A study on Synchronization method for Mutual Cooperative Control in the Chaotic UAV

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Abstract**—**In this paper, we propose to synchronization method for mutual cooperative control method that have unstable limit cycles in a chaos trajectory surface in the chaotic UAVs. We assume all obstacles in the chaos trajectory surface have a Van der Pol equation with an unstable limit cycle.

We also show computer simulation results of Arnold equation, Chua's equation trajectories with one or more Van der Pol as a obstacles. We proposed and verified the results of the method to make the embedding chaotic UAV to synchronization with the chaotic trajectory in any plane.

Index Terms**—**Chaos, UAV, Arnold equation, Chua's equation, synchronization.

I. INTRODUCTION

CHAOS theory has been drawing a great deal of attention in the scientific community for almost two decades. Remarkable research efforts have been spent in recent years, trying to export concepts from Physics and Mathematics into real world engineering applications. Applications of chaos are being actively studied in such areas as chaos control [1]-[2], chaos synchronization and secure/crypto communication [3]-[7], Chemistry [8], Biology [9] and robots and their related themes [10].

Recently, Nakamura, Y. et al [10] proposed a chaotic mobile robot where a mobile robot is equipped with a controller that ensures chaotic motion and the dynamics of the mobile robot are represented by an Arnold equation. They applied obstacles in the chaotic trajectory, but they did not mention obstacle avoidance methods.

In this paper, we propose to synchronization method for mutual cooperative control in the chaotic UAVs using coupled- synchronization with unstable limit cycles in the chaos trajectory surface. We assume that all obstacles in the chaos trajectory surface have a Van der Pol equation with an unstable limit cycle. When the chaos UAVs meet to obstacle among their arbitrary wandering in the chaos trajectory, which is derived using chaos circuit equations such as the Arnold equation, Chua's equation, the target absorptive the chaos UAVs.

Computer simulations also show multiple obstacles can be avoided with an Arnold and Chua's equation We proposed and verified the results of the method to make the embedding chaotic UAV to target search with the chaotic trajectory in any plane. It searched the target when it meets or closes to the target.

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II. CHAOTIC UAV EQUATION

A. UAV[24]

We assume that each UAV is equipped with standard autopilots for heading hold and mach hold. In order to focus on the essential issues, we will assume that altitude is held constant. Let $(x,y),\psi,$ and v denote the inertial position, heading angle, and velocity for the UAV respectively. Then the resulting kinematics equations of motion are

$$\begin{aligned}\dot{x} &= v\cos(\psi)\\ \dot{y} &= v\sin(\psi)\\ \dot{\psi} &= \alpha_\psi(\xi^c-\psi)\\ \dot{v} &= \alpha_v(v^c-v)\end{aligned} \tag{1}$$

where ψ^c and v^c are the commanded heading angle and velocity to the autopilots, and α_ψ and α_v are positive constraints [22,23].

Assuming that α_v is large compared to α_ψ, Eq. (1) reduces to

$$\begin{aligned}\dot{x} &= v\cos(\psi)\\ \dot{y} &= v\sin(\psi)\\ \dot{\psi} &= \alpha_\psi(\xi^c-\psi)\end{aligned} \tag{2}$$

Letting $\psi^c = \psi + (1/\alpha_\psi)\omega$ and $v^c \approx v$, Eq. (2) becomes

$$\begin{aligned}\dot{x} &= v\cos(\psi)\\ \dot{y} &= v\sin(\psi)\\ \dot{\psi} &= \omega\end{aligned} \tag{3}$$

Eq.(3) rewritten as follows,

$$\begin{pmatrix}\dot{x}\\ \dot{y}\\ \dot{\psi}\end{pmatrix} = \begin{pmatrix}\cos\theta & 0\\ \sin\theta & 0\\ 0 & 1\end{pmatrix}\begin{pmatrix}v\\ \omega\end{pmatrix} \tag{4}$$

Eq. (3) is similar to two wheel mobile robot equation.

B. Chaos equations

In order to generate chaotic motions for the UAV, we apply chaos equations such as an Arnold equation or Chua's circuit equation.

1) Arnold equation [10]

We define the Arnold equation as follows:

$$\begin{aligned} \dot{x}_1 &= A\sin x_3 + C\cos x_2 \\ \dot{x}_2 &= B\sin x_1 + A\cos x_3 \\ \dot{x}_3 &= C\sin x_2 + B\cos x_1 \end{aligned} \quad (5)$$

where A, B, C are constants. The Arnold equation describes a steady solution to the three-dimensional (3D) Euler equation

$$\frac{\partial v_i}{\partial t} + \sum_{k=1}^{3} v_k \frac{\partial v_i}{\partial x_k} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + f_i \quad (6)$$

$$\sum_{i=1}^{3} \frac{\partial v_i}{\partial x_i} = 0 \quad (7)$$

which express the behaviors of noncompressive perfect fluids on a 3D torus space. (x_1, x_2, x_3) and (v_1, v_2, v_3) denote the position and velocity of particle and p, and (f_1, f_2, f_3) and ρ denote the pressure, external force, and density, respectively. It is known that the Arnold equation shows periodic motion when one of the constant, for example C, is 0 or small and shows chaotic motion when C is large[14].

2) Chua's Circuit Equation (2-Double Scroll)

Chua's circuit is one of the simplest physical models that has been widely investigated by mathematical, numerical and experimental methods. One of the main attractions of Chua's circuit is that it can be easily built with less than a dozen standard circuit components, and has often been referred to as the "poor man's chaos generator." Since the Chua's circuit is endowed with an unusually rich repertoire of nonlinear dynamical phenomena, it has become a universal paradigm for chaos. The Chua's circuit and their nonlinear resister are shown on Fig. 1 ,2 respectively.

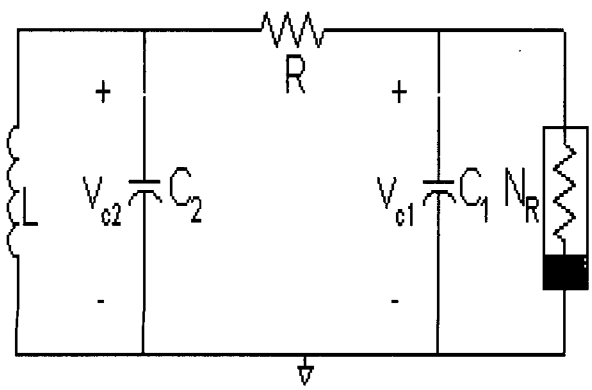


Fig. 1 Chua's circuit.

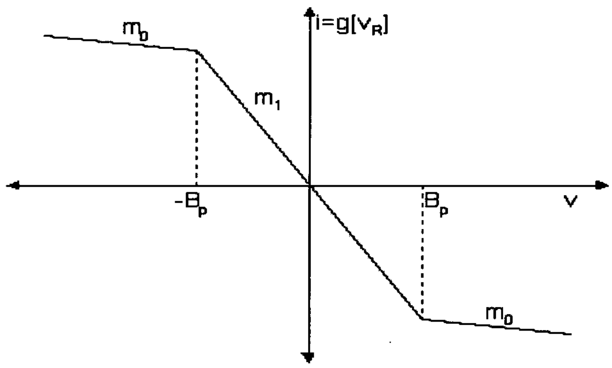


Fig. 2 Nonlinear resistor.

We can derive the state equation of Chua's circuit following as from Fig. 1 and 2 and then we also can get the phase plane looks like Fig. 3

$$\begin{aligned} \dot{x}_1 &= \alpha(x_2 - g(x_1)) \\ \dot{x}_2 &= x_1 - x_2 + x_3 \\ \dot{x}_3 &= -\beta x_2 \end{aligned} \quad (8)$$

where

$$g(x) = m_{2n-1}x + \frac{1}{2}\sum_{k=1}^{2n-1}(m_{k-1} - m_k)(|x + c_k| - |x - c_k|).$$

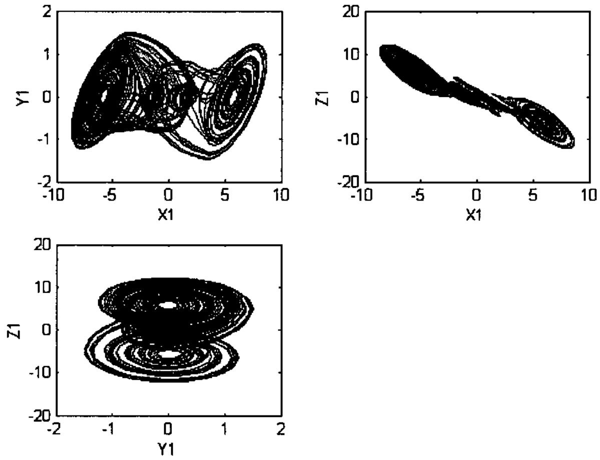


Fig. 3 Phase plane of Chua's circuit.

C. Embedding of chaos circuit in the UAV

In order to embed the chaos equation into the UAV, we define and use the Arnold equation and Chua's circuit equation as follows.

1) Arnold equation

We define and use the following state variables:

$$\begin{aligned} \dot{x}_1 &= D\dot{y} + C\cos x_2 \\ \dot{x}_2 &= D\dot{x} + B\sin x_1 \\ \dot{x}_3 &= \theta \end{aligned} \quad (9)$$

where B, C, and D are constant.

Substituting (4) into (9), we obtain a state equation on $\dot{x}_1$, $\dot{x}_2$, and $\dot{x}_3$ as follows:

$$\begin{aligned} \dot{x}_1 &= Dv + C\cos x_2 \\ \dot{x}_2 &= Dv + B\sin x_1 \\ \dot{x}_3 &= \omega \end{aligned} \tag{10}$$

We now design the inputs as follows [10]:

$$\begin{aligned} v &= A/D \\ \omega &= C\sin x_2 + B\cos x_1 \end{aligned} \tag{11}$$

Finally, we can get the state equation of the UAV as follows:

$$\begin{aligned} \dot{x}_1 &= A\sin x_3 + C\cos x_2 \\ \dot{x}_2 &= B\sin x_1 + A\cos x_3 \\ \dot{x}_3 &= C\sin x_2 + B\cos x_1 \\ \dot{x} &= V\cos x_3 \\ \dot{y} &= V\sin x_3 \end{aligned} \tag{12}$$

Equation (12) includes the Arnold equation. Fig. 3 shows the phase plane of the gradients of the UAV of Arnold equation in x-y plane and in 3D plane respectively.

In the Nakamura et al.[10], they used phase plane components such as $(x,y),(y,z),(z,x)$ in the equation (12), but we used gradients of each variables such as, $\frac{\partial x}{\partial t},\frac{\partial y}{\partial t},\frac{\partial z}{\partial t}$ for convenience in computation of chaotic path of the UAV .

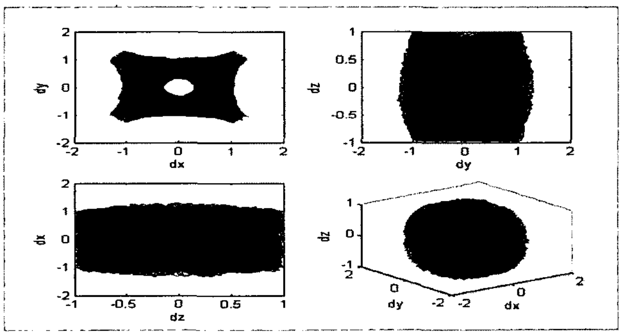


Fig. 3 Phase plane of gradient $(\frac{\partial x}{\partial t},\frac{\partial y}{\partial t},\frac{\partial z}{\partial t})$ of Arnold equation in x-y plane and in 3D (v=1, A=1, B=0.5, C=0.5)

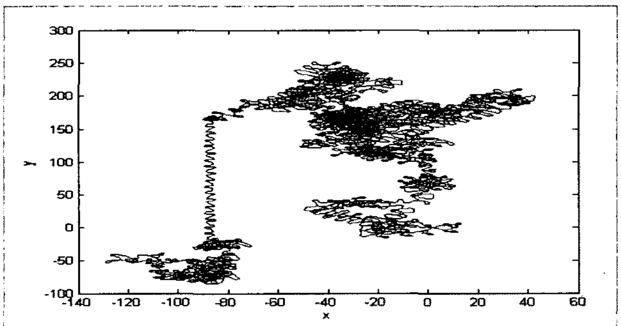


Fig. 4 Trajectory of the UAV of Arnold equation, when there is no boundary.

2) Chua's equation

Using the methods explained in equations (9)-(12), we can obtain equation (13) with Chua's equation embedded in the UAV.

$$\begin{aligned} \dot{x}_1 &= \alpha(x_2 - g(x_1)) \\ \dot{x}_2 &= x_1 - x_2 + x_3 \\ \dot{x}_3 &= -\beta x_2 \\ \dot{x} &= V\cos x_3 \\ \dot{y} &= V\sin x_3 \end{aligned} \tag{13}$$

Using equation (10), we obtain the embedding UAV trajectories with Chua's equation. Fig. 5 shows the phase plane of the gradients of Chua's equation, which is used for the computational convenience as in the Chua's equation.

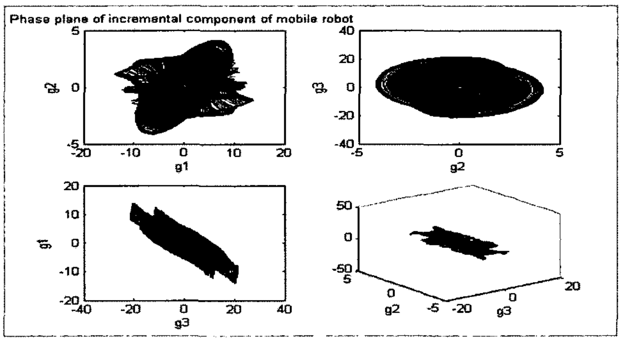


Fig. 5 Phase portrait of gradient vector $(\frac{\partial x}{\partial t},\frac{\partial y}{\partial t},\frac{\partial z}{\partial t})$ in Chua's circuit.

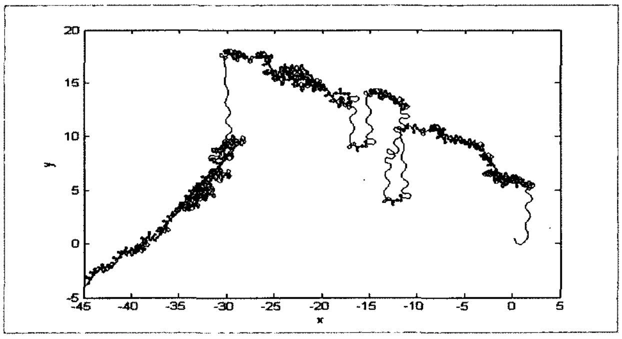


Fig. 6 Trajectory of the UAV of Chua's equation, when there is no boundary.

D. Mirror mapping.

Equation (12) and (13) assume that the UAV moves in a smooth state space without boundaries. However, real UAV move in space with boundaries like walls or surfaces of obstacles. To avoid a boundary or obstacle, we consider mirror mapping when the UAV approach walls or obstacles using Eq. (14) and (15). Whenever the UAVs approach a wall or obstacle, we calculate the UAVs' new position by using Eq. (14) or (15).

$$A = \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix} \tag{14}$$

$$A = 1/1+m \begin{pmatrix} 1-m^2 & 2m \\ 2m & -1+m^2 \end{pmatrix} \quad (15)$$

We can use equation (11) when the slope is infinity, such as $\theta = 90$, and use equation (12) when the slope is not infinity.

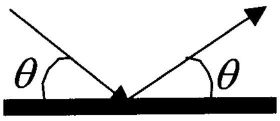


Fig. 7 Mirror mapping

III. NUMERICAL ANALYSIS OF THE BEHAVIOR OF THE CHAOS UAV

We investigated by numerical analysis whether the UAV with the proposed controller actually behaves in a chaotic manner. In order to computer simulation, we applied mirror mapping and have shown it in Fig. 7. The parameters and initial conditions are used as follows:

A. Arnold equation case

Coefficients:

v= 1[m/s], A= 0.5[1/s], B=0.25[1/s], C=0.25[1/s]

Initial conditions:

$x_1 = 4, \quad x_2 = 3.5, \quad x_3 = 0, \quad x = 0, \quad y = 0$

B. Chua's equation case

Coefficients:

