Fuzzy Trajectory Tracking Control of an Autonomous Air Vehicle

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***Abstract*—The development and the implementation of a new guidance law are addressed for a six dimensional trajectory tracking problem, three dimensions for position tracking and three dimensions for velocity tracking, of a micro air vehicle. To generate the desired trajectory a virtual leader is defined which is moved in space. In the guidance law, position and velocity feedbacks are used by fuzzy controllers to generate two acceleration commands. Then, a fuzzy coordinator is applied to coordinate the acceleration commands. Nonlinear six-degree-of-freedom equations of motion are used to model the vehicle dynamics. Also, a bank-to-turn acceleration autopilot for vehicle is considered to follow the acceleration commands. Simulations were carried out to verify the performance of the system. The results demonstrate the ability of the vehicle to track the desired trajectory.**

Keywords: Trajectory Tracking, Guidance Law, Fuzzy Logic, Micro Air Vehicle.

I. INTRODUCTION

Employment of micro air vehicles (MAVs) which are small, agile, and autonomous in urban areas is feasible thanks to progressing in the technology. The missions of the MAVs in urban areas can be sorted out into: over-buildings, among-buildings, and in-door operations. Accordingly, it is significant to precisely guide such vehicles along a desired trajectory. This is also vital for the operations involving groups of cooperative autonomous vehicles in which tracking a leader is one of the most important problem to be investigated as presented in [1]-[3]. Guiding a vehicle along a desired trajectory is called trajectory tracking. Note that the trajectory tracking is at least a four dimensional problem in which a desired point on the trajectory must be followed at each time. However, path following is a three dimensional problem in which the objective is to follow a desired path regardless of the time component. In [4], [5], the difference between the trajectory tracking and the path following is highlighted, notice that the each of them has its own characteristics.

There are two types of methods considered in the literatures for steering autonomous vehicles along a desired path or trajectory, which are underlined in [6]. One type regards the control and the guidance as two separate entities. In this approach, the guidance law is designed based on some simple rules in an outer loop to generate guidance commands to steer the vehicle. In addition, the autopilot is designed in an inner loop to control the vehicle to follow the guidance commands. In [6], [7], this approach is studied by using a derivation of the proportional navigation guidance law. Other work on this approach is presented in [8], where four different controllers are implemented. However, in the other type, designing the guidance law and the autopilot is taken place simultaneously in which modern control techniques can be employed. One of the works based on this approach is presented in [9] where the theory of gain-scheduled is used. Other works on this approach are [10], [11] which the controllers are designed via neural networks.

In this study, due to its advantages, the former method, which employing acceleration guidance commands, is used for the trajectory tracking. These advantages are, namely using the maximum performance of the vehicle, utilizing a simple guidance law which does not depend on the dynamics of the vehicle, and providing the possibility of applying traditional control theories in the inner loop. Besides, considering the time component provides the ability to track a real-time trajectory rather than a pre-defined path considered in the path following problem. However, it puts some constraints on the performance of the system. In this paper, position and velocity feedbacks are used by fuzzy controllers to generate two acceleration commands. For practical applications, it is expected to minimize the control efforts. The advantage of employing the fuzzy logic is to assure the effectiveness of the system with the constrained magnitude acceleration commands. Then, a fuzzy coordinator is applied to coordinate the acceleration commands by adjusting weights which are used in a combination. Since the control and guidance systems for the trajectory tracking include nonlinearities and uncertainties, the fuzzy logic is an appropriate approach for adjusting the weights since providing the robustness for the system.

In [12], using the fuzzy logic for adjusting the weights in the trajectory tracking problem is introduced, but the guidance law constitutes of unbounded gain feedbacks of position, speed, flight-path angle, and heading angle. In [13], a five dimensional guidance law is proposed for the trajectory tracking problem in which fuzzy controllers are used to produce smooth and bounded commands, however the flight-path angle is not followed and no coordination between generated commands is considered. Both of aforementioned works which are the most related works in the fuzzy trajectory tracking have some inadequacies. In this study, a general fuzzy guidance law together with a fuzzy coordinator for a six dimensional trajectory tracking, three dimensions for position tracking and three dimensions for velocity tracking, is developed and implemented on a six-degree-of-freedom dynamic model of an MAV.

