Swarm Target Tracking Collective Behavior Control with Formation Coverage Search Agents & Globally Asymptotically Stable Analysis of Stochastic Swarm

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***Abstract*—According to the viewpoints of swarm dynamic, this paper elaborates that introducing the target tracking control and global asymptotic stability respectively of the two kinds of different swarm systems with aggregation functions, the study of multi-agent systems is start with two aspects: one hand is starting off from formation coverage search, but on the other hand, researching the character of high noise inhibiting ability and stability. By use of the swarm dynamical models, meanwhile, considering the interactions among agents, based on the artificial potential functions (APFs) and Newton-Raphson iteration updating behavior rules, theoretical analysis and simulation experimental studies results are presented to illustrate the performance and viability of the proposed algorithm which is robust with respect to the system uncertainties and additive disturbances.**

***Index Terms*—swarm dynamic; aggregation; formation; target tracking; coverage search; stochastic noise perturbation; global asymptotic stability; multi-agent systems (MAS); numerical simulations**

I. Introduction

Swarming behavior has been observed in nature. For example, bees, ants and birds often work together in groups for viability. It is known that such cooperative behavior has certain advantages, for example, predator avoidance, foraging success and so on. The general understanding in biology is that the swarming behavior is a result of an interplay between a long range attraction and a short range repulsion between the individuals. Understanding the cooperative and operational principles of such systems may provide useful ideas for modeling and exploring the collective dynamics of swarming behavior in bionics for using in engineering applications, such as the coordinated control of multi-agent systems [1].

In the natural world, population appears in patterns of aggregation (flocking/ grouping/ herding - a natural mechanism important for the survival of individuals). Aggregation (or gathering together) is a basic behavior exhibited by many swarms in nature, including simple bacteria colonies, flocks of birds, schools of fish, and herds of mammals. Such behavior of biological swarms is observed to be helpful in meeting various tasks such as avoiding predators, increasing the chance of finding food, etc. This can be explained by the relative appropriateness of an aggregated swarm structure to meet these tasks collaboratively as compared to a non-aggregated setting. Because of the same reason, aggregation is a desired behavior in engineering multi-agent dynamic systems as well. Moreover, many of the collective behaviors being seen in biological swarms and some behaviors to be possibly implemented in engineering multi-agent dynamic systems emerge in aggregated swarms. Therefore, studying the dynamics and properties of swarm aggregations is important in developing efficient cooperative multi-agent dynamic systems. Foraging can be considered as a constrained form of aggregation, where the environment affects the motion or behavior of agents. Hence, for a foraging task, the swarm coordination and control scheme to be developed need to guarantee aggregation in the favorable regions while avoiding unfavorable ones. Aggregation in biological swarms usually occurs during social foraging. Social foraging has many advantages such as increasing probability of success for the individuals. Therefore, social foraging is an important problem since swarm studies in engineering may benefit from similar advantages. Flocking, in general, can be defined as

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collective motion behavior of a large number of interacting agents with a common group objective. Flocking, also, can be considered as a group of mobile agents is said to asymptotically flock, when all agents attain the same velocity vector, distances between agents are stabilized and no collisions occur between them. Flocking motion can be seen everywhere in nature, e.g., flocking of birds, schooling of fish, and swarming of bees. Understanding the mechanisms and operational principles in them can provide useful ideas for developing distributed cooperative control and coordination of multiple mobile autonomous agents/robots. In recent years, distributed control/coordination of the motion of multiple dynamic agents/robots has emerged as a topic of major interest [2].

In spite of the stochastic noise in environment, the biological swarm is still able to harmonize the individual behavior inside the swarm to accomplish the collective task, which a single individual fails to accomplish. However, most available analysis results in the literature are on the stability of the swarm system flocking behavior are all based on the determinate system model, but do not give consideration to the effect of random disturbance caused by factors such as environmental noise on the flocking behavior of the swarm system. However as far as modeling of real systems, factors like random noise must be considered [3]. It is, in fact, convincing results on the effect of random disturbance on the dynamic behavior control of the swarm system are relatively few.

In view of this, in [4], a novel Lagrangian "individual-based" isotropic continuous time exponential type stochastic swarming model in an n-dimensional Euclidean space with a family of attraction/repulsion function is proposed, to study the effect of random disturbance on the dynamic behavior of the swarm system.

