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Research Article

Research on Cooperative Combat for Integrated Reconnaissance-Attack-BDA of Group LAVs

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LAVs (loitering air vehicles) are advanced weapon systems that can loiter autonomously over a target area, detect and acquire the targets, and then attack them. In this paper, by the theory of Itô stochastic differential, a group system was analyzed. The uniqueness and continuity of the solution of the system was discussed. Afterwards the model of the system based on the state transition was established with the finite state machine automatically. At last, a search algorithm was proposed for obtaining good feasible solutions for problems. And simulation results show that model and method are effective for dealing with cooperative combat of group LAVs.

1. Introduction

LAV is a new kind of aerial vehicle [1], which can loiter in the air over the targets. It comes out with the development of UAV and munitions. While a single LAV performing a single task will bring some benefits, greater benefits will come from the cooperation of group LAVs. The main motivation for group cooperation stems from the possible synergy, as the group performance is exceed the sum of the performance of the individual LAVs [2].

The recent development of group LAV technology has a great number of interests within the intelligence gathering and remote sensing communities [3]. Through cooperation, the team can reconfigure its distribution architecture to minimize the performance degradation to such expected failures. Such cooperation should take advantage of the following capabilities available to the group: Global Information, Resource Management, and Robustness.

In the past few years, the problem of cooperation problems has been widely studied by researchers. Group cooperation is the strongest degree of cohesive group action. Consider a set of LAVs that have been designated to be part of the group; the group could have more than one payoff function that it wishes to optimize, which would then entail multiobjective optimization [4].

However, the current study, whether for its cooperation with automatic organization or conscious cooperation, is carried out only for a specific problem. Flight formation is investigated in [5–7]. In [8], the method of Mixed Integer Linear Programming approach is applied to path planning. A similar cooperative path planning problem is also discussed in [9–11]. Cooperative task allocation problem is discussed in [12, 13] using game theory. In [14, 15], cooperative task allocation problem is discussed by intelligent algorithm. Collision and obstacle avoidance are discussed in [16, 17]. Cooperative information consensus is discussed in [18–20] and many others [21, 22].

In this paper we focus on autonomous LAVs, which are designed to operate as a pack of vehicles that search, detect, and attack targets. We develop analytic probability model for analyzing some design and operational aspects relating to group LAVs. The rest of the paper is organized as follows. We describe the differential equation model with finite state machine automatically. And the optimization function is established based on the combat efficiency. Finally, we provide some test results and give our conclusions.

2. Problem Formulation and Analysis

2.1. The Behaviors in the Process of Cooperative Combat. Each LAV has an identical set of behaviors governed by the same controller. A LAV can be in one of four possible situations: Searching, Attacking, BDA, and Removed.

The rules of the behavior are as in Algorithm 1.

If the LAV satisfied the physical characteristics and communication capability,
then over the target area searching for valuable targets;
If the LAV confirms the targets are the valuable, **then** acquires the target and attacks it;
If After the attacks on targets, **then** over the target area for BDA;
If achieve the targets' BDA, **then** enter the next round of decisions;

Algorithm 1

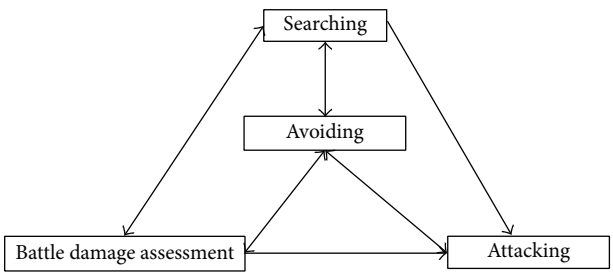

Figure 1: State diagram of the group LAVs behaviors.

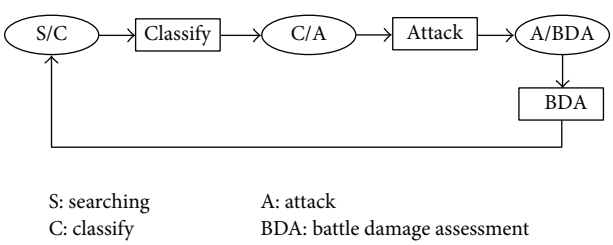

Figure 2: LAV mission timeline.

