様　式　Ｃ－１９、Ｆ－１９、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

平成　２８　年　　６　月　　９　日現在

機関番号：　２４４０２
研究種目：　若手研究(B)
研究期間：　2014～2015
課題番号：　２６８７０１６９

研究課題名（和文）Internal-Model Distributed Control Design for Complex Networks of Dynamic Agents

研究課題名（英文）Internal-Model Distributed Control Design for Complex Networks of Dynamic Agents

研究代表者
蔡　凱（CAI, KAI）

大阪市立大学・都市研究プラザ・特任准教授

研究者番号：２０７２８２６６

交付決定額（研究期間全体）：（直接経費）　　1,700,000円

研究成果の概要（和文）：In this research, we first designed two specific algorithms that enable networks of agents to perform local estimation and distributed optimization, and then proposed two general methodologies effective in controlling networks of heterogeneous agents and varieties of cooperative tasks.

研究成果の概要（英文）：Networks of dynamic agents play a fundamental role in many natural and engineered systems: for instance, gene regulatory networks, neuron networks, electrical power grids, sensor networks, and the Internet. In this research, we first designed two specific algorithms that enable networks of agents to perform local estimation and distributed optimization, and then proposed two general methodologies effective in controlling networks of heterogeneous agents and varieties of cooperative tasks. Moreover, we built an experiment platform of multiple unmanned aerial vehicles for testing the derived theoretical results.

研究分野：　制御・システム工学

キーワード：　Distributed control　Control over networks　Networks of agents　Complex networks　Internal model principle

１．研究開始当初の背景

Networks of dynamic agents play a fundamental role in many natural and engineered systems: for instance, gene regulatory networks, neuron networks, electrical power grids, sensor networks, and the Internet. These networks exhibit complex global behavior, emerging through interactions of large number of local agents. To understand and control the behavior of such networks has become a cutting-edge research topic, both domestic and international, across various disciplines in science and engineering.

Distributed control of networked agents has been the focus of this researcher's work. In particular, this researcher has done substantial work, and received several awards, on the multi-agent (average) consensus problem, the goal being to drive all agents' states to a common value. This topic is also one of the most active in the systems control field in the last decade. However, there was yet a systematic control design method that can deal with general specifications on network's behavior, with possibly heterogeneous agent dynamics subject possibly to internal parameter uncertainties and external disturbances. Therefore, this researcher was motivated to propose general distributed control design effective for complex networks of agents.

２．研究の目的

The purpose of this research is to develop systematic design methodologies for effective control of complex multi-agent networks that appear in both engineering and nature. In particular, the goal is to be able to deal with heterogeneous agent dynamics subject possibly to internal parameter uncertainties and external disturbances.

The research also aims to develop an experimental platform using multiple robots, in order to test the effectiveness of the derived theoretical results.

３．研究の方法

A variety of methods are used in this research, as listed below.

(1) Graph theory, matrix theory, and consensus-based distributed algorithms

(2) Eigenstructure assignment

(3) Internal model principle

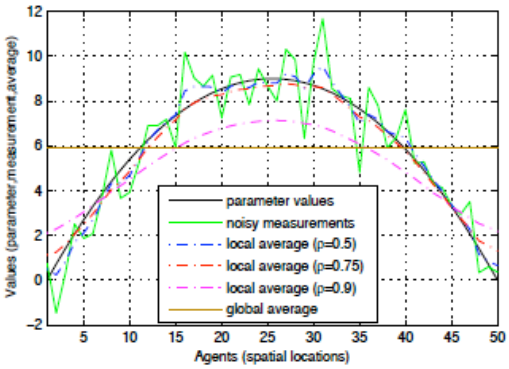
４．研究成果

The following results are obtained through this research.

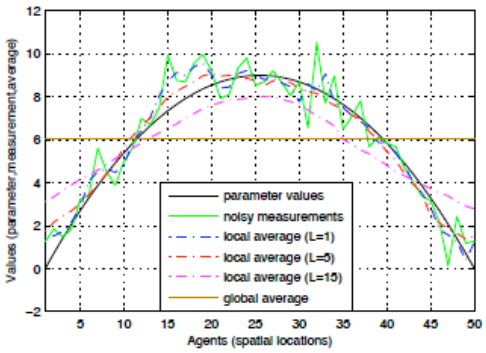
(1) Collaborating with Prof. Brian D.O. Anderson in Australian National University, we proposed a new concept of "local average consensus" and designed a distributed algorithm for a network of agents to perform local measurement of a parameter which has both spatial and temporal variations. We have shown that our designed algorithm effectively captures useful local information regarding spatial variation, as well as mitigates the effect of time-varying measurement errors.

Concretely, our idea is to maintain potentially useful local information regarding spatial variation, as contrasted with reaching a single, global consensus, as well as to mitigate the effect of measurement errors. We employ two schemes for computation of local average consensus: exponential weighting and uniform finite window. In both schemes, we design local average consensus algorithms to address first the case where the measured parameter has spatial variation but is constant in time, and then the case where the measured parameter has both spatial and temporal variations. Our designed algorithms are distributed, in that information is exchanged only among neighbors. Moreover, we analyze both spatial and temporal frequency responses and noise propagation associated with the algorithms. The tradeoffs of using local consensus, as compared to standard global consensus, include higher memory requirement and degraded noise performance. Arbitrary updating weights and random spacing between sensors are also analyzed in the proposed algorithms.