The remainder of the paper is organized as follows. In section II, the guidance law is presented by designing two fuzzy controllers and then producing the resultant command by a fuzzy coordinator. The consideration in designing an acceleration autopilot is expressed in section III. In section IV, the MAV dynamics are modeled based on six-degree-of-freedom equations of motion. Section V offers detailed simulation results for the proposed guidance law and section VI summarizes the results and highlights our key points.

II. GUIDANCE LAW

The guidance law is used as a high-order control strategy which is placed in the outer loop. The purpose of the guidance law is to steer the vehicle along the desired trajectory such that the position and the velocity of the MAV asymptotically converge to those of the desired trajectory. To define the desired trajectory a point can be imagined which is moved in space; this point is called virtual leader (VL). Fig. 1 illustrates the geometry of the trajectory tracking problem which consists of the VL, the MAV, and an inertial frame by defining the displacement and velocity vectors.

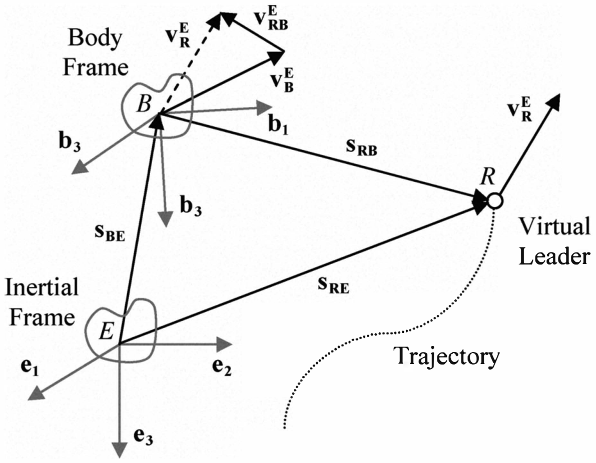

Figure 1. Geometry of the trajectory tracking problem.

where B is the base point and $\mathbf{b}_1$, $\mathbf{b}_2$, and $\mathbf{b}_3$ are the three base vectors of the MAV frame B, E is the base point and $\mathbf{e}_1$, $\mathbf{e}_2$, and $\mathbf{e}_3$ are the three base vectors of the inertial frame E, R is the point which stands for the VL, $\mathbf{s}_{BE}$ and $\mathbf{s}_{RE}$ are the displacement vectors of the MAV and the VL with respect to the inertial reference point respectively, $\mathbf{s}_{RB}$ is the displacement vector of the VL with respect to the MAV, $\mathbf{v}_B^E$ and $\mathbf{v}_R^E$ are the velocity vectors of the MAV and the VL with respect to the inertial reference frame respectively, and $\mathbf{v}_{RB}^E$ is inertial differential velocity of the VL with respect to the MAV. Notice, throughout this paper, the body coordinate system and the local level coordinate system are represented as $[.]^B$ and $[.]^L$. The symbols used in this paper are mainly quoted from [14].

The guidance law consists of two parts. One part generates acceleration command by using the position feedback of the MAV and comparing it with the position of the VL. This can be written as

$$[a_1]^L = \frac{f_1(|s_{RB}| - d_e)}{|s_{RB}|}[s_{RB}]^L \tag{1}$$

where $|.|$ represents the magnitude of a vector, d_e is the equilibrium distance between the MAV and the VL, and $\mathbf{s}_{RB}$ can be calculated as

$$[s_{RB}]^L = [s_{RE}]^L - [s_{BE}]^L \tag{2}$$

In (1) f_1 is a control function, so the acceleration command $\mathbf{a}_1$ is in the direction of $\mathbf{s}_{RB}$ and has the magnitude of $f_1(|s_{RB}|)$. Note that f_1 specifies the quickness of the control system response.

The other part of the guidance law works by comparing the velocity feedback of the MAV with the velocity of the VL, which its associated acceleration command can be written as

$$[a_2]^L = \frac{f_2(|v_{RB}^E|)}{|v_{RB}^E|}[v_{RB}^E]^L \tag{3}$$

where $\mathbf{v}_{RB}^E$ can be calculated as

$$[v_{RB}^E]^L = [v_R^E]^L - [v_B^E]^L \tag{4}$$

In (3) f_2 is a control function, so the acceleration command $\mathbf{a}_2$ is in the direction of $\mathbf{v}_{RB}^E$ and has the magnitude of $f_2(|v_{RB}^E|)$. Note that f_2 determines the damping characteristics of the control system. In fact, in the perspective of the control theory, this leads to an axial damping works in the direction of the line of sight (LOS), i.e. the line that connects the MAV to the VL, and a side damping operates perpendicular to the LOS. This causes the velocity of the VL to be followed by the MAV, i.e. the speed, the flight-path angle, and the heading angle of the VL are followed.

