



Flocking in Distributed Control and Optimization

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Final Report

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14. ABSTRACT In recent years, the study of biological systems in which flocking and/or swarming phenomena is observed has received increased attention by researchers in control and optimization. In these systems, a great deal of coordination is achieved under relatively minimal communication requirements. In this research project we developed and formally analyzed techniques for control and global optimization that are inspired by flocking and other forms coordinated behavior from biological systems. Most notably we have developed a new approach for simulation-based optimization that makes use of a flocking potential. We show that the flocking-based approach has an important noise reduction property. Under a flocking discipline, simulation noise realizations that induce trajectories differing too much from the group average are likely to be discarded because of each individual's need to maintain cohesion. As result the group trajectories are less affected by such noise.					
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Flocking in Distributed Control and Optimization
FA9550-12-1-0163

Final Report
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1. Objectives

In recent years, the study of biological systems in which flocking and/or swarming phenomena is observed has received increased attention by researchers in control and optimization. In these systems, a great deal of coordination is achieved under relatively minimal communication requirements. In this research project we have developed and formally analyzed techniques for control and global optimization that are inspired by flocking and other forms of coordinated behavior from biological systems. Most notably we have developed a new approach for simulation-based optimization that makes use of a flocking potential. We show that the flocking-based approach has an important noise reduction property. Under a flocking discipline, simulation noise realizations that induce trajectories differing too much from the group average are likely to be discarded because of each individual's need to maintain cohesion. As a result the group trajectories are less affected by such noise.

2. Results

- 2.a The paper “Interactive Model-based Search for Global Optimization” by Yuting Wang and Alfredo Garcia was published in the *Journal of Global Optimization*. In this paper, we propose a new algorithmic design for global optimization based upon multiple interacting threads. In this design, each thread implements a model-based search in which the allocation of exploration versus exploitation effort does not vary over time. Threads interact through a simple acceptance-rejection rule preventing duplication of search efforts. We show the proposed design provides a speedup effect which is increasing in the number of threads. Thus, in the proposed algorithmic design, exploration is a complement rather than a substitute to exploitation.
- 2.b The papers “Consensus of discrete-time multi-agent systems with transmission non-linearity,” and “Consensus of discrete-time second order multi-agent systems based on infinite products of general stochastic matrices,” were respectively published in *Automatica* and *SIAM Journal on Control and Optimization*.
- 2.c The paper “Distributed Synchronization Control of Multi-agent Systems with Unknown Nonlinearities” by Shize Su, Zongli Lin and Alfredo Garcia was published in *IEEE Transactions on Cybernetics*. In this paper, we consider a distributed adaptive control problem for synchronization of multiagent systems where the dynamics of the agents are nonlinear, nonidentical, unknown, and subject to external disturbances. Distributed neural networks are used to approximate the uncertain dynamics. Decentralized adaptive control protocols are then constructed to solve the cooperative tracker problem, the problem of synchronization of all follower agents to a leader agent.

- 2.d The paper “Interactive Model-based Search with Reactive Resource Allocation” by Yue Sun and Alfredo Garcia has been accepted for publication at *Journal of Global Optimization*. In this paper, we consider an implementation of the interactive model-based approach (as in Wang and Garcia (2015)) that accounts for real time, that is, it takes into account the possibility that several threads may fail to identify a locally optimal solution whenever the acceptance-rejection rule is implemented. We propose a modified acceptance-rejection rule that alternates between enforcing diverse search (in order to prevent duplication) and reallocation of computational effort (in order to speed up the identification of local optima). We show that the rate of convergence in real-time increases with the number of threads. This result formalizes the idea that in parallel computing, exploitation and exploration can be complementary provided relatively simple rules for interaction are implemented.
- 2.d The paper “Noise Reduction by Swarming in Social Foraging” by Pu Shi, Alfredo Garcia and Zongli Lin has been submitted to *IEEE Transactions on Automatic Control*. In this paper, In this paper we develop a mathematical model for analyzing the benefits of social foraging in a noisy environment. We identify conditions on the nutrient profile ensuring that local agent actions will lead to cohesive foraging. For convex, smooth nutrient profiles we formalize the way in which swarming for social foraging is better at handling the effects of noise when compared to the average of individual foraging strategies. Under a swarming discipline, observational noise realizations that induce trajectories differing too much from the group average are likely to be discarded because of each individual’s need to maintain cohesion. As result the group trajectories are less affected by noise. Simulation experiments indicate our theoretical results are robust to inter-agent communication constraints and non-convex nutrient profiles. These results suggest that swarming-like approaches for the control of networked agents may provide an additional level of robustness.
- 2.e The paper “Flocking for Simulation-based Optimization” by Pu Shi and Alfredo Garcia has been submitted to *Operations Research*. We describe the main findings in section 3 below.

