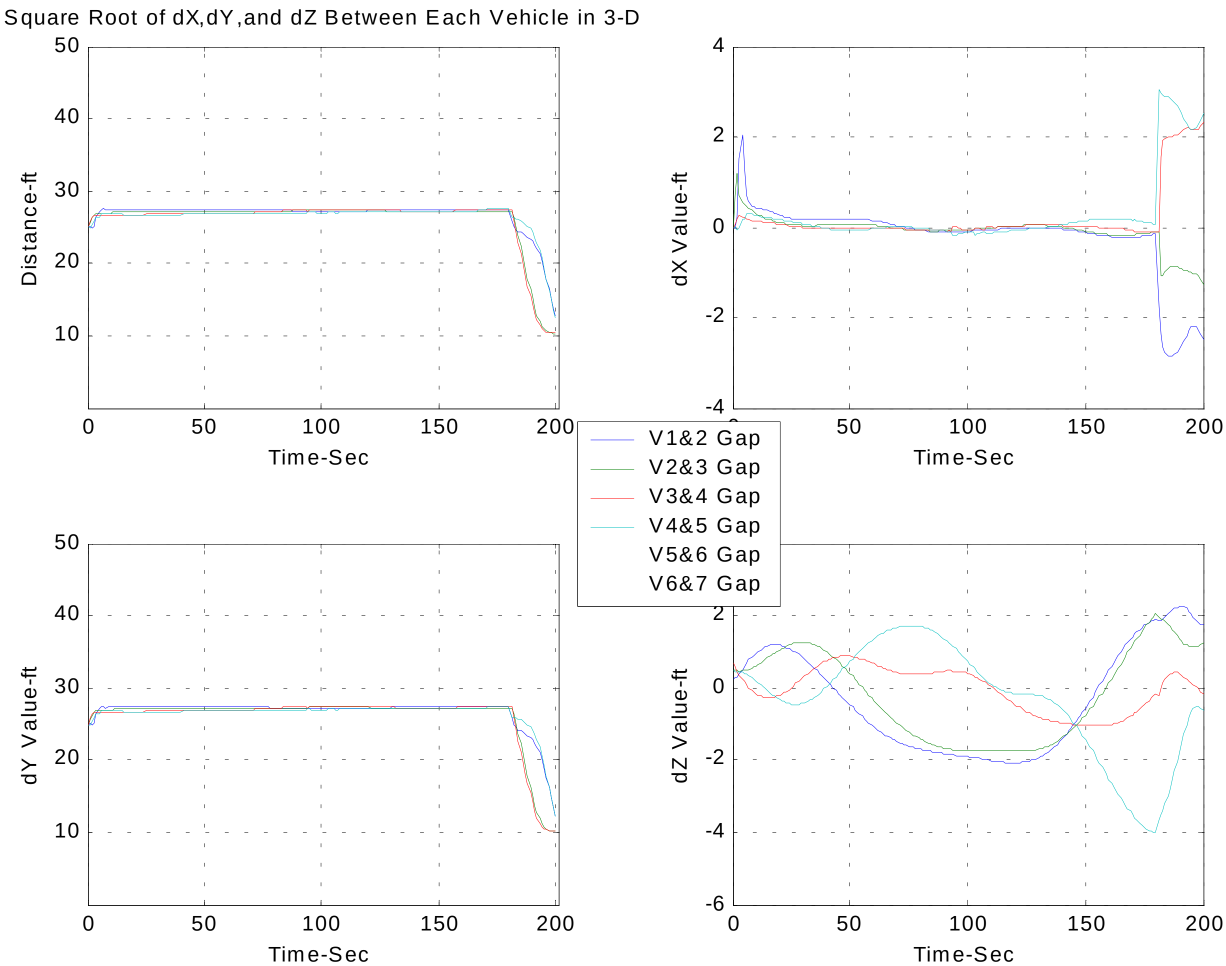

Fig. 4.3 The Mutual Distances of X,Y, and Z Values between Individual Vehicle

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