Figure 1 shows the sequence of behaviors that the LAV engages in during the combat process. Figure 2 describes the aforementioned mission time parameters.

2.2. Influence Analysis of the Group LAVs System. Consider dynamic model described by the following equation;

$$F_i(t) = \left(\prod_{j=1}^{N} U_{ji}(t)^{\alpha_{ji}}\right) S_i(t)^{\beta_i} E_i(t)^{\gamma_i}, \quad i = 1, 2, \ldots, N;\ j = 1, 2, \ldots, N,\ j \neq i, \tag{1}$$

where $U_{ji}(t)$ is the influence from j individual of Swarms system, $S_i(t)$ is the UAV i self-influence, E_i is the positive factor of environment, and $\alpha_{i,j}$ and β_i are the constant parameters.

In order to describe the influence function from the system science we use the *Itô* stochastic differential.

Set

$$U_i(t)^{\alpha_i} = \prod_{j=1}^{N} U_{ji}(t)^{\alpha_{ji}}, \tag{2}$$

satisfying $\beta_i + \alpha_i = 1$, $i = 1, \ldots, N$.

According to the *Itô* stochastic differential we can get the stochastic differential equations of the factor function $F_i(t)$:

$$\begin{aligned} dF_i(t) = {} & \frac{\partial F_i(t)}{\partial(U_i, S_i, E_i, t)} + \frac{1}{2}\frac{\partial^2 F_i(t)}{\partial(U_i^2, E_i^2, S_i^2)} \\ & + \frac{\partial^2 F_i(t)}{\partial U_i \partial S_i} dU_i(t)\, dS_i(t) + \frac{\partial^2 F_i(t)}{\partial U_i \partial E_i} dU_i dE_i \\ & + \frac{\partial^2 F_i(t)}{\partial S_i \partial E_i} dS_i dE_i. \end{aligned} \tag{3}$$

Theorem 1. *Consider the following Itô stochastic differential equation:*

$$\begin{aligned} dF_i(t) = {} & \frac{\partial F_i(t)}{\partial(U_i, S_i, E_i, t)} + \frac{1}{2}\frac{\partial^2 F_i(t)}{\partial(U_i^2, E_i^2, S_i^2)} \\ & + \frac{\partial^2 F_i(t)}{\partial U_i \partial S_i} dU_i(t)\, dS_i(t) + \frac{\partial^2 F_i(t)}{\partial U_i \partial E_i} dU_i dE_i \\ & + \frac{\partial^2 F_i(t)}{\partial S_i \partial E_i} dS_i dE_i. \end{aligned} \tag{4}$$

Structure a Borel measurable function and satisfied Lipschitz condition. Then if

$$F_i(x, y, z, 0) = Const, \qquad E(F_i(x, y, z, 0))^2 < +\infty, \tag{5}$$

the differential equation $dF_i(t)$ has the unique and continuous solution $F_i(t)$ and convergence in probability.

Proof. The stochastic differential equation is derived by Variable replacement, which is described as follows:

$$\begin{aligned} F_{U_iU_i} &= \alpha_i(\alpha_i - 1)\rho^2 U_i^{\alpha_i} S_i^{\beta_i} E_i^{\gamma_i} dt, \\ F_{S_iS_i} &= \beta_i(\beta_i - 1)\sigma^2 U_i^{\alpha_i} S_i^{\beta_i} E_i^{\gamma_i} dt, \\ F_{E_iE_i} &= \gamma_i(\gamma_i - 1)\delta^2 U_i^{\alpha_i} S_i^{\beta_i} E_i^{\gamma_i} dt, \\ F_{U_iS_i} &= \alpha_i\beta_i\sigma\rho U_i^{\alpha_i} S_i^{\beta_i} E_i^{\gamma_i} dt, \\ F_{U_iE_i} &= \alpha_i\gamma_i\rho\delta U_i^{\alpha_i} S_i^{\beta_i} E_i^{\gamma_i} dt, \\ F_{S_iE_i} &= \alpha_i\gamma_i\sigma\delta U_i^{\alpha_i} S_i^{\beta_i} E_i^{\gamma_i} dt. \end{aligned} \tag{6}$$