A. *Fuzzy Controller*

In this study, the control functions f_1 and f_2, which are described in the guidance law, are designed by fuzzy logic controllers (FLCs). Suppose that the FLC1 is employed for f_1 and the FLC2 for f_2. The main reason for employing the fuzzy logic is to generate the smooth and constrained magnitude acceleration commands. For constructing the FLC1 and the FLC2 Takagi-Sugeno (T-S) fuzzy systems are used, which are simple implementable fuzzy systems. The general form of the output of a T-S fuzzy system is

$$y^* = \frac{\sum_{l=1}^{m}\prod_{i=1}^{n}\mu_{A_i^l}(x_i)y^l}{\sum_{l=1}^{m}\prod_{i=1}^{n}\mu_{A_i^l}(x_i)} \tag{5}$$

where x_i is the ith component of the input vector, μ represents a membership function, A_i^l is the ith fuzzy set of the lth rule, y^l is the output of the lth rule, and y^* is the output of the T-S fuzzy system.

The input of the FLC1 is $|s_{RB}| \in [0, |s_{RB}|_{\max}]$ and the input of the FLC2 is $|v^E_{RB}| \in [0, |v^E_{RB}|_{\max}]$. The output of the FLC1 is $|a_1|$ and the output of the FLC2 is $|a_2|$.

The Fuzzy sets for inputs, $|s_{RB}|$ and $|v^E_{RB}|$, of the FLC1 and the FLC2 are negative (N), zero (Z), and positive (P). The membership functions correspond to these fuzzy sets are illustrated in Fig. 2.

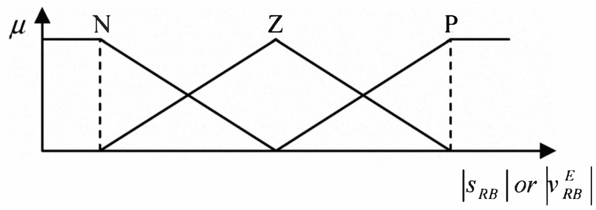

Figure 2. Input fuzzy membership functions of FLC1 and FLC2.

The fuzzy rule bases of the FLC1 and the FLC2 consist of three rules which are defined by Tables I and II.

TABLE I. FUZZY RULE BASE OF FLC1

	$\lvert s_{RB}\rvert$		
FLC1	N	Z	P
	y_s^1	y_s^2	y_s^3

TABLE II. FUZZY RULE BASE OF FLC2

	$\lvert v^E_{RB}\rvert$		
FLC2	N	Z	P
	y_v^1	y_v^2	y_v^3

In Table I, y_s^1 and y_s^3 is considered constant, and y_s^2 is considered an input linear function. The contents of Table I should be read as follows

$$IF\ |s_{RB}|\ is\ NB,\ THEN\ |a_1|\ is\ y_s^1 \quad \vdots \tag{6}$$

Also, in Table II, y_v^1 and y_v^3 is considered constant, and y_v^2 is considered an input linear function. The contents of Table II should be read as follows

$$IF\ |v^E_{RB}|\ is\ NB,\ THEN\ |a_2|\ is\ y_v^1 \quad \vdots \tag{7}$$

Notice that shapes and parameters of the membership functions and the rules in the fuzzy rule base affect the performance of the control system, so they should be specifically adjusted to achieve an appropriate performance for a particular system.

B. *Fuzzy Coordinator*

Having produced the two acceleration commands, they must be combined in order to obtain the resultant acceleration command. This is done by a fuzzy coordinator (FC). Employing the fuzzy logic as a coordinator provides an improved performance since making the system to be robust against disturbances and uncertainties. The resultant acceleration is considered as a weighted summation of the two accelerations, so it can be expressed as

$$[a]^L = w_1 [a_1]^L + w_2 [a_2]^L \tag{8}$$

where w_1 is the weight associated to the position feedback acceleration command and w_2 is the weight associated to the velocity feedback acceleration command.