Dynamic change of the environment including random noise disturbance, local observation and nonlinear characteristics are ubiquitous phenomena in nature. However, most available results in the literature are on the isotropic global perceive swarming model, convincing results on the isotropic local perceive swarming model are relatively few, but the study is very difficult and it has profound engineering significance. Reference [5] proposed an isotropic limited-range perceived swarming dynamic model, so it is able to provide some results on this topic.

In this paper, we mainly analyze the target tracking control and global asymptotic stability respectively of the two kinds of different swarm systems as mentioned above.

An outline of the paper is as follows. In Section 2, the related work is introduced. In Section 3, the problem statements of multiple agents are established. Main results on the target tracking control and global asymptotic stability analysis of two different swarm systems are obtained in Section 4 and 5, respectively. Finally, in the last section, the concluding remarks are given.

II. RELATED WORK

In [1] and [2], based on the isotropic perceived group dynamic model that was proposed in [5], to propose reasonable solving scheme based on the analysis of various biological swarm systems on the effect of flocking motion behavior mechanism in an *n*-dimensional Euclidean space. And then to consider the collision-eluding and formation behavior control of such swarm systems. As the model is a kinematic model. It is fit for individuals in which move basing on the Newton's law in an environment can capture the basic convergence properties of biological populations in nature. Therefore, the final behavior of the swarms described by the model may be in harmony with real biological swarms well. Numerical simulation agrees very well with the theoretical analysis of coordinated motion and obstacle-eluding aggregating stability of the swarm systems, the convex polygon formation behavior control and obstacle-eluding aggregating behavior for multi-agent system is analyzed and discussed also.

Due to the fact of the motion of the swarms is inevitable subjected to noise in the environment, hence, here we must consider stability of the swarms with the effect of noise, which has few been studied before [6].

In [4], theoretical analysis and numerical simulation results about the globally asymptotically stable in isotropic stochastic swarm under a standard white Gaussian noise perturbation in plan social potential field profile environment are both verified the capability of the proposed relevant theories.

III. PROBLEM FORMULATION

We consider a group of N （$N \geq 2$） agents moving in an *n*-dimensional Euclidean space; each has point mass dynamics described by

$$\dot{x}^i = v^i,$$
$$m_i \dot{v}^i = u^i, i = 1, \cdots, N. \tag{1}$$

Where $x^i \in R^n$ is the position vector of agent i, $v^i \in R^n$ is its velocity vector, $m_i > 0$ is its mass, and $u^i \in R^n$ is the control input acting on agent i.

Our objective is to make the entire group move at a desired velocity and maintain constant distance between agents [7].

In this paper, we mainly analyze the problem of coverage tracking search with formation configuration of the isotropic limited-range perceived swarm and the global asymptotic stability of the isotropic continuous time exponential type stochastic swarm for the two kinds of different multi-agent systems, respectively.

IV. MAIN RESULTS

In this section, we investigate the formation coverage tracking problem and the effect of random disturbance in environment on the flocking behavior of multiple agent systems.

A. Swarm Formation Coverage Search Target Tracking Control

1) Formation Aggregation

Based on the inspiration from biology, referring to the known results in literatures [5], we consider a swarm of N individuals (members) in a n–dimensional Euclidean space, assume synchronous motion and no time delays, and model the individuals as points and ignore their dimensions. The equation of collective motion of individual i is given by as follows

$$\dot{x}^i = -\nabla_{x^i}\sigma(x^i) + \sum_{j=1, j\neq i}^{N} g(x^i - x^j), i = 1, \cdots, N. \quad (2)$$

Where $x^i \in R^n$ represents the position of individual i ; $-\nabla_{x^i}\sigma(x^i)$ stands for the collective motion's direction resting with the different social attractant/repellent potential fields environment profile around individual i ; $g(\cdot)$ represents the function of attraction and repulsion between the individuals members. The above $g(\cdot)$ functions are odd (and therefore symmetric with respect to the origin). This is an important feature of the $g(\cdot)$ functions that leads to aggregation behavior [8].

The attraction/repulsion function that we consider is

$$g(y) = -y[g_a(\|y\|) - g_r(\|y\|)] = -y\left[a - \frac{b(v-r)}{(r-\rho)\|y\|^2}\right]. \quad (3)$$

Where, a, b, v, r, ρ are arbitrary constants, is normal number, $v > r > \rho > 0$, the 2-norm $\|y\| = \sqrt{y^T y}$. The numerical imitation of $g(\cdot)$ as Fig. 1 and Fig. 2 shows.