Then the equation $dF_i(t)$ converts into the following form:

$$dF_i(t) = \left(\begin{bmatrix} \frac{1}{2}\left(\alpha_i(\alpha_i - 1)\rho^2 + \beta_i(\beta_i - 1)\sigma^2 + \gamma_i(\gamma_i - 1)\delta^2\right) \\ (\alpha_i\rho + \beta_i\sigma + \gamma_i\delta) \end{bmatrix} + \begin{bmatrix} (\alpha_i\beta_i\sigma\rho + \alpha_i\gamma_i\rho\delta + \beta_i\gamma_i\sigma\delta) \\ 0 \end{bmatrix} \right)^T \begin{bmatrix} dt \\ dz \end{bmatrix} F_i(t). \tag{7}$$

So we structure the Borel measurable function as follows:

$$\begin{aligned} g(t, F_i) = \frac{1}{2}\Big(&\left(\alpha_i(\alpha_i - 1)\rho^2 + \beta_i(\beta_i - 1)\sigma^2 + \gamma_i(\gamma_i - 1)\delta^2\right) \\ &+ 2\left(\alpha_i\beta_i\sigma\rho + \alpha_i\gamma_i\rho\delta + \beta_i\gamma_i\sigma\delta + n\rho + s\alpha + \delta m\right)\Big) \\ &\times F_i(t)\, h(t, F_i) = (\alpha_i\rho + \beta_i\sigma + \gamma_i\delta) F_i(t). \end{aligned} \tag{8}$$

According to the lemma in [23] lemma, we will prove that the Borel measurable function satisfied the Lipchitz condition:

$$\begin{aligned} &|g(t, F_{i1}) - f(t, F_{i2})| + |h(t, F_{i1}) - \delta(t, F_{i2})| \\ &\quad = \left|\frac{1}{2}\left(\alpha_i(\alpha_i - 1)\rho^2 + \beta_i(\beta_i - 1)\sigma^2 + \gamma_i(\gamma_i - 1)\delta^2\right) F_i(t)\right| \\ &\qquad \times |F_{i1} - F_{i2}| + |\alpha_i\beta_i\sigma\rho + \alpha_i\gamma_i\rho\delta + \beta_i\gamma_i\sigma\delta + n\rho + s\alpha + \delta m| \\ &\qquad \times F_i(t)|F_{i1} - F_{i2}| + (\alpha_i\rho + \sigma\beta_i + \gamma_i\delta)|F_{i1} - F_{i2}| \\ &\quad \le \left|\frac{1}{2}\left(\alpha_i(\alpha_i - 1)\rho^2 + \beta_i(\beta_i - 1)\sigma^2 + \gamma_i(\gamma_i - 1)\delta^2\right)\right| \\ &\qquad \times |F_{i1} - F_{i2}| + |(\alpha_i\beta_i\sigma\rho + \alpha_i\gamma_i\rho\delta + \beta_i\gamma_i\sigma\delta)|\,|F_{i1} - F_{i2}| \\ &\qquad + |(n\rho + s\alpha_i + \delta m + \alpha_i\rho + \sigma\beta_i + \gamma_i\delta)|\,|F_{i1} - F_{i2}|, \\ &|g(t, F_i)|^2 + |h(t, F_i)|^2 \\ &\quad = \frac{1}{4}\Big(\alpha_i(\alpha_i - 1)\rho^2 + \beta_i(\beta_i - 1)\sigma^2 + \gamma_i(\gamma_i - 1)\delta^2 \\ &\qquad + 2\alpha_i\beta_i\sigma\rho + 2\alpha_i\gamma_i\rho\delta + 2\beta_i\gamma_i\sigma\delta + 2n\rho + 2s\alpha\Big)^2 F_i^2 \\ &\qquad + (\alpha_i\rho + \sigma\beta_i + \gamma_i\delta)^2 F_i^2 \\ &\quad \le \Big\{\Big[\alpha_i(\alpha_i - 1)\rho^2 + \beta_i(\beta_i - 1)\sigma^2 + \gamma_i(\gamma_i - 1)\delta^2 \\ &\qquad + (\alpha_i\beta_i\sigma\rho + \alpha_i\gamma_i\rho\delta + \beta_i\gamma_i\sigma\delta + n\rho + s\alpha + \delta m)\Big]^2 \\ &\qquad + (\alpha_i\rho + \sigma\beta_i + \gamma_i\delta)^2\Big\} F_i^2, \\ &\omega_1 = \left|\frac{1}{2}\left(\alpha_i(\alpha_i - 1)\rho^2 + \beta_i(\beta_i - 1)\sigma^2 + \gamma_i(\gamma_i - 1)\delta^2\right)\right| \\ &\qquad + |(\alpha_i\beta_i\sigma\rho + \alpha_i\gamma_i\rho\delta + \beta_i\gamma_i\sigma\delta)| \\ &\qquad + |(n\rho + s\alpha_i + \delta m + \alpha_i\rho + \sigma\beta_i + \gamma_i\delta)|, \\ &\omega_2 = \sqrt{2} * \mathrm{Max}\Big\{\Big[\alpha_i(\alpha_i - 1)\rho^2 + \beta_i(\beta_i - 1)\sigma^2 + \gamma_i(\gamma_i - 1)\delta^2 \\ &\qquad + (\alpha_i\beta_i\sigma\rho + \alpha_i\gamma_i\rho\delta + \beta_i\gamma_i\sigma\delta + n\rho \\ &\qquad + s\alpha + \delta m)\Big]^2, (\alpha_i\rho + \sigma\beta_i + \gamma_i\delta)^2\Big\}, \\ &\omega = \mathrm{Max}\{\omega_1, \omega_2\}. \end{aligned} \tag{9}$$