Intuitively, we know that if the distance between the vehicle and the VL is too far, it is preferred to move the vehicle toward the VL quickly. So a big control signal is desired to reach a fast rise time. To produce a big control signal, the FC should increase w_1 and decrease w_2. On the other hand, if the vehicle is in the almost equilibrium distance with respect to the VL, it is preferred to amplify the damping characteristics to eliminate the overshoots. For this purpose, the FC should increase w_2 and decrease w_1. The fuzzy system theory makes it feasible to model the human linguistic knowledge and experiences in the mathematical form. So to model the above remarked knowledge, a fuzzy coordinator is used.

In this study, the fuzzy coordinator is designed based on a fuzzy system constitutes of a singleton fuzzifier, a Mamdani-product fuzzy inference engine, and a center of gravity defuzzifier. This fuzzy system is able to completely represent human knowledge in a mathematical form. Hence, the mathematical function of this fuzzy system can be expressed as

$$\mu_{B'}(y) = \max_{l=1}^{m}\left(\prod_{i=1}^{n} \mu_{A_i^l}(x_i)\,\mu_{B^l}(y)\right) \tag{9}$$

$$y^* = \frac{\int_v y\,\mu_{B'}(y)\,dy}{\int_v \mu_{B'}(y)\,dy} \tag{10}$$

where x_i is the ith component of the input vector, μ represents a membership function, A_i^l is the ith fuzzy set in the if-part of the lth rule, y is the output variable, B^l is the fuzzy set in the then-part of the lth rule, B' is the output fuzzy set, and y^* is the crisp output of the fuzzy system.

The inputs of this fuzzy coordinator are considered $|s_{RB}| \in [0, |s_{RB}|_{\max}]$ and $|v^E_{RB}| \in [0, |v^E_{RB}|_{\max}]$, and its outputs are the corresponding weights to each acceleration command, which are $w_1 \in [0,1]$ and $w_2 \in [0,1]$. As it was expressed, w_1, w_2 are considered the normalized weights between zero and one.

It should be mentioned, fuzzy systems are multi-input single-output systems so two fuzzy systems must be employed here, each of which generates one weight as an output, although they have similar inputs. It is considered that the FC1 is employed for w_1 and the FC2 for w_2.

The fuzzy sets for each input of the FC1 and the FC2 are negative big (NB), negative medium (MM), negative small (NS), approximately zero (ZO), positive small (PS), positive medium (PM), and positive big (PB). The fuzzy sets for their outputs are small (SM) and big (BG). The membership functions correspond to these fuzzy sets are illustrated in Fig. 3 and Fig. 4.

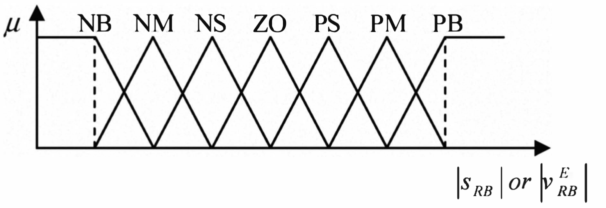

Figure 3. Input fuzzy membership functions of FC1 and FC2.

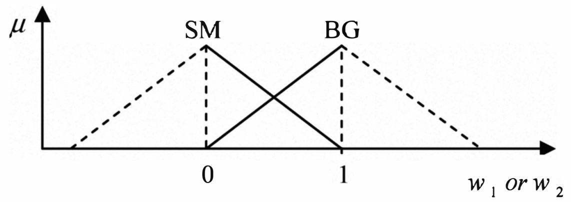

Figure 4. Output fuzzy membership functions of FC1 and FC2.

A fuzzy rule base is the most important part of a fuzzy system, which carries the linguistic knowledge with itself. The fuzzy rule base of the FC1 is shown in Table III and that of the FC2 is shown in Table IV.

TABLE III. FUZZY RULE BASE OF FC1

FC1		$\lvert v^E_{RB} \rvert$						
		NB	NM	NS	ZO	PS	PM	PB
$\lvert s_{RB} \rvert$	NB	BG	BG	BG	BG	BG	BG	BG
	NM	SM	BG	BG	BG	BG	BG	SM
	NS	SM	SM	BG	BG	BG	SM	SM
	ZO	SM	SM	SM	BG	SM	SM	SM
	PS	SM	SM	BG	BG	BG	SM	SM
	PM	SM	BG	BG	BG	BG	BG	SM
	PB	BG	BG	BG	BG	BG	BG	BG

