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Velocity Adaptation for Synchronizing a Mobile Agent Network

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Abstract. This paper investigates the problem of synchronizing a mobile agent network by means of a velocity adaptation strategy, where each agent is assigned different moving velocities to establish a time-varying network topology, and the velocity of each agent develops adaptively according to the local property between itself and its neighbors. We show that our strategy is effective in enhancing the synchronizability of the mobile agent network, i.e., the region of power density for which the network can achieve synchronization is enlarged as compared to the fast-switching case. In addition, the influence of the controlling parameter on network evolution is studied by assessing the convergence time.

Keywords: mobile agents, velocity adaptation, complex coupled networks, synchronization.

1. Introduction

In the past decade, network-based approaches have attracted an increasing interest and have been proved to be prominent candidates to investigate the collective dynamics in many branches of science and engineering [1], [2], [3], [4], [5]. As a typical collective motion, synchronization in complex dynamical networks has been extensively studied. And a number of studies have pointed out that topological structure plays a significant role in the formation of network synchronization [6], [7], [8].

However, most investigations have focused on networks that do not change with the dynamics, i.e., network topological structures and weights are fixed as time evolves. As a matter of fact, a great deal of real-world complex networks in biological, social and communication systems exhibit time-varying topological structures: edges are deleted, added or rewired according to some rules. Therefore, many researchers have recently devoted their attention to the study of time-varying networks [9], [10], [11], [12], [13], [14], [15], [16], [17], particularly to the co-evolution of dynamical states and network structures. As a result, lots of models of adaptive networks have been proposed and the corresponding synchronization issues have been intensively investigated [18], [19], [20], [21].

In this paper, we focus our discussions on the synchronization issue in a power-driven mobile agent network [22]. Since this type of agent network has a remarkable feature of switching topology, it could be used as a good representation to explore many kinds of real-world problems, e.g., synchronous motion in clock of mobile robots [23], bulk oscillations of yeast cells [24], and collective reaction of a group of animals [25]. We propose a velocity adaptive rule to guarantee its synchronous behavior based on the moving agent network with heterogeneous moving velocities. The general idea behind the adaptation strategy is that, each agent develops its moving velocity according to local synchronization property between itself and its neighbors. In the following sections, we will show that when power density is large, synchronization of the considered network can be effectively guaranteed under the velocity adaptation strategy. In addition, by assessing the convergence time, we investigate the influence of controlling parameter on network synchronization.

The rest of this paper is organized as follows: Related work is presented in Section 2. In Section 3, a moving agent network model with velocity adaptation strategy is proposed. And synchronization analysis of the considered network is given in Section 4. Further discussions including the Influence of controlling parameter are shown in Section 5. Conclusions are finally drawn in Section 6.

2. Related Work

Mobile agent network seems to be a good solution to investigate various synchronization problems in different complex systems. Generally speaking, each agent in the agent network is equipped with an identical oscillator, and switching topology is constructed via the change of neighbouring interactions. The mobile agent network, indeed, can be used to explore many problems such as clock synchronization in mobile robots, swarming animals or the appearance of synchronized bulk oscillations, consensus problem in multi-agent systems and so on, partially because of a good choice to capture jumps or switches of coupling evolutions.

Frasca et al investigated the fast-switching synchronization of a moving agent network and pointed out that the density of mobile agents determines network synchronization [13]. Shi et al developed the mobile agent network model by assigning different emission powers to each agent, which further provides an insight into the collective behaviours of coupled agent systems [19], [21], [22]. To enhance network synchronizability, Wang et al proposed an power-adaptation rule to synchronize the power-driven mobile agent network model [27]. Also, Wang et al introduced pinning control strategy (apply localized feedback control to small fraction of the network model) to regulate the mobile agent network [28].

Based on the moving agent network with heterogeneous moving velocities, the paper presents a velocity adaptive rule to guarantee its synchronous behavior. Different from the existing agent network models [19], [21], [22], [26], [27], [28], we assign each agent different moving velocities, so as to establish a time-varying coupling mechanism, which can be used to characterize the heterogeneous moving capabilities of the mobile agents. It has been found that the heterogeneous moving capabilities widely exist in individuals of real-world systems. For instance, insects or animals fly or run with different velocities [29]; treated as agents, pedestrians and automobiles apparently show different moving abilities [30] and so on.