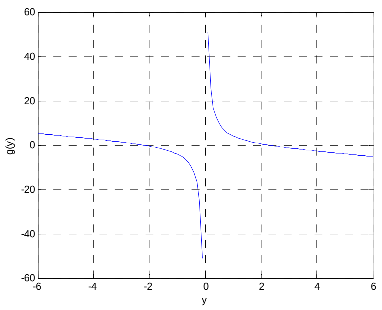

Figure 1. Linear attraction/unbounded repulsion function

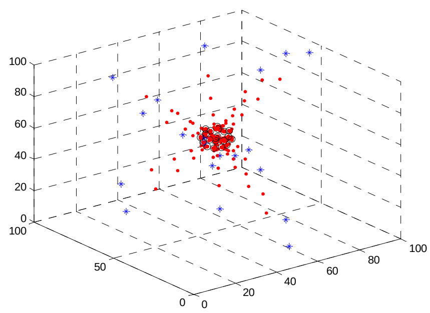

Figure 2. Convergent trajectories of linear attraction/unbounded repulsion swarms

In Fig. 2, blue "*" represent original position, black "。" represent final position, read ". " represent convergent trajectories of individuals.

The formation concept, first explored in the 1980's to allow multiple geostationary satellites to share a common orbital slot [9], has recently entered the era of application with many successful real missions [10].

Formation control is an important issue in coordinated control for multi-agent systems (such as, a group of unmanned autonomous vehicles (UAV)/robots). In many applications, a group of autonomous agents are required to follow a predefined trajectory while maintaining a desired spatial pattern. Moving in formation has many advantages over conventional systems, for example, it can reduce the system cost, increase the robustness and efficiency of the system while providing redundancy, reconfiguration ability and structure flexibility for the system. Formation control has broad applications, for example, security patrols, search and rescue in hazardous environments. Research on formation control also helps people to better understand some biological social behaviors, such as swarm of insects and flocking of birds [11].

Control of systems consisting of multiple vehicles (or agents) with swarm dynamical models are intend to perform a coordinated task is currently an important and challenging field of research. Formation of geometric shapes with autonomous robots is a particular type of the coordination problem of multi-agent systems [12].

In fact, we consider formation control as a special form of swarm aggregation, where the final aggregated form of the swarm is desired to constitute a particular predefined geometrical configuration that is defined by a set of desired inter-agent distance values. This is achieved by defining the potential function to achieve its global minimum at the desired formation. For this case, however, due to the fact that potential functions may have many local minima, the results obtained are usually local. In other words, unless the potential function is defined to have a single (unique) minimum at the desired formation, convergence to that formation is guaranteed only if the agents start from a "sufficiently close" configuration or positions to the desired formation. Some of these works are based on point mass agent dynamics [8].

2) Swarm Tracking

Multi-agent's target tracking applications have been an active research area for many years. The advantages of MAS over single agent system in various military and civil applications which often require agents to move autonomously in dynamic environment where the target and obstacle are moving, rather than to simply follow a pre-planned path designated by an offline mission-level planning algorithm include reducing cost and increasing robustness. Because potential function method is simple and intuitional, it has been widely used in target tracking and obstacle avoidance for multi-agent system. This method is based on a simple and powerful principle, first proposed by O. Khatib. The agents are considered as particles that move in a potential field generated by the target and obstacle present in the environment. The target generates an attractive potential field while any obstacle generates a repulsive potential field. The agents immersed in the potential field are subject to the action of a force, which drives them to the target and keeps them away from the obstacle [13].

Based on the above considerations, a novel control scheme for target tracking and obstacle avoidance of multi-agent systems is proposed in this section. The objective is to make the agents track a moving target, while avoiding collision with a moving obstacle and other agents.

According to that whether agent is within the actuation region of its neighbors' influence, based on the information of the target and obstacle, then the moving target can be tracked down (or caught) by the pursuer agent.

Where, we consider the swarm target tracking flocking problem of groups of mobile agents with a dynamic virtual leader which can generate a reference trajectory (RT).

As we known, flocking model requires all agents to have a common heading and maintain constant distances between each other while avoiding collision. Generalizations of this model include a leader-following strategy, in which one agent acted as a group leader and the other agents would just follow the leader [14].