3. Accomplishments/New Findings

In a recent paper “Flocking for Simulation-based Optimization” by Pu Shi and Alfredo Garcia we have made what we believe is an important discovery. We analyze a distributed approach for simulation-based optimization based upon a flocking discipline. Swarms, flocks and other group formations can be found in nature in many organisms ranging from simple bacteria to mammals. Such collective and coordinated behavior is effective for avoiding

predators and/or for increasing the chances of finding food (foraging). We consider an algorithmic scheme with several independent threads each updating a solution in greedy fashion based upon a noisy evaluation of the gradient and a flocking potential which is a combination of *repulsive* and *attractive* forces. We show that the flocking-based approach has an important noise reduction property. Under a flocking discipline, simulation noise realizations that induce trajectories differing too much from the group average are likely to be discarded because of each individual's need to maintain cohesion. As result the group trajectories are less affected by such noise.

We now provide an example that illustrates the robustness of a flocking-based approach for optimization. In Figure 1 (a) and (c) we respectively show the sample paths of individual threads solution and the distance to the optimal solution. It can inferred from Figure 1 (b) and (d) that individual threads operating in parallel are unable to approximate the optimal solution due to noise. Even when a solution that is close to optimal is reached the algorithm is not robust to noise perturbation. In contrast, the flocking discipline can be seen to reduce the effects of noise. This can be succinctly explained as follows. Under a flocking discipline noise realizations that induce trajectories differing too much from the group average are likely to be discarded because of each individual's need to maintain cohesion. As result the group trajectories are less affected by noise.

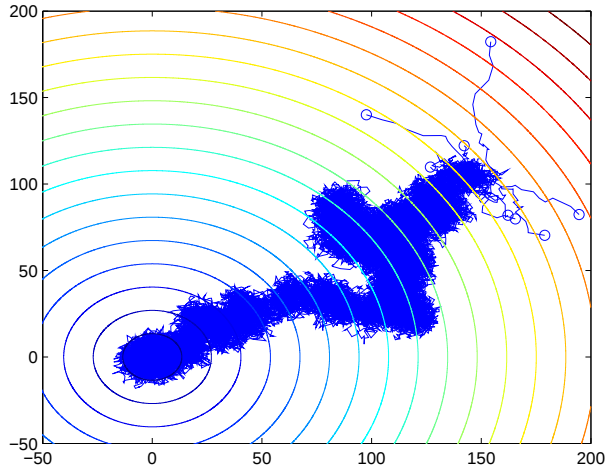
4. Personnel Supported

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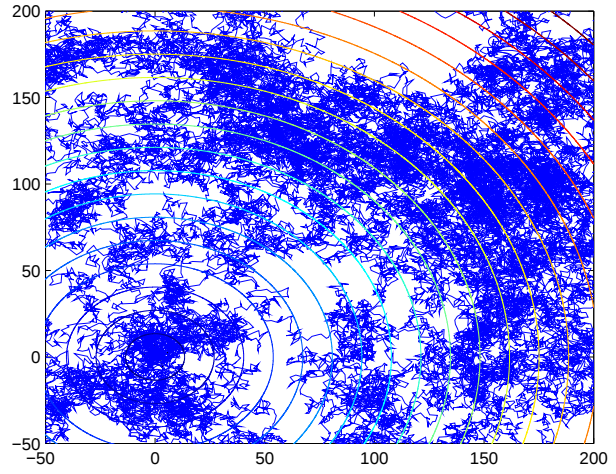
Alfredo Garcia	PI	1 $\frac{1}{2}$ summer month
Zongli Lin	Co-PI	1 summer month
Pu Shi	PhD student	9 month, full support
Yue Sun	PhD student	9 month, partial support
Shize Su	PhD student	9 month, partial support

5. Publications:

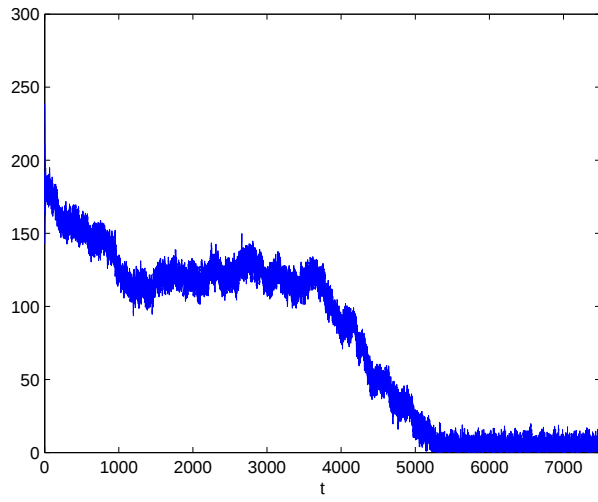
1. Y. Chen, J. Lu and Z. Lin, "Consensus of discrete-time multi-agent systems with transmission nonlinearity, *Automatica*, Vol. 49, No. 6, 2013, pp. 1768-1775
2. Y. Chen, J. Lu, X. Yu and Z. Lin, "Consensus of discrete-time second order multi-agent systems based on infinite products of general stochastic matrices," *SIAM Journal on Control and Optimization*, Vol. 51 No. 4, 2013, pp. 3274-3301.
3. Y. Sun and A. Garcia, "Interactive Diffusions for Global Optimization," *Journal of Optimization Theory and Applications*, Vol. 163, No. 2, 2014, pp 491-509