TABLE IV. FUZZY RULE BASE OF FC2

FC2		$\lvert v^E_{RB} \rvert$						
		NB	NM	NS	ZO	PS	PM	PB
$\lvert s_{RB} \rvert$	NB	SM	SM	SM	SM	SM	SM	SM
	NM	BG	BG	SM	SM	SM	BG	BG
	NS	BG	BG	BG	SM	BG	BG	BG
	ZO	BG	BG	BG	BG	BG	BG	BG
	PS	BG	BG	BG	SM	BG	BG	BG
	PM	BG	BG	SN	SM	SM	BG	BG
	PB	SM	SM	SM	SM	SM	SM	SM

The contents of Table III, since it has two inputs, should be read as follows

$$IF\ \lvert s_{RB} \rvert\ is\ NB\ AND\ \lvert v^E_{RB} \rvert\ is\ NB,\ THEN\ w_1\ is\ BG \tag{11}$$

$\vdots$

The contents of Table IV, since it has two inputs, should be read as follows

$$IF\ \lvert s_{RB} \rvert\ is\ NB\ AND\ \lvert v^E_{RB} \rvert\ is\ NB,\ THEN\ w_2\ is\ SM \tag{12}$$

$\vdots$

III. AUTOPILOT

In order to execute the generated acceleration guidance commands, an autopilot is used to convert them into the MAV's control surfaces commands. Thus, the autopilot is a low level controller which is placed in the inner loop. In Fig. 5 the inner and the outer control loops and the positions of the guidance law and the autopilot for an autonomous air vehicle is demonstrated.

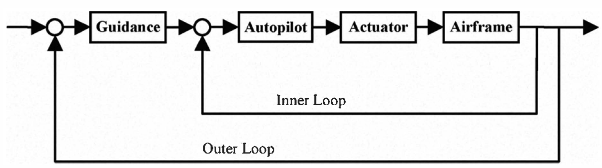

Figure 5. Guidance law and autopilot in the inner and outer loops.

It is necessary to modify the output of the guidance law to an appropriate form before it is used by the MAV's autopilot. These modifications are applied in several steps. In the first step, in order to consider the ballistic part of the acceleration, the acceleration command produced by guidance law, **a** , must be compensated by the gravity acceleration. This can be written as

$$[a_{comp}]^L = [a]^L - [g]^L \tag{13}$$

where $\mathbf{a_{comp}}$ is the compensated acceleration command and **g** is the gravity acceleration vector.

Furthermore, inasmuch as the acceleration command is expressed in the local level coordinate system, it must be transformed to the body coordinate system. This is done by using the transformation matrix between the body coordinate system and the local level coordinate system

$$[a_{comp}]^B = [T]^{BL} [a_{comp}]^L \tag{14}$$

where $[T]^{BL}$ is the transformation matrix between the body coordinate system and the local level coordinate system.

Finally, since the produced acceleration command is suitable for skid-to-turn (STT) vehicles it is required to be converted to an acceleration which can be used by the MAV as a bank-to-turn (BTT) vehicle. The STT acceleration command can be expressed as

$$[\bar{a}_{comp}]^B = [a^S_x \quad a^S_y \quad a^S_z] \tag{15}$$

By applying the conversion between the STT and the BTT coordinates, roll command and acceleration command for a BTT vehicle is derived as

$$\Delta\phi = \tan^{-1}\left(\frac{-a^S_y}{a^S_z}\right) \tag{16}$$

$$a^B = \mathrm{sgn}\left(a_z^S\right)\sqrt{\left(a_y^S\right)^2 + \left(a_z^S\right)^2} \quad (17)$$

where $\Delta\phi$ is the BTT error roll command, a^B is the BTT acceleration command, and sgn is the sign function.

To design the autopilot, the linear model of MAV must be determined since almost all of the control theory is based on the linear systems. Herein, the linear model was derived based on the perturbation method. In this study, the linear model of the MAV was investigated in 4 channels which are roll, pitch, yaw, and axial. Then, a controller was designed based on modern control theory in the each channel.