For the convenience of analysis, where, we firstly consider the problem of only moving one pursuer agent toward a moving target, then, toward a group of pursuer agents further extension, while avoiding collision with the moving obstacle and other agents.

For ease of plotting we use only n = 2, during the numerical simulation examples. Figure 3 shows a simulation for the case with the "kinematic" model. Initially the target is located at the position (1, 1) in the plane, whereas the pursuer is located at the origin. The target tries to escape following a sinusoidal type of trajectory, according to the target dynamics

$$\dot{x}_{t1} = 0.25, \qquad \dot{x}_{t2} = \sin(0.25 \cdot t). \tag{4}$$

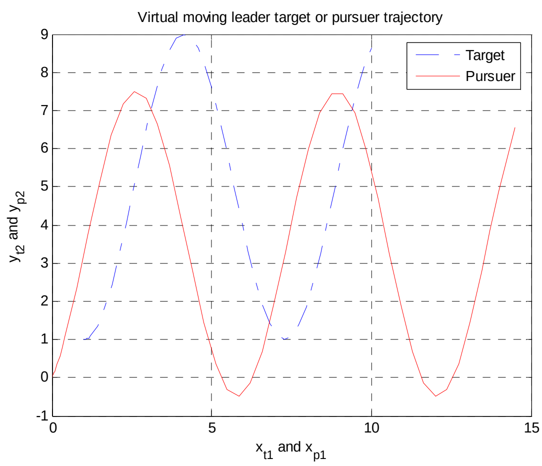

Figure 3. Trajectories of the target and the pursuer

As one can see the pursuer catches up with the target in a short period of time and follows it after that. Similar results are obtained for other trajectories of the target such as trajectory generated with a random velocity.

Using such a method may also allow us to let a group of pursuer agents to pursue a moving virtual leader target. The corresponding simulation results as Figure 12~ figure 13 shows.

3) Coverage Search Tracking of A "Virtual Leader"Moving Target with Flocking Strategies

Multi-agent networks have been an important role in distributed collection and control information. Distributed design with advantages such as low cost, reliability, and flexibility provides a feasible way to deploy a large number of networked agents over a region of interest to achieve desired collective tasks. In practice, agents are usually equipped with various sensors. Since a single agent may be difficult to complete the task due to its limited capacities, a group of agents (or viewed as a mobile sensor network) are usually teamed up to complete the tasks by communicating and coordinating their actions through network. The coordination algorithms for multiple agents have been reported, including formation, flocking, consensus, and rendezvous. By reaching a consensus, we mean asymptotically converging to a state agreement space. Consensus algorithms have recently been studied extensively in the context of cooperative control of multiple autonomous vehicles. For example, teams of mobile autonomous agents require the ability to cover a region of interest, to assume a specified pattern, to rendezvous at a common point, or to move in a synchronized manner as in flocking behaviors. The formation stabilization problem requires that agents collectively maintain a prescribed geometric shape, i.e. prescribed relative positions and orientations with respect to each other. The flocking is a form of collective behavior of large number of interacting agents with a common group objective.

Coverage problems of multiple agents have drawn much attention to the researchers in recent years. In general, this reflects how well a region of interest is monitored or tracked by sensors. In most applications, we are interested in a reliable coverage of the environment in such a way that there are no gaps left in the coverage. It includes many interesting problems such as region coverage, target coverage, and optimization design of sensor networks. The main objective of this section is to discuss the problem of coverage tracking of a moving target by mobile agents. If the position of the moving target is known and each sensor can get enough measurable variables, this problem becomes a traditional tracking problem. However, in practice, there are some uncertainties or estimation errors for the target and each sensor may only get partially-observable measurements. Therefore, coverage tracking with cooperative agents is considered in order to make the considered moving target located in an actuation region of some agent after a period of time. Then the target coverage problem can be viewed as covering a moving region problem. Flocking strategy is given to perform this coverage mission by us, in this section. Moreover, the number of desired agents is also explained based on the range of the estimation error region and the limited actuated radius. In order to improve the system behaviors, the coverage mission is achieved in finite time with just linear protocols. Since each agent has a limited actuation coverage range and there are uncertainties, these agents have to work together to cover the region where the target may be [14].

Based on the objects to be covered, there are two different types: 1) Area Coverage and 2) Target Coverage. As the names reflect themselves, the interest region to be covered in the former is an area while in the latter is a set of targets. Here, a target can be a point. Indeed, an area coverage can be transformed to a target coverage.