3. A Moving Agent Network Model with Velocity Adaptation Strategy

3.1. Moving Agent Network with Heterogeneous Velocities

Consider a set of N agents, each of which is equipped with a chaotic oscillator $x_i(t) \in \mathbb{R}^n$, i=1,2, ⋯,N. Assume that all the agents move randomly in a two-dimensional space of size L with periodic boundary conditions, and their positions and orientations are updated according to:

$$y_i(t+\Delta t) = y_i(t) + v_i(t)\ \Delta t \qquad (1)$$

$$\theta_i(t+\Delta t) = \eta_i\ (t+\Delta t)\ .$$

where $y_i(t)$ is the position of agent i in the plane at time t, $v_i(t)$ with modulus $V_i(t)$ and direction angle $\theta_i(t)$ is the moving velocity of agent i, $\eta_i(t)$, i=1,2, …,N, are N independent random variables chosen at each time unit with uniform probability in the interval [$-\pi$, π], and Δt is the time unit. It is noted that, differing from the existing mobile rules [19], [21], [22], [26], [27], [28], the velocity modulus $V_i(t)$ of agents are generally different from each other.

First of all, we recall the power-driven mechanism [22] to establish connections among the mobile agents. In detail, each agent is regarded to be a wave source with emission power P_e^i, which reads:

$$P_e^i = 4\pi d^2 s^i(d),\ s^i(d) \geqslant S_c. \qquad (2)$$

where d indicates the distance from agent i, $S^i(d)$ as a function of d is the intensity of wave emitted by agent i, and S_c is a critical wave intensity, if the intensity of wave is beyond S_c, then agents can perceive it accurately. If agent i has emission power P_e^i, then there exists an influence radius, denoted by $R_i=(P_e^i/4\pi S_c)^{1/2}$, within which $S^i(d) \geqslant S_c$. That is, directed couplings from agent i to its neighboring agents will be established immediately when the neighboring ones move into its influence range. For the sake of simplicity, we here consider that each agent is of the same emission power, denoted by $P_e^1 = P_e^2 = \ldots = P$.

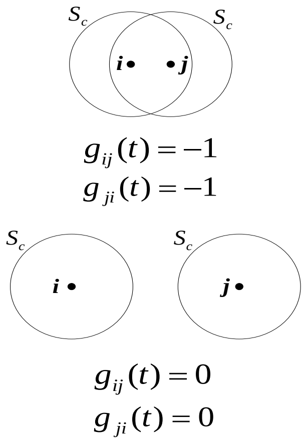

Fig. 1. Coupling relationship between agents i and j, where the circle means the influence area.

Hence, we construct a time-varying dynamical network by combining the mobile agents, chaotic oscillators and their power-driven coupling rules. Moreover, the mobile agent network can be formulated as follows:

$$\dot{x}_i = f(x_i) - \sigma \sum_{j=1}^{N} g_{ij}(t) h(x_j) \,. \tag{3}$$

where i=1,2, …,N, $f: R^n \rightarrow R^n$ governs the local dynamics of oscillator, $h: R^n \rightarrow R^n$ is a vectorial output function, $\sigma > 0$ is the coupling strength, and Laplacian matrix $G(t) = [g_{ij}(t)] \in R^{N \times N}$ defines the coupling relationship of agents at a given time t. For specific details, for two agents i and j, if the relative distance between i and j is larger than the influence radius $R = (P/4\pi S_c)^{1/2}$, then $g_{ij}(t) = g_{ji}(t) = -1$, otherwise $g_{ij}(t) = g_{ji}(t) = 0$. Fig. 1 shows the detailed coupling relationship between two agents i and j. The diagonal elements of G(t) satisfy: $g_{ii}(t) = m_i(t)$, where $m_i(t)$ is the number of neighbors of agent i at time t. In this paper, without lack of generality, we consider the *Rössler* oscillator, and we choose $h(x_j) = Hx_j$ with H=diag(1,0,1).

3.2. Velocity Adaptive Strategy of the Moving Agent Network

We here introduce a simple scheme of velocity adaptation according to local synchronization property to synchronize the moving agent network (3). To achieve a global synchronization of network (3), we suppose that each agent develops its moving velocity if its state has a deviation from the mean state of its neighbors. Specifically, the velocity modulus $V_i(t)$ of agent performs according to the following law using the information of all its neighbors, i.e.,

$$\dot{V}_i(t) = \frac{\gamma\Delta_i(t)}{1+\Delta_i(t)}$$
$$\Delta_i(t) = \| \sum_{j=1}^{N} g_{ij}(t)x_j(t) \|^2 . \tag{4}$$

where the derivative of $V_i(t)$ is to suppress its difference Δ_i from the mean activity of its neighbors, $\gamma>0$ is a controlling parameter which is used to adjust the convergence rate.