IV. Vehicle Dynamics

The nonlinear six-degree-of-freedom equations of motion of the MAV which consist of the dynamic and the kinematic equations can be written as below. More information about derivation is available in [14].

$$\left[I_B^B\right]^B\left[\frac{d\,\omega^{BE}}{dt}\right]^B + \left[\Omega^{BE}\right]^B\left[I_B^B\right]^B\left[\omega^{BE}\right]^B = \left[m_B\right]^B \quad (18)$$

$$m\left[\frac{dv_B^E}{dt}\right]^B + m\left[\Omega^{BE}\right]^B\left[v_B^E\right]^B = \left[f_a\right]^B + \left[f_p\right]^B + m\left[T\right]^{BL}\left[g\right]^L \quad (19)$$

$$\left[\frac{ds_{BE}}{dt}\right]^L = \left[\bar{T}\right]^{BL}\left[v_B^E\right]^B \quad (20)$$

$$\{\dot{q}\} = \frac{1}{2}\begin{bmatrix} 0 & -\left[\bar{\omega}^{BE}\right]^B \\ \left[\omega^{BE}\right]^B & -\left[\Omega^{BE}\right]^B \end{bmatrix}\{q\} \quad (21)$$

where m is the mass and $\mathbf{I_B^B}$ is the moment of inertia matrix of the MAV, $\mathbf{v_B^E}$ and $\boldsymbol{\omega}^{\mathbf{BE}}$ are the linear and angular velocity vectors of the MAV with respect to the inertial frame respectively, $\boldsymbol{\Omega}^{\mathbf{BE}}$ is the skew symmetric matrix of the angular velocity vector, $\mathbf{s_{BE}}$ is the displacement vector of the MAV with respect to the inertial frame, $\mathbf{f_a}$ and $\mathbf{f_P}$ are the aerodynamic and propulsion force vectors respectively, $\mathbf{m_B}$ is the aerodynamic moment vector with respect to the center of mass of the MAV, $[\bar{T}]^{BL}$ is the transpose of $[T]^{BL}$, and $\mathbf{q}$ is the four-component quaternion; note that the quaternions rather than the Euler angles are used to express the attitude of the MAV to avoid the singularities of the Euler angles in the high pitch maneuvers.

Not that the control inputs of the vehicle are elevator, ailerons, rudder, and throttle setting. The aerodynamic model of the MAV was obtained by using the extension series of the aerodynamic coefficients about a nominal reference condition. A simple propulsion model is used by neglecting the propulsion moments and considering the thrust force in the direction of the first axis of the body coordinate system. Moreover, the control surfaces and throttle actuators are modeled as first-order filters with rate and magnitude limits. The general specifications of the studied MAV are as follow: $m = 0.445\ kg$, $I_{xx} = 0.002\ kg.m^2$, $I_{yy} = 0.008\ kg.m^2$, $I_{zz} = 0.01\ kg.m^2$, $I_{xz} = 2.10e-4\ kg.m^2$, $b = 0.61\ m$, $S = 0.089\ m^2$, $\bar{c} = 0.147\ m$, $V_{cruise} = 15\ m/s$, $T_{max} = 3.2\ N$, the minimum and the maximum control surface deflections are $-15\deg$ and $+15\deg$, and the minimum and the maximum control surface rate limits are considered $-50\deg/s$ and $+50\deg/s$.

V. Simulation

The designed system consists of the inner loop and the outer loop controllers as well as the MAV dynamics were tested in a scenario with a nonlinear simulation environment developed by using MATLAB®/Simulink. In this scenario the MAV is to track a coordinated and level turn trajectory specified by the VL. The initial conditions of the MAV are

$$\left[\bar{s}_{BE}\right]^L = \begin{bmatrix}-100 & 110 & 0\end{bmatrix} \quad (23)$$

$$\left[\bar{v}_B^E\right]^B = \begin{bmatrix}15 & 0 & 0\end{bmatrix} \quad (24)$$

It is considered $d_e = 0\ m$ and the desired trajectory for the coordinated and level turn defined by the VL is written as

$$\left[\bar{s}^{RE}\right]^L = \left[100\sin(0.15t+0.1) \quad 100\cos(0.15t+0.1) \quad -100\right] \quad (25)$$

where t stands for time component. Therefore, the velocity vector of the VL is computed as

$$\left[\bar{v}_R^E\right]^L = \left[15\cos\left(0.15t+0.1\right) \quad -15\sin\left(0.15t+0.1\right) \quad 0\right] \quad (26)$$

The trajectories of the MAV and the VL are illustrated in Fig. 6. As it can be seen, the MAV could move toward the desired trajectory from the initial position and then could converge to it. The reason that the MAV could smoothly converge to the trajectory is its attempt to match its speed, flight-path angle, and heading angle with those of the VL while approaching to the VL, i.e. while matching its position with position of the VL. Fig. 7 shows how the position vector of the MAV could converge to the position vector of the VL in spite of the position deviation seen at the initial time and Fig. 8 shows how the velocity vector of the MAV could converge to the velocity vector of the VL.