All most of these work on connected coverage problem focus on the area coverage. Less work has addressed this problem on the target coverage yet and we expect to see more research in this specific area.

WSN's connectivity is an important problem. The active nodes must form a connectivity so that the sensed data can be sent to a base station. In this section, we consider a sensor network consisting of *N* sensors s_i, $i = 1, \cdots, \mathrm{N}$. *N* sensors are deployed to monitor an interest region which is either an area or a set of targets. Let r_i and R_i denote the sensing range and the communication range of a sensor s_i respectively [15].

- **Theorem 1** When the number of sensors in any finite area is finite, a necessary and sufficient condition for the complete coverage of a convex region to imply connectivity is R≥ 2*r*.

Recall that *R* is a communication range and *r* is a sensing range of a sensor. This theorem indicates that all the above algorithms on the area coverage problem are also a solution for the connected coverage problem.

In the following, we will show the finite-time coverage mission can be completed by the leader-following flocking algorithm. Note that we assume a sensing area of a node s_i being a disk centered at sensor s_i with radius r_i.

We performed simulations, taking diamond formation tracking as an example, related the swarm tracking numerical imitation results as Figure 12 ~ Figure 15 shows.

B. Global Asymptotic Stability Analysis of Stochastic Swarm

In [4], based on the inspiration from biology, we consider an isotropic exponential type swarm model of aggregating for multi-agent system.

The attraction/repulsion function that we consider is

$$g(y) = sign(y)\left[g_a(\|y\|) - g_r(\|y\|)\right]. \quad (5)$$

$$g_a(\|y\|) = A\exp\left(-\frac{\|y\|}{a}\right). \quad (6)$$

$$g_r(\|y\|) = \mathrm{Re}\,xp\left(-\frac{\|y\|}{r}\right). \quad (7)$$

Where 2-norm $\|y\| = \sqrt{y^T y}$, $y \succ 0$ is distance between an inter-acting pair. The functions are extended to negative values of y as odd functions.

The parameters $R, A \succ 0$ are magnitudes (positive constants) and $r, a \succ 0$ (positive constants) are the spatial ranges of the repulsion and attraction.

Note that, if $R \succ A$ and $a \succ r$. This is the short-ranged repulsion and long-ranged attraction case, and is the most interesting and biologically relevant: In this case, for a pair of individuals in isolation, there is a comfortable distance, s :

$$s = \frac{a}{\left(\left(\frac{a}{r}\right) - 1\right)} \ln\left(\frac{R}{A}\right).$$

(8)

Where, $Rr^2 \succ Aa^2$. This condition quantifies explicitly what is meant by the assertion that repulsion has to be strong enough to prevent collapse of the group.

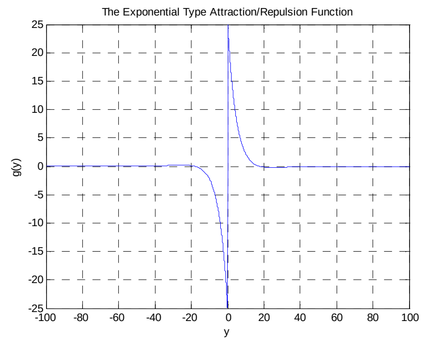

Figure 4. The exponential attraction/repulsion function $g(\cdot)$

However, in reality, the motion of the swarms is inevitable subjected to noise in the environment. Hence, here we consider stability of the swarms with the effect of noise, which has few been studied before.

Consider the motion equation of individual i in the stochastic swarm system described by

$$dx^i = \sum_{j=1, j\neq i}^{N} g\left(x^i - x^j\right)dt + f\left(x^i - \bar{x}\right)\omega^i(t)dt .$$

(9)

Suppose that the swarm system (9) is under the influence of a permanently acting perturbation $p(x^i)$ with its bound $\|p(x^i)\| \le \delta$, $\delta \succ 0$, so that the swarms system can be rewritten as

$$dx^i = \sum_{j=1, j\neq i}^{N} g\left(x^i - x^j\right)dt + p\left(x^i\right)dt + f\left(x^i - \bar{x}\right)\omega^i(t)dt \circ$$

(10)

Where, $i = 1, 2, \cdots, N$.

Now, using the stochastic swarms model, we obtain the following corresponding numerical simulation results of the stochastic swarm systems as Figure 16 ~ Figure 19 shows.