So we can get the equation and satisfy the Lipchitz condition as follows:

$$\begin{aligned} &|g(t, F_{i1}) - h(t, F_{i2})| + |\sigma(t, F_{i1}) - \sigma(t, F_{i2})| \le \omega|F_{i1} - F_{i2}|, \\ &|g(t, F_i)|^2 + |h(t, F_i)|^2 \le \omega^2\left(1 + |F_i|^2\right). \end{aligned} \tag{10}$$

The conclusion that the influence function $F_i(t)$ has unique and continuous solution and convergence in probability 1 is correct. □

3. Mathematical Model and Analysis of System

3.1. Mathematical Model of the System Based on the State Transition. Differential equation model was established using finite state machine automatically:

$$\begin{aligned} \frac{dN_{\text{Searching}}(t)}{dt} &= \frac{1}{\lambda_{\text{Avoiding}}} N_{\text{AS}}(t) + \frac{1}{\lambda_{\text{BDA}}} N_{\text{BDA}}(t) \\ &\quad - \alpha_s N_{\text{Searching}}(t) N_{\text{Tarket}}(t) - \alpha_{\text{As}} N_{\text{Searching}}(t) \\ &\quad \times \left(N_{\text{Searching}}(t) + N + B\right), \\ \frac{dN_{\text{AS}}(t)}{dt} &= -\frac{1}{\lambda_{\text{Avoiding}}} N_{\text{AS}}(t) + \alpha_{\text{As}} N_{\text{Searching}}(t) \\ &\quad \times \left(N_{\text{Searching}}(t) + N + B\right), \\ \frac{dN_{\text{AA}}(t)}{dt} &= -\frac{1}{\lambda_{\text{Avoiding}}} N_{\text{AA}}(t) + \alpha_{\text{AA}} N_{\text{Attacking}}(t) \\ &\quad \times \left(N_{\text{Attacking}}(t) + N + B\right), \\ \frac{dN_{\text{AB}}(t)}{dt} &= -\frac{1}{\lambda_{\text{Avoiding}}} N_{\text{AB}}(t) + \alpha_{\text{AB}} N_{\text{BDA}}(t) \\ &\quad \times \left(N_{\text{BDA}}(t) + N + B\right), \\ \frac{dN_{\text{Attacking}}(t)}{dt} &= \alpha_s N_{\text{Searching}}(t) N_{\text{Tarket}}(t) \\ &\quad - \frac{1}{\lambda_{\text{Attacking}}} N_{\text{Attacking}}(t), \end{aligned}$$

$$\frac{dN_{\mathrm{BDA}}(t)}{dt} = \alpha_{\mathrm{AB}} N_{\mathrm{AB}}(t) - \frac{1}{\lambda_{\mathrm{BDA}}} N_{\mathrm{BDA}}(t) + \alpha_{\mathrm{AB}} N_{\mathrm{BDA}}(t) \times \left(N_{\mathrm{BDA}}(t) + N + B\right),$$
$$\frac{dN_{\mathrm{Tarket}}(t)}{dt} = -\alpha_s N_{\mathrm{Searching}}(t) N_{\mathrm{Tarket}}(t). \tag{11}$$