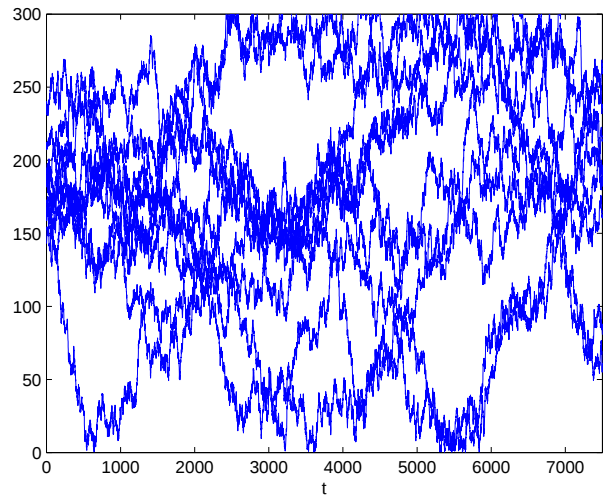
(a) Sample Paths with Interaction.



(b) Independent Sample Paths.



(c) Distance to optimum with Interaction.



(d) Distance to optimum for Independent Threads.

Figure 1: Performance comparison.

4. Y. Wang and A. Garcia, "Interactive Model-based Search for Global Optimization," *Journal of Global Optimization* Vol. 61, No. 3, 2015, pp 479-495
5. H. Hu, S.Y. Yoon and Z. Lin, "Flocking of Wheeled Vehicles in the Presence of Large Communication Delay through a Potential Functional Approach, in *Proceedings of The 52nd IEEE Conference on Decision and Control, Florence, Italy*. December 10-13, 2013,
6. S. Su, Z. Lin and A. Garcia "Distributed Synchronization Control of Multi-agent Systems with Unknown Nonlinearities" in *Proceedings of American Control Conference ACC* 2014, pp. 5361-5366.
7. S. Su, Z. Lin and A. Garcia "Distributed Synchronization Control of Multi-agent Systems with Unknown Nonlinearities" accepted *IEEE Transactions on Cybernetics*, published online (DOI 10.1109/TCYB.2015.2402192)
8. Y. Sun and A. Garcia "Interactive Model-based Search with Reactive Resource Allocation accepted *Journal of Global Optimization*.
9. P. Shi, A. Garcia and Z. Lin "Noise Reduction by Swarming in Social Foraging" under review at *IEEE Transactions on Automatic Control*.
10. P. Shi and A. Garcia "Flocking for Simulation-based Optimization" under review at *Operations Research*.

6. Interactions/Transitions

- a. In the Spring semester 2014 we taught a course in decision analysis which covered mathematical models of learning. Emphasis was made on collective learning behavior (such as herding and cascades). A paper on flocking and learning which resulted from a final course project is currently being drafted.

7. New discoveries, inventions, or patent disclosures.

None

1.

1. Report Type

Final Report

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Alfredo Garcia

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Abstract

In recent years, the study of biological systems in which flocking and/or swarming phenomena is observed has received increased attention by researchers in control and optimization. In these systems, a great deal of coordination is achieved under relatively minimal communication requirements. In this research project we developed and formally analyzed techniques for control and global optimization that are inspired by flocking and other forms coordinated behavior from biological systems. Most notably we have developed a new approach for simulation-based optimization that makes use of a flocking potential. We show that the flocking-based approach has an important noise reduction property. Under a flocking discipline, simulation noise realizations that induce trajectories differing too much from the group average are likely to be discarded because of each individual's need to maintain cohesion. As result the group trajectories are less affected by such noise.

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Archival Publications (published) during reporting period:

1. Y. Chen, J. Lu and Z. Lin, ``Consensus of discrete-time multi-agent systems with transmission nonlinearity, Automatica, Vol. 49, No. 6, 2013, pp. 1768-1775
2. Y. Chen, J. Lu, X. Yu and Z. Lin, ``Consensus of discrete-time second order multi-agent systems based on infinite products of general stochastic matrices," SIAM Journal on Control and Optimization, Vol. 51 No. 4, 2013, pp. 3274-3301.
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Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

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Reporting Period

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Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, \$K)

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Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

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Appendix Documents

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