V. Numerical Simulations

As well known, the behavior of the two kinds of different swarm systems in the proposed algorithm is largely divided into five parts: group migration aggregation (flocking/ grouping/ herding), collision avoidance, group formation, target tracking coverage search, and global asymptotic stability of interference suppression.

In this section, we will present some numerical simulations for the two kinds of different swarm systems as mentioned above to illustrate the theoretical results and the effectiveness of the control schemes (namely, algorithms) discussed in the previous sections.

By means of the range limited-perceive swarm dynamical model, based on artificial potential field (APF) function and Newton-Raphson iteration update rule to numerical imitation analyze how a large-scale swarm system can form desired particular predefined an approximation of a simple convex polygon or circle formation in the plane by collective motion, related the range limited-perceive swarm pattern formation behavior results examples as Figure 5 ~ Figure 11 shows [2]

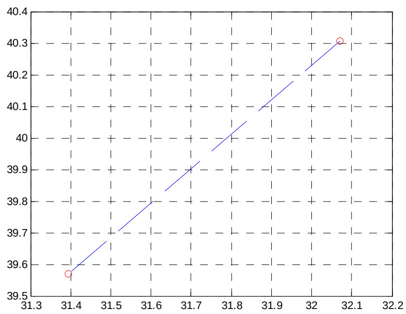

Figure 5. Congregated positions of entire of the ideal formation configuration of the line segment for 2 agents in plane

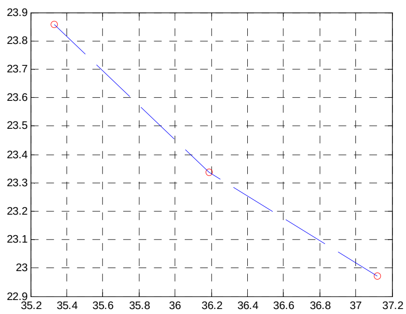

Figure 6. Congregated positions of entire of the ideal formation configuration of the line segment for 3 agents in plane

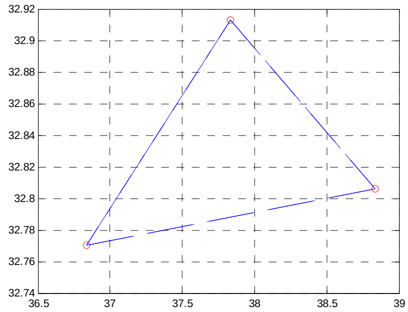

Figure 7. Congregated positions of entire of the ideal formation configuration of the equilateral triangle for 3 agrnts in plane

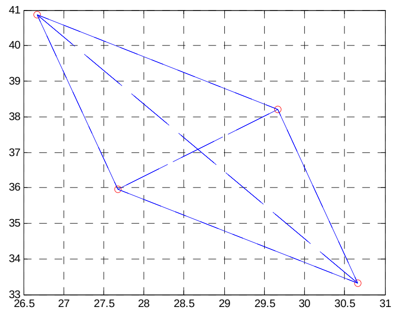

Figure 8. Congregated positions of entire of the ideal formation configuration of the parallelogram for 4 agents in plane

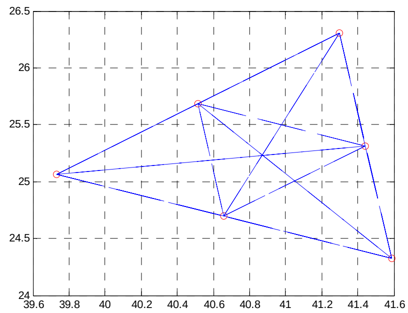

Figure 9. Congregated positions of entire of the ideal formation configuration of the equilateral triangle for 6 agents in plane

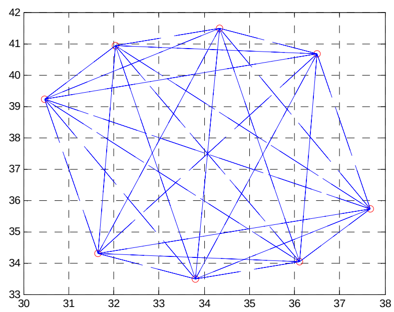

Figure 10. Congregated positions of entire of the desired formation configuration of the circle for 8 agents in plane

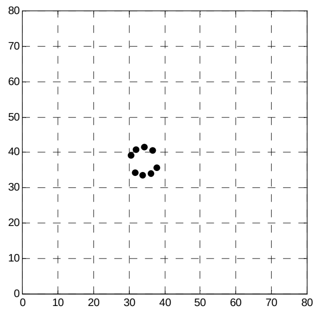

Figure 11. Circular formation motion final position of eight agents

According to the target dynamics model (4), let $N = 4$, our task is to make the four agents form an diamond with the target in the mid-point.