This work was published in Automatica. The two figures below show the performance of our designed algorithms of both exponential weighting and uniform finite window:



(a) Exponential weighting

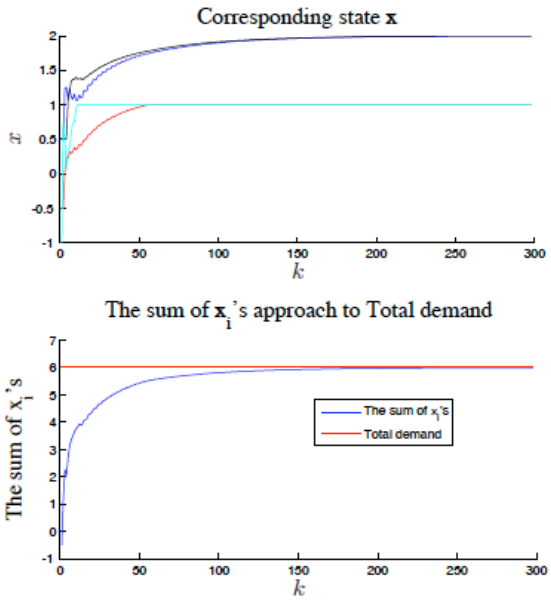


(b) Uniform finite window

(2) Collaborating with Prof. Zhiyun Lin in Zhejiang University, we developed a surplus-based distributed algorithm for a network of agents to achieve constrained optimization over time-varying networks with general (strongly connected) topologies. This algorithm finds applications in various distributed resource allocation problems.

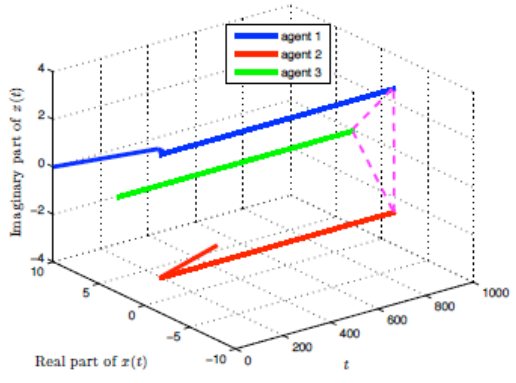
Specifically, each agent in the network has access to its own convex cost function, but its goal is to minimize the total cost collectively subject to individual state constraints, collective equality constraints, and the network constraint for information exchanging. The major challenge of the problem comes from the co-existence of collective equality constraints and time-varying directed network constraints. To overcome the difficulty, we developed a nonnegative surplus based distributed optimization algorithm for the case with a single collective equality constraint. Then it is extended to deal with the case with multiple collective equality constraints. It is shown that the proposed distributed algorithms converge to the minimizer globally provided that the time-varying directed graphs are jointly strongly connected. The most promising characteristic of the algorithms is that the parameters used in the iterations by each agent rely only on local knowledge of the in-degree and out-degree of itself and thus can be designed in a distributed manner, yet the algorithms converge globally for time-varying directed graphs.

This work was presented at Asian Control Conference and Annual Conference of the Institute of Systems, Control and Information Engineers 2015, and its journal version current under review. The following figure shows the performance of our designed distributed optimization algorithm:



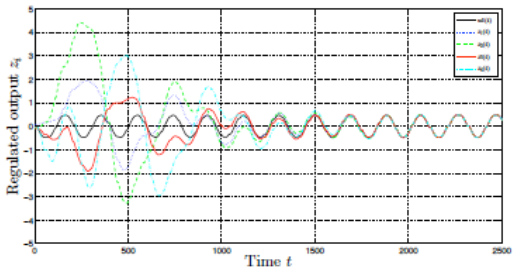
(3) Working with my student, we proposed a centralized methodology, based on eigenstructure assignment, to design control algorithms for networks of heterogeneous agents and general specifications (subsuming consensus and formation control). We apply eigenstructure assignment to multi-agent control problems, and prove that for first-order heterogeneous agents there always exists a state-feedback control that achieves consensus, formation, or circular motion. The approach is top-down, in that one first computes a feedback gain matrix globally, and then implements the resulting control locally (at individual agents). We demonstrate that special inter-agent topologies may be generated by choosing appropriate eigenstructures. Moreover, we propose a hierarchical synthesis strategy to speedup the computation of feedback gain matrix.

We built an experiment of multiple UAVs to test the derived theoretic results. This work was presented at the Institute of Systems, Control and Information Engineers meeting 2015. The following figure shows that using our method, three agents achieve a triangular formation:



(4) I proposed a distributed internal model principle to solve multi-agent output regulation problem, where not all agents have access to the exosystem's dynamics. I designed a distributed controller that solves the problem for linear, heterogeneous, and uncertain agent dynamics as well as time-varying network topologies. The distributed controller consists of two parts: (i) an exosystem generator that creates a local copy of the exosystem dynamics by using consensus protocols, and (ii) a dynamic compensator that uses (again) consensus to approach the internal