It is worth noting that the mathematical expression of the velocity adaptive strategy seems similar to that in [18], [19], [20], [21]. However, the velocity adaptation strategy is quite different from those in [18], [19], [20], [21] in principle. The basic idea of adaptation in Ref [18] and Ref [20] is to strengthen the coupling weights of edges; the fundamental principle in Ref [19] is to establish more edges among nodes, and the idea in Ref [21] is to adjust the blinking pace so as to achieve a proper blinking mode that can facilitate synchronization of the network; while the essence of the velocity adaptation in Eq. (4) is to accelerate the rate of information exchange by increasing the moving velocity.

4. Synchronization Analysis of the Moving Agent Network under the Velocity Adaptive Strategy

We first briefly consider the case that all the agents move with sufficiently high velocities. Under such case, the topology of network (3) switches among each possible configuration with sufficiently high speed. Then, according to the results in [31], we can derive that, if the following time-average network achieves synchronization

$$\dot{x}_i = f(x_i) - \sigma\sum_{j=1}^{N} g'_{ij}h(x_j), . \tag{5}$$

then network (3) with time-varying topologies can realize synchronization, where $g'_{ij}(t)$ is the element of the average Laplacian matrix $G' = \int G(s)/T_b ds$, and time window T_b is a constant. Apparently, by recalling the maser-stability-function (MSF) method [6], we can deduce that network (5) achieves synchronization if all the non-zero eigenvalues of G' locate in the interval $[\alpha_1/\sigma, \alpha_2/\sigma]$, where α_1 and α_2 are constants determined by MSF corresponding to network (5).

By elementary transformation, we derive the N eigenvalues of G': $\lambda_1=0$, $\lambda_2=\ldots=\lambda_N=NP/(4S_cL^2)$. Thus, under the case of sufficiently high moving velocity $V_i(t)$, network (3) is synchronizable when the power density of agents lies in the bounded region [ρ_{e1}, ρ_{e2}], where $\rho_{e1}=4S_c\alpha_1/\sigma$, $\rho_{e2}=4S_c\alpha_2/\sigma$. This result indicates that, under the case of sufficiently high moving velocity $V_i(t)$, regardless of the network size, synchronization of network (3) can be achieved when the power density satisfies the above condition.

4.1. Adaptive Synchronization under the Case that Power Density Locates in the Interval [ρ_{e1}, ρ_{e2}]

As moving velocities $V_i(t)$ of the agents evolve according to adaptive law (4), we consider the case of power density locating in the interval [ρ_{e1}, ρ_{e2}], where synchronization of network (3) can be guaranteed if all the agents move with sufficiently high moving velocities. Suppose each agent starts from a random small moving velocity. In this case, synchronization of network (3) can be always guaranteed by adaptive law (4). We can use the method of proof by contradiction to explain. If network (3) evolves sufficiently long time without synchronization, then, according to adaptive law (4), the moving velocity $V_i(t)$ of each agent develops gradually and finally achieves sufficiently high. Thus the topology switching will be sufficiently fast under sufficiently high moving velocities, which results in convergence of network (3) as power density locates in the interval [ρ_{e1}, ρ_{e2}].

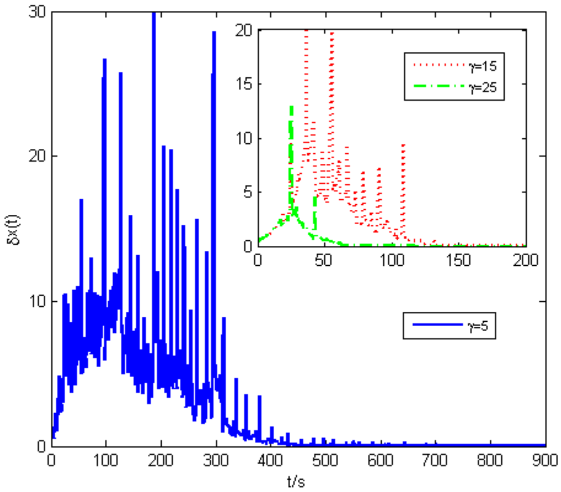

Fig. 2. Evolution of synchronization error $\delta x(t)$ for the case that power density locates in the interval [ρ_{e1}, ρ_{e2}]

Fig. 2 gives the corresponding simulation of network (3) under adaptive law (4), where the synchronization error is defined as $\delta x(t)=(\sum||x_i-x_1||)/N$, network size N=100, power density $\rho_{e1}<\rho_e=0.2<\rho_{e2}$, the other parameters are set as: $\sigma=10$, P=3.14, $S_c=0.25$, and $\Delta t=10^{-3}$s. It is easy to see that network (3) under adaptive law (4) can achieve synchronization for different controlling parameter γ and the main trends of synchronization error $\delta x(t)$ perform almost the same though differences exist in γ: $\delta x(t)$ increases with t at the beginning since the initial moving velocity of each agent is small and the whole network can be regarded as an unconnected one, thus the network has no propensity to synchronization; as time evolves, moving velocities $V_i(t)$ develop gradually under adaptive law (4) and switching among all possible topological configurations becomes more and more fast; furthermore, $\delta x(t)$ is prone to decrease, and finally converges to zero, which means a complete synchronization of network (3). Also notice in Fig. 2 that enhancing γ will speed up the convergence rate.