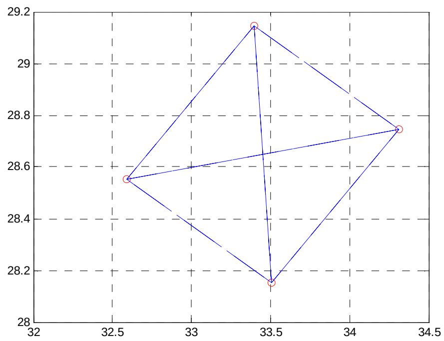

Figure12. Desired diamond formation for 4 agents in plane

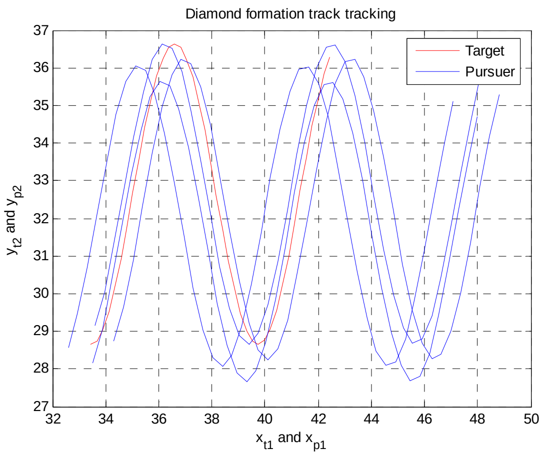

Figure13. Paths of swarm members

Figure 13 shows the paths of the swarm members and the target. It is observed that with random initial positions the swarm members quickly form the desired geometrical shape and track the target such that the target is surrounded/enclosed by the agents in the swarm. This implies that the target is within the convex hull formed by the positions of the agents in finite time. It is observed that when the tracking agents try to keep the target at the center of the diamond but this time it becomes more difficult for the agents to keep the desired inter-agent distances.

In figure 13, the initially swarm's center (namely, the rendezvous center of the diamond) is located at the position (33.4508, 28.6480) in the plane, whereas the four pursuers are respectively located at the (34.3114, 28.7446), (33.5066, 28.1511), (32.5902, 28.5513), and (33.3950, 29.1449).

In WSN, one important observation is that if the communication range is at least twice the sensing range, the complete coverage of a convex region implies the connectivity, as Figure 15 shows.

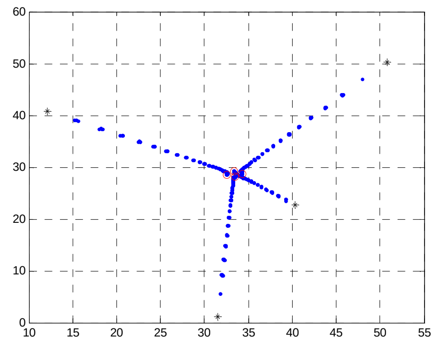

Figure 14. Convergent trajectories of the ideal formation configuration of the diamond for 4 agents in plane

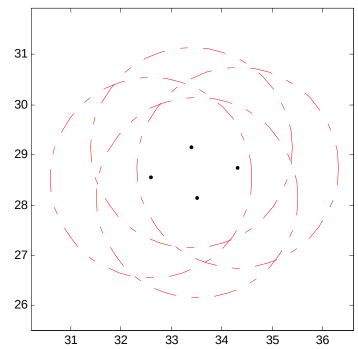

Figure 15. The communication and coverage search capabilities showing for 4 agents members in the swarm to form the ideal diamond formation in plane at the time of entire positions

The relationship between coverage and connectivity is true for a convex area, but not necessary true for a set of targets. Few of these work has studied this relationship in the target coverage yet. Hence more work on the connected target coverage problem need to be done. Where, preliminary attempt for the target coverage problem in WSN being done by us, these analysis and computation results have direct reference value for nodes and system design of wireless sensor networks.