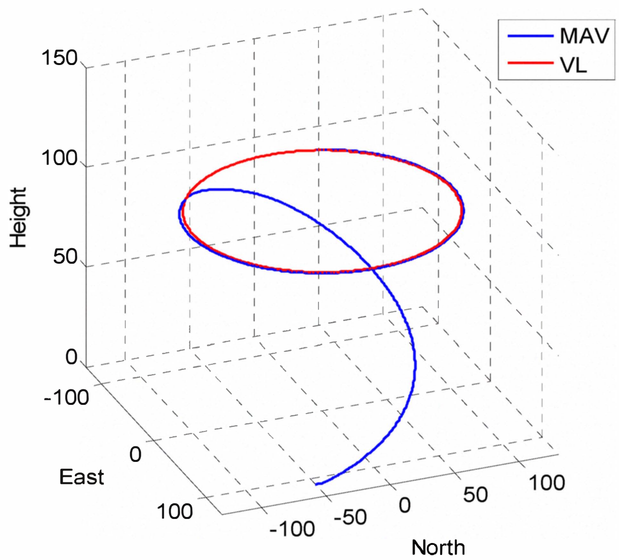

Figure 6. Trajectories of MAV and VL in the 3D space.

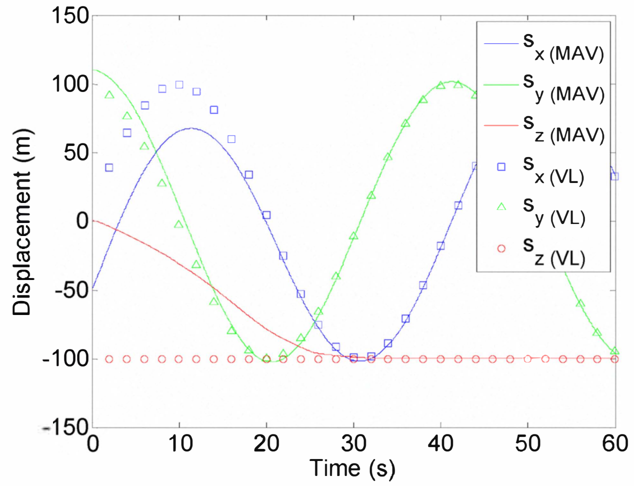

Figure 7. Components of the displacement vectors of MAV and VL.

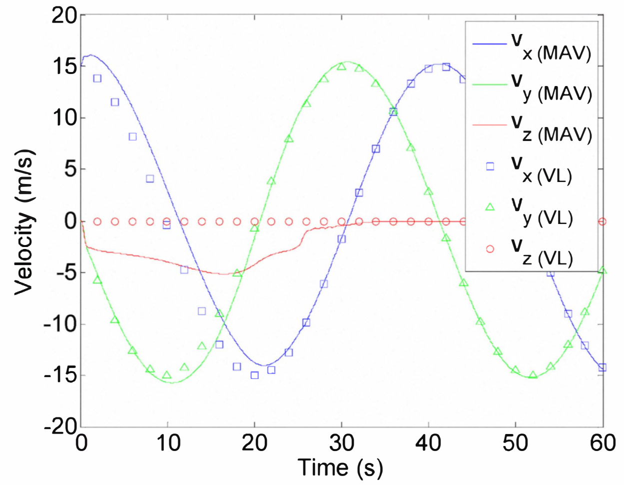

Figure 8. Components of the velocity vectors of MAV and VL.

VI. CONCLUSION

In this study, a new guidance law based on the fuzzy logic was investigated for the trajectory tracking problem. Two guidance commands were constructed by employing the fuzzy controllers. Then, the fuzzy coordinator was used to coordinate these guidance commands. The autopilot and the six-degree-of-freedom equations of motion for a MAV were also taken into account. The simulation results showed that the vehicle is able to move toward a desired trajectory from any initial point in the space, and then converges to it asymptotically. Since the guidance law is a six dimensional one, the vehicle approaches to the desired trajectory while attempting to match its speed, flight-path angle, and heading angle with those of the VL so it leads the vehicle to move on a smooth tracking course.

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