4.2. Adaptive Synchronization under the case that Power Density is Larger than ρ_{e2}

In the following, we consider the case that power density of network (3) is larger than the critical value ρ_{e2}. According to the results derived under the fast-switching condition, network (3) cannot achieve synchronization in such a case if the moving velocity of each agent is sufficiently high. While numerical simulations show that synchronization of network (3) can still be guaranteed by velocity adaptive law (4).

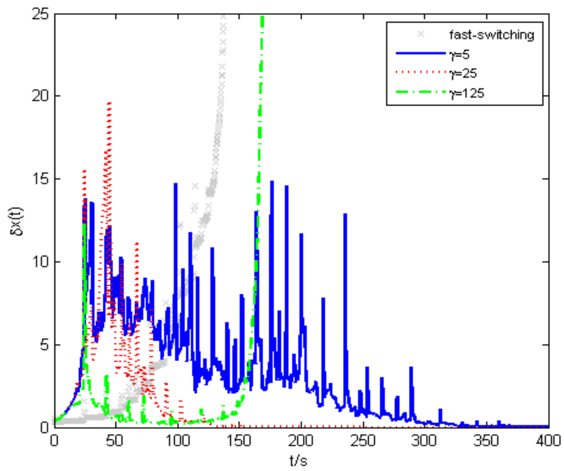

Fig. 3. Evolution of synchronization error $\delta x(t)$ for the case that power density is larger than ρ_{e2}

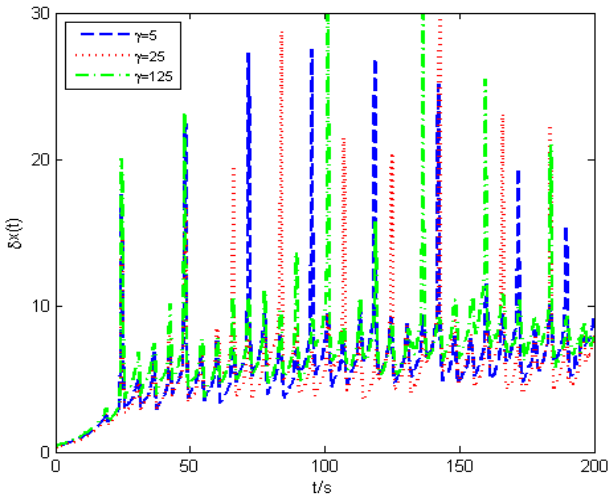

Fig. 4. Evolution of synchronization error $\delta x(t)$ for the case that power density is smaller than ρ_{e1}.

Fig. 3 gives the result of synchronization error $\delta x(t)$ evolving with time t under fast-switching case and velocity adaptive law (4) respectively, where network size N=100, power density $\rho_e=0.53>\rho_{e2}$, and the other parameters are set as: $\sigma=10$, P=3.14, $S_c=0.25$, and $\Delta t=10^{-3}$s. It can be seen from Fig. 3 that synchronization error $\delta x(t)$ increases with time t when all the agents in network (3) move with sufficiently high speed, i.e., fast-switching condition is satisfied, which means network (3) cannot achieve synchronization. When network (3) evolves according to velocity adaptive law (4), synchronization error $\delta x(t)$ will converge to zero if the controlling parameter γ is relatively small ($\gamma=5$ and $\gamma=25$), which means network (3) achieves complete synchronization. While, if the controlling parameter γ is relatively large ($\gamma=125$), synchronization error $\delta x(t)$ cannot realize convergence, i.e., network (3) cannot achieve complete synchronization. This phenomenon can be explained as follows: if controlling parameter γ is sufficiently large, then moving velocity $V_i(t)$ of each agent will develop sufficiently fast. Thus, moving velocities $V_i(t)$ become sufficiently high before complete synchronization of network (3) is achieved; furthermore, fast-switching condition is satisfied. While network (3) cannot realize synchronization under fast-switching condition if power density is larger than ρ_{e2}. In conclusion, network (3) cannot realize synchronization by velocity adaptive law (4) if controlling parameter γ is relatively large. Therefore, we can choose a relatively small γ to guarantee synchronization of network (3).