Parameters Notation. N is the number of LAVs in the system, $N_{\mathrm{Searching}}(t)$ is the number of LAVs in the searching state at time t, $N_{\mathrm{Avoiding}}(t)$ is the number of LAVs in the avoiding state at time t, $N_{\mathrm{Attacking}}(t)$ is the number of LAVs in the attacking state at time t, $N_{\mathrm{BDA}}(t)$ is the number of LAVs in the BDA state at time t, $N_{\mathrm{Tarket}}(t)$ is the number of targets at time t, $\lambda_{\mathrm{Avoiding}}$, $\lambda_{\mathrm{Attacking}}$, and λ_{BDA} are the average sustained time of Avoiding, Attacking, and BDA, α_S is the rate of searching a valuable target, and α_{AS}, α_{AA}, α_{AB} are the rate of encounter obstacles on Searching, Attacking, and BDA.

3.2. Cost Function Based on Effectiveness. In this paper we consider the total flight distance of the group system:

$$\min \sum_{k=1}^{K} \left(\sum_{l=1}^{N_c} \sum_{i=1}^{N_u} \sum_{j=1}^{N_{\mathrm{target}}} C_{l,i,j}^{X_{l-1}} x_{l,i,j} \right). \tag{12}$$

Parameter $x_{l,i,j} \in \{0,1\}$ is the decision variable and $s \in (1,2,3)$ is the stages of the task; if $l \in s$, then $x_{l,i,j} = 1$; else $x_{l,i,j} = 0$, and $c_{l,i,j}^{x_{l-1}}$ is the distance for LAV i to the target j.

Subject to

$$\sum_{l=1}^{N_c} \sum_{i=1}^{N_u} x_{l,i,j} = N, \quad j \in T,$$
$$\sum_{l=1}^{N_c} \sum_{j=1}^{N_{\mathrm{target}}} r_{l,i,j}^{X_{l-1}} x_{l,i,j} \le b_i, \quad i \in U, \tag{13}$$
$$d_{A\min} \ge d_{\min} + v\Delta t_1,$$
$$d_{V\min} \ge d_{V\min} + v\Delta t_2.$$

Parameter b_i is the flight capability and Δt_m is the min. time between the tasks.

3.3. Search Algorithm. According to the proposed cooperative combat, each LAV uses a cost function to select and update its behaviour. This method is quite flexible in that it allows the characterization of various mission-level objectives.

The flowchart depicting the optimization algorithm for the LAV group scenario is shown in Figure 3.

The data as in Tables 1 and 2.

In this example, eight LAVs are searching an area containing three targets of similar types.

LAVs trajectories through the 10 seconds are shown in Figure 4; at $t = 10$ s the targets are discovered by the searching LAVs, nearly simultaneously. LAV1, 5 and 6 are assigned to verify the targets.

LAVs trajectories through the 50 seconds are shown in Figure 5, at $t = 39$ s Target 3 is classified by LAV6, at $t = 44$ s Target 1 is classified by LAV1, at $t = 49$ s Target 2 is classified by LAV5, and then the LAVs perform attack on targets.

LAVs trajectories through the 115 seconds are shown in Figure 6, at $t = 91$ s Targets 1 was attacked by LAV4, then LAV2 performs BDA on target 1.