In above graphs, black "*" represent original position, read "。" represent final position, blue "." represent convergent trajectories of individuals, the polygonal vertex shows the final numerical imitation configuration position of UAV/robots. Considering the convenience of simulation, let $\nabla_y \sigma(y) = 0$. In the figure 12 of the relations between sides and angles of the desired diamond formation configuration, read "。" represent final configuration positions, the rendezvous represent the center of the diamond swarm, and $i = 1,\cdots,N$. represent different agents in the swarm systems.

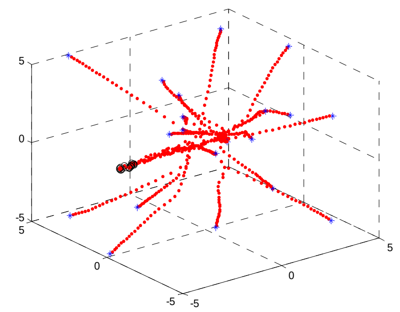

Figure16. Convergent trajectories of individuals in isotropic exponential type swarm model

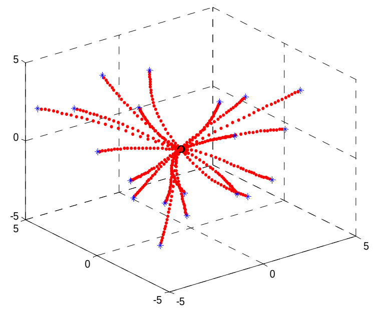

Figure17. Convergent trajectories of individuals in isotropic exponential type swarm model and we used the tanh(·) function instead of the sign(·) function to smooth the motion trajectories

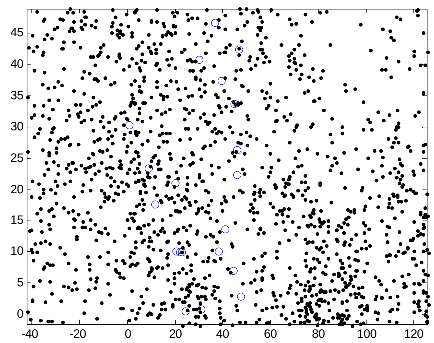

Figure18. Original position of individuals in isotropic exponential type swarms

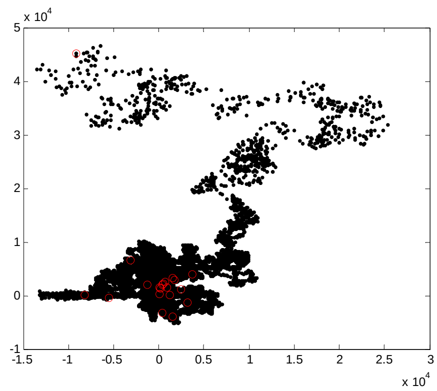

Figure19. Convergent trajectories of individuals about the globally asymptotically stable in isotropic exponential type swarms under a standard white Gaussian noise perturbation in plan social potential field profile environment

In Fig 16 and Fig 17, blue "*" represents original position, black "。" represents final position, red "." represents convergent trajectories of individuals.

In Fig 18 and Fig 19, blue "。" represents original position, red "。" represents final position, black "." represents convergent trajectories of individuals. Meanwhile, the simulation result in Fig 18 and Fig 19 show that such an isotropic swarms model it can realize the social foraging swarms aggregation in plane social potential field environment under a standard white Gaussian noise perturbation also verify the globally asymptotically stable capability.

The simulation results in this section reify our theories for multi-agent systems.

VI. Conclusions

The purpose of this paper is to focus on the target tracking application for single and multiple targets flocking moving in an n-dimensional Euclidean space with a dynamic virtual leader, and describe related problems such as target modeling. The tracking agents are required to capture and enclose the target while moving as a geometric formation. The coordinated tracking task stated above is actually consisting of two-subtasks for the swarm: Tracking a moving target and maintaining the geometric swarm formation (shape). In order to perform these two sub-tasks simultaneously, we consider a distributed control strategy based on artificial potential functions. To solve the problem, we proposed a set of control laws, and the control law acting on each agent relies on the state information of its neighbors and the external signal. We proved that, in the case where the acceleration input of the virtual leader is known, all agents can follow the virtual leader, freedom from collisions between neighboring agents is ensured, the final tight formation minimizes all agents potentials.

Moreover, in this article, we analyze the global asymptotic stability of the proposed exponential type stochastic swarm systems model which has better robust with respect to the system uncertainties and additive disturbances in theory.

Meanwhile, numerical simulation agrees very well with the theoretical analysis.

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