4.3. Adaptive Synchronization under the Case that Power Density is Smaller than ρ_{e1}

For the case that power density is smaller than ρ_{e1}, we conduct simulations to see how network (3) evolves under velocity adaptive law (4). Fig. 4 give the result of synchronization error $\delta x(t)$ evolving with time t under different controlling parameter γ, where network size N=100, power density $\rho_e=0.01<\rho_{e1}$, and the other parameters are set as: $\sigma=10$, P=3.14, $S_c=0.25$, and $\Delta t=10^{-3}$s. From Fig. 4, we can see that no matter what value of controlling parameter γ is, synchronization error $\delta x(t)$ cannot converge to zero as time evolves, i.e., network (3) cannot achieve synchronization under velocity adaptive law (4) when power density is smaller than ρ_{e1},. That is to say, velocity adaptive law (4) works little in enhancing synchronizability of network (3) when power density is smaller than ρ_{e1},.

5. The Influence of Controlling Parameter γ on Adaptive Synchronization of the Agent Network

The discussions above show that controlling parameter γ plays a significant role in making network (3) realize synchronization. Here, we conduct simulations and give the results of synchronization index $<\delta x>=<\delta x(t)>$ evolving with power density ρ_e under velocity adaptive law (4) with different controlling parameter γ in Fig. 5, where synchronization index $<\delta x>$ is the average of $\delta x(t)$ during the period [T, T+ΔT]. The other parameters in simulations are set as: T=200s, ΔT=50s, $\sigma=10$, P=3.14, $S_c=0.25$, and $\Delta t=10^{-3}$s. It can be seen from Fig. 5 that, network (3) under velocity adaptive law (4) possesses a relatively large power density region as compared to the fast-switching case, in which synchronization of network (3) can be realized. Velocity adaptive law (4) broadens the upper bound of the power density region, while it works little in broadening the lower bound. It can be noticed that, as controlling parameter γ decreases, the upper bound of the power density region increases, which indicates that lowering γ is in favor of enhancing the synchronizability of network (3).

However, lowering γ also results in some poor performance indexes. Fig. 6 gives the result of convergence time T_c evolving with controlling parameter γ, where the convergence time T_c is defined to be the total time from the beginning to the moment that full synchronization of network (3) is achieved [32] (in simulations, when $\delta x(t)< 10^{-4}$, network (3) is regarded to realize synchronization). The other parameters in simulations are set as: N=100, $\sigma=10$, P=3.14, $S_c=0.25$, and $\Delta t=10^{-3}$s. From Fig. 6, convergence time T_c is a finite value for a particular γ, which means network (3) can realize synchronization. It is noted that, when γ is small, convergence time T_c is considerably long, which means poor performance index. Therefore, we should choose a proper controlling parameter γ to meet system requirement, not being too large or too small.

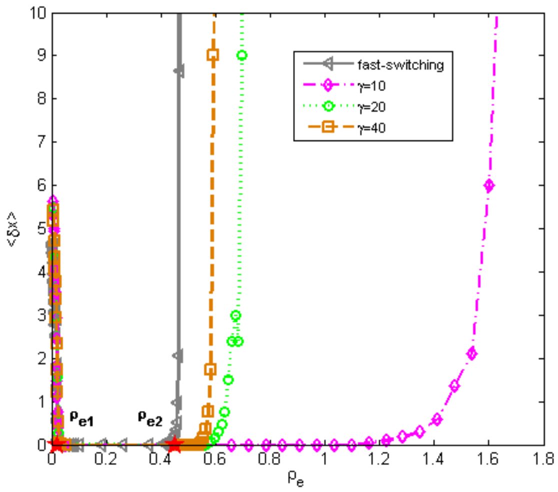

Fig. 5. Evolution of synchronization index <δx> with power density ρ_e for different controlling parameter γ

6. Conclusion

In conclusion, different moving velocities are introduced for the mobile agent network to characterize the heterogeneous moving capability of each agent. For such an agent network with heterogeneous moving velocities, we suggest a velocity adaptive strategy in order to guarantee the corresponding synchronization motion. Theoretical analysis and numerical simulations have shown that the proposed velocity adaptive tactic is quite efficient in enhancing the synchronizability of the considered network. In addition, we also discussed the impact of controlling parameter on network synchronization by assessing the convergence time. All these investigations may provide some insights for the future research work on synchronization enhancement in coupled oscillator networks and also may open up new possibility to design potential engineering applications, e.g., mobile sensor networks, moving robotics systems, as well as unmanned aerial vehicles.

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