$\alpha = 9, \ \beta = 14.286$

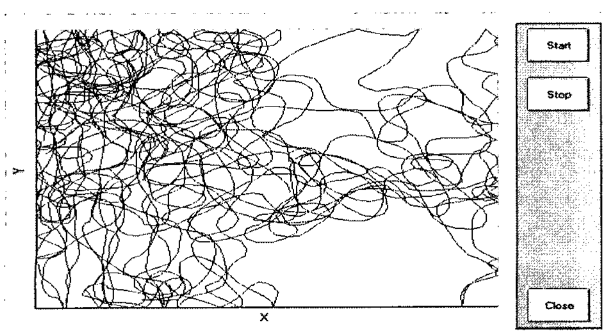
$m_0 = -\frac{1}{7}, \ m_1 = \frac{2}{7}, m_2 = -\frac{4}{7}, \ m_3 = m_1$

$c_1 = 1, \ c_2 = 2.15, \ c_3 = 3.6$

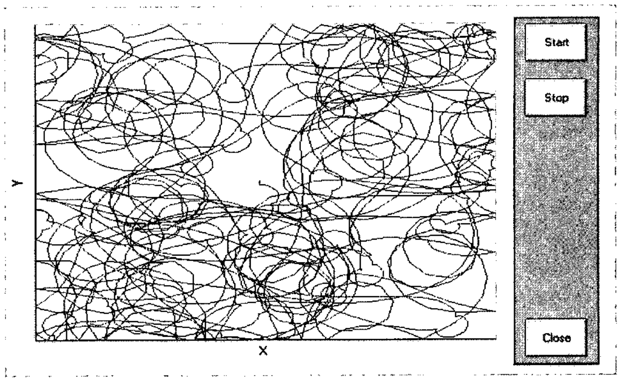
Initial conditions:

$x_1 = 4, \quad x_2 = 3.5, \quad x_3 = 0, \quad x = 0, \quad y = 0$

Fig. 8 shows the trajectories in which mirror mapping was applied only on the outer wall. In this case, the chaos UAV has no obstacles, and we can confirm that the UAV is adequately meandering along the trajectories of Arnold and Chua's equation, and are covering the whole space in their chaotic manner.



(a) Arnold equation



(b) CHUA'S EQUATION

Fig. 8 Trajectory of the UAV, when boundary exists.

IV. THE CHAOTIC BEHAVIOR OF CHAOS UAV WITH MIRROR MAPPING AND OBSTACLE

In this section, we will study avoidance behavior of a chaos trajectory with obstacle mapping, relying on the Arnold equation and Chua's equation respectively.

Fig. 9 and 10 show that a chaos UAV trajectories to which mirror mapping was applied in the outer wall and in the inner obstacles as well using Eq. (11) and (12), relying on Arnold equation (9) and Chua's equation (10). The chaos UAV has two fixed obstacles, and we can confirm that the UAV adequately avoided the fixed obstacles in the Arnold and Chua's chaos UAV trajectories.

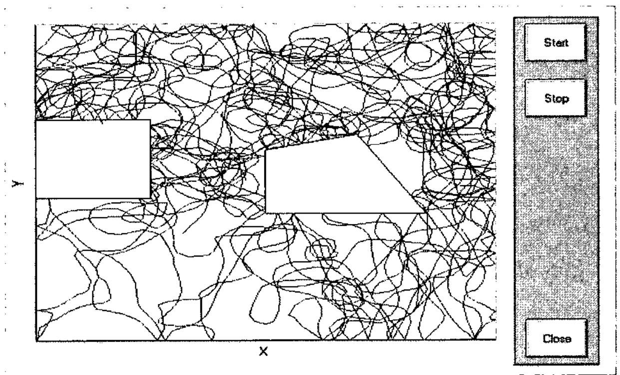


Fig. 9 Arnold equation trajectories of chaos UAV with obstacle.

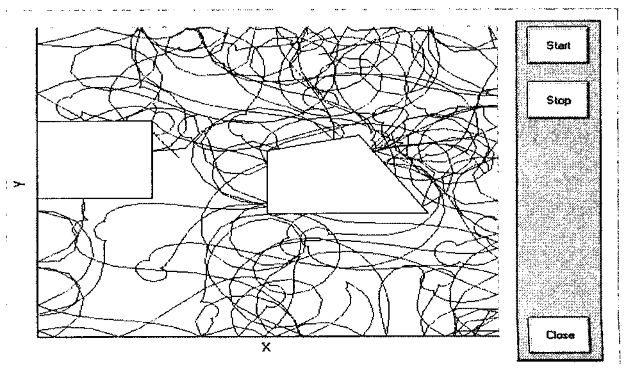


Fig. 10 Chua's equation trajectories of chaos UAV with obstacles.

V. THE UAV WITH VAN DER POL EQUATION OBSTACLE.

In this section, we will discuss the UAV's avoidance of Van der Pol(VDP) equation obstacles. We assume the obstacle has a VDP equation with a stable limit cycle, because in this condition, the UAV can not move close to the obstacle and the obstacle is avoided.

A. VDP equation as an obstacle

In order to represent an obstacle of the UAV, we employ the VDP, which is written as follows:

$$\begin{aligned} \dot{x} &= y \\ \dot{y} &= (1-y^2)y - x \end{aligned} \tag{13}$$

From equation (13), we can get the following limit cycle as shown in Fig. 11.

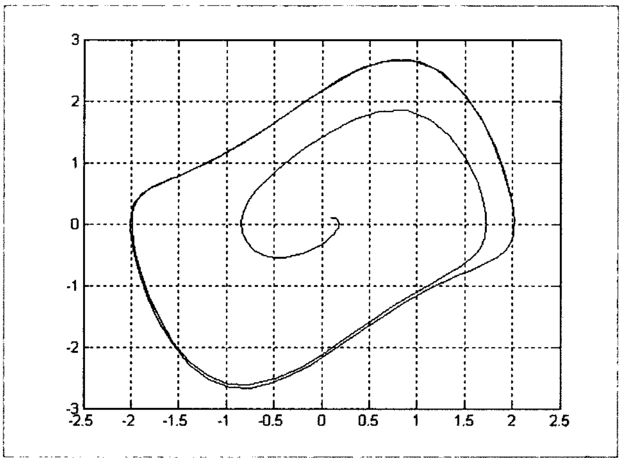


Fig. 11 Limit cycle of VDP.

B. Magnitude of Distracting force from the obstacle

We consider the magnitude of distracting force from the obstacle as follows:

$$D = \frac{0.325}{(0.2D_k + 1)e^{3(0.2D_k - 1)}} \tag{14}$$

where D_k is the distance between each effective obstacle and the UAV.

We can also calculate the VDP obstacle direction vector as follows:

$$\begin{bmatrix} \vec{x}_k \\ \vec{y}_k \end{bmatrix} = \begin{bmatrix} x_o - y \\ 0.5(1-(y_o-y)^2)(y_o-y)-(x_o-x) \end{bmatrix} \tag{15}$$

where (x_o, y_o) are the coordinates of the center point of each obstacle. Then we can calculate the magnitude of the VDP direction vector (L), the magnitude of the moving vector of the virtual UAV (I) and the enlarged coordinates (I/2L) of the magnitude of the virtual UAV in VDP $(x_k^{'}, y_k^{'})$ as follows:

$$\begin{aligned} L &= \sqrt[2]{(\vec{x}_{vdp}^{\,2} + \vec{y}_{vdp}^{\,2})} \\ I &= \sqrt{(x_r^2 + y_r^2)} \\ x_k^{'} &= \frac{\vec{x}_k}{L}\frac{I}{2}, \; y_k^{'} = \frac{y_k^{'}}{L}\frac{I}{2} \end{aligned} \tag{16}$$

Finally, we can get the Total Distraction Vector (TDV) as shown by the following equation.

$$\begin{bmatrix} \dfrac{\sum_k^n ((1-\frac{D_k}{D_0})\vec{x} + \frac{D_k}{D_0}\vec{x}_k)}{n} \\ \dfrac{\sum_k^n ((1-\frac{D_k}{D_0})\vec{y} + \frac{D_k}{D_0}\vec{y}_k)}{n} \end{bmatrix} \tag{17}$$

Using equations (14)-(17), we can calculate the avoidance method of the obstacle in the Arnold equation and Chua's equation trajectories with one or more VDP obstacles.

In Fig. 12, the computer simulation result shows that the chaos UAV has two UAVs and a total of 5 VDP obstacles, including two VDP obstacles at the origin in the Arnold equation trajectories. We can see that the UAV sufficiently avoided the obstacles in the Arnold equation trajectories.

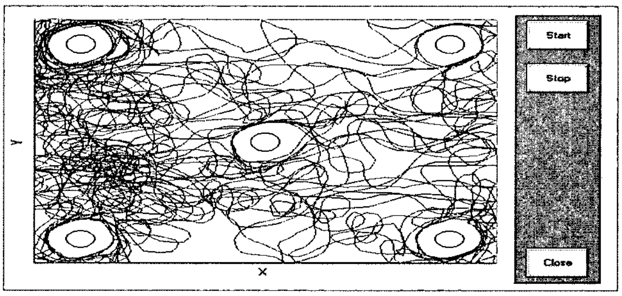


Fig. 12 Computer simulation result of obstacle avoidance with 2 UAVs and 5 obstacles in Arnold equation trajectories.

In Fig. 13, the computer simulation result shows that the chaos UAV surface has two UAVs and total of 5 VDP obstacles, including 2 VDP obstacles at the origin in the Chua's equation trajectory. We can see that the UAV sufficiently avoided the obstacles in the Chua's equation trajectory.

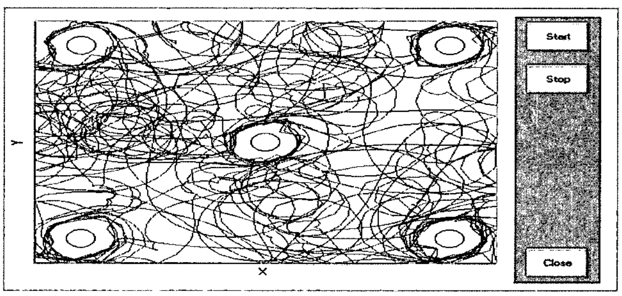


Fig. 13 Computer simulation result of obstacle avoidance with 2 UAVs and 5 obstacles in Chua's equation trajectory.

VI. MUTUAL COOPERATIVE CONTROL BY USING SYNCHRONIZATION METHODS

To achieve mutual cooperative control in the Chaotic UAVs, we applied the chaotic synchronization technique from the several mobile robot trajectories. Firstly, we applied coupled synchronization method and then we also applied driven synchronization method for mutual cooperative control between the several UAVs.

A. Coupled synchronization method.

In order to accomplish mutual cooperative control in the several chaotic UAVs, we applied a coupled synchronization method proposed by Cuomo [11] in the Arnold chaotic UAVs.

To apply coupled synchronization method in the Arnold circuit, transmitter-receive state equations are following:

Transmitter state equation

$$\begin{aligned}
\dot{x}_1 &= A\sin x_3 + C\cos x_2 + k(x_1 - x_2)\\
\dot{x}_2 &= B\sin x_1 + A\cos x_3\\
\dot{x}_3 &= C\sin x_2 + B\cos x_1\\
\dot{x} &= V\cos x_3\\
\dot{y} &= V\sin x_3
\end{aligned} \tag{18}$$

Receiver state equation

$$\begin{aligned}
\dot{x}_1 &= A\sin x_3 + C\cos x_2 + k'(x_2 - x_1)\\
\dot{x}_2 &= B\sin x_1 + A\cos x_3\\
\dot{x}_3 &= C\sin x_2 + B\cos x_1\\
\dot{x} &= V\cos x_3\\
\dot{y} &= V\sin x_3
\end{aligned} \tag{19}$$

In order to accomplish synchronization of the Eq. (18), (19), we need to find stable coupled- factor k value between the transmitter and the receiver.

The Fig. 14 showing synchronization of two chaotic UAVs after using Eq.(18) and (19) in the Arnold Chaotic UAVs. .

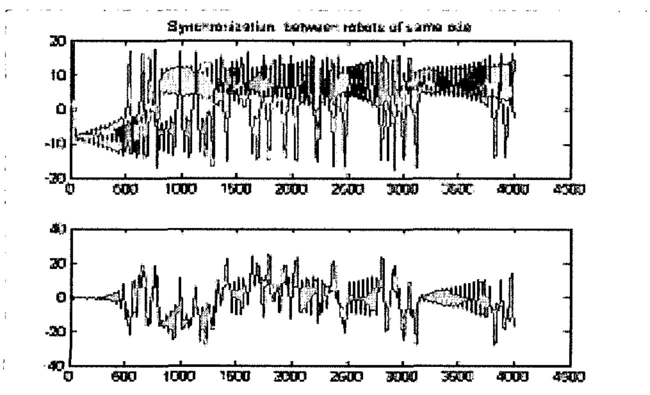


Fig. 14 The result of synchronization in the Arnold chaotic UAVs.

B. Coupled mutual cooperative control in the Chua's chaotic UAVs by using coupled synchronization

To accomplish synchronization of the two chaotic UAVs embedding Chua's circuit, first we formed each state equation for Eq. (20), (21). Then found coupled coefficient k and k' by using stability criteria. After that, we applied k and k' within stable area to perform computer simulation.

Main chaotic UAVs's state equation

$$\begin{aligned}
\dot{x}_1 &= \alpha(x_2 - g(x_1)) + k(x_1 - x_2)\\
\dot{x}_2 &= x_1 - x_2 + x_3\\
\dot{x}_3 &= -\beta x_2\\
\dot{x} &= V\cos x_3\\
\dot{y} &= V\sin x_3
\end{aligned} \tag{20}$$

Sub chaotic UAVs's state equation

$$\begin{aligned}
\dot{x}_1 &= \alpha(x_2 - g(x_1)) + k'(x_2 - x_1)\\
\dot{x}_2 &= x_1 - x_2 + x_3\\
\dot{x}_3 &= -\beta x_2\\
\dot{x} &= V\cos x_3\\
\dot{y} &= V\sin x_3
\end{aligned} \tag{21}$$

The Fig. 15 showing synchronization of two Chua's chaotic UAVs after using Eq.(20) and (21).

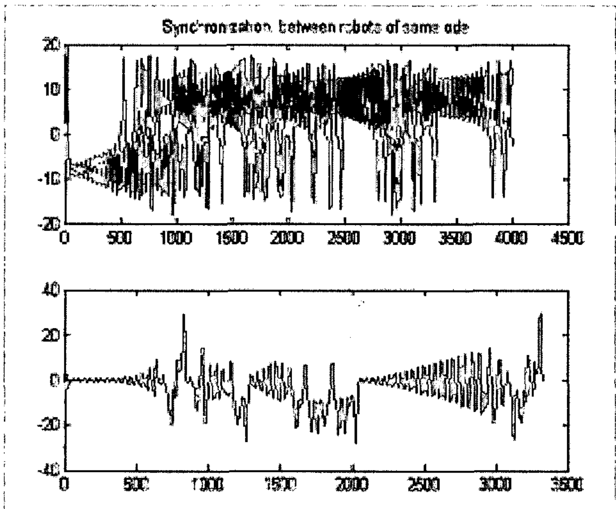


Fig. 15 The result of synchronization in the Chua's chaotic UAVs.

CONCLUSION

In this paper, we proposed a chaotic UAV, which employs a UAV with Arnold equation and Chua's equation trajectories, and also proposed a synchronization method for mutual cooperative control in which we assume that the obstacles has a Van der Pol equation with an unstable limit cycle.

We designed UAV trajectories such that the total dynamics of the UAV was characterized by an Arnold equation and Chua's equation and we also designed the UAVs trajectories to include an obstacle avoidance method. By the numerical analysis, it was illustrated that obstacle avoidance methods with a Van der Pol equation that has an unstable limit cycle gave the best performance.

In order to make synchronization method for the mutual cooperative control in the UAV system, we applied the Arnold equation and Chua's equation with obstacle. As a result, we realized that there are satisfy to synchronization method for mutual cooperative control in the chaotic UAVs.

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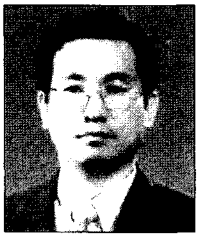

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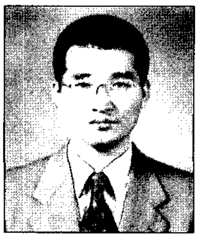

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