LAVs trajectories through the 235 seconds are shown in Figure 7, at $t = 120$ s Targets 2 was attacked by LAV8, then

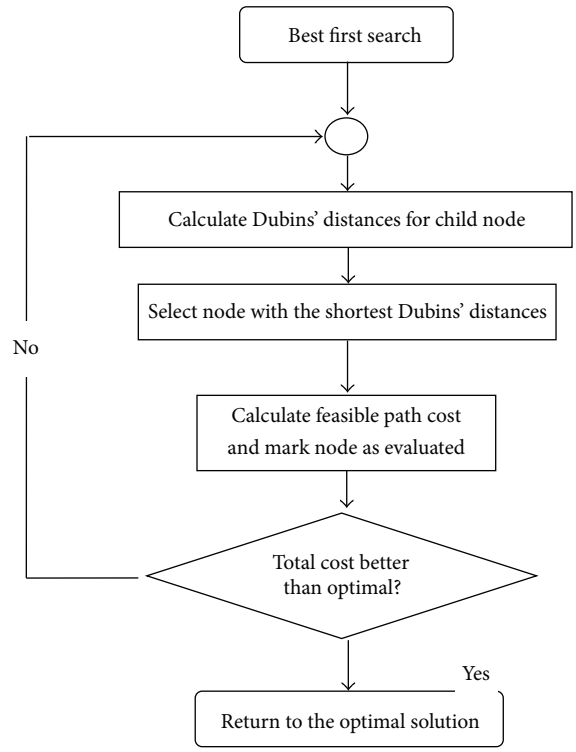

Figure 3: Search flowchart.

Table 1: Dynamics performance parameters.

Parameter	Value
Loitering velocity	100 m/s
Maximum range	180 km
Minimum turning radius	500 m

Table 2: Initialization of the MAV.

Index	Location (km)	Orientation (rad)	Period of flight time(s)
LAV1	(3.93, 18.34)	3.335	129
LAV2	(5.02, 5.72)	4.895	635
LAV3	(12.32, 15.14)	5.868	248
LAV4	(9.47, 15.07)	0.816	422
LAV5	(7.03, 7.61)	3.574	132
LAV6	(16.62, 11.36)	2.949	481
LAV7	(11.71, 1.52)	0.074	210
LAV8	(10.99, 1.08)	2.118	523

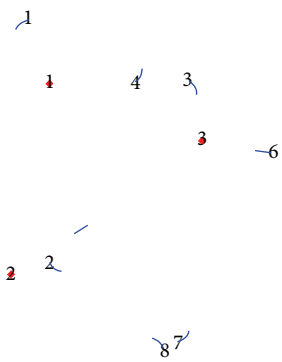

Figure 4: $T = 10$ s trajectories with respect to time.

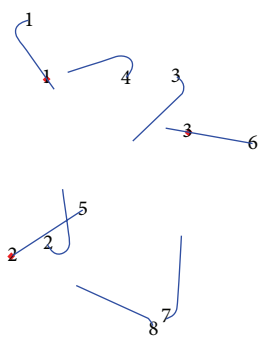

Figure 5: $T = 50$ s trajectories with respect to time.

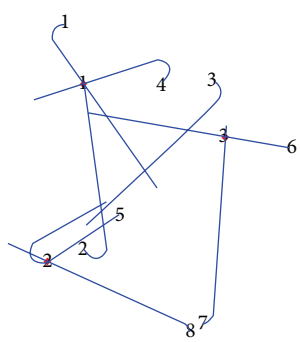

Figure 6: $T = 115$ s trajectories with respect to time.

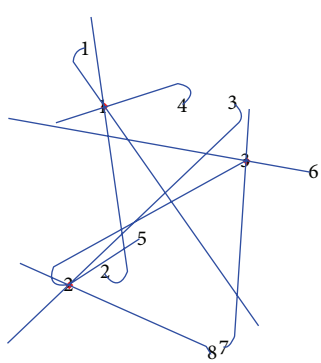

Figure 7: $T = 235$ s trajectories with respect to time.

LAV3 performs BDA on target 2, at $t = 138$ s Targets 3 was attacked by LAV7, then LAV5 performs BDA on target 3.

At $T = 230$ s, the tasks are completely finished by the group LAVs.

4. Conclusion

In this paper the problem of the cooperative combat associated with the group LAVs system has been solved. Afterwards, by the theory of *Itô* stochastic differential, a group system was analyzed. The model of the system based on the state transition was established with the finite state machine automatically. At last, a search algorithm was proposed for obtaining good feasible solutions for problems. And we took simulation tests to verify the conclusion.

Conflict of Interests

The authors declare that they have no conflict of interests regarding the publication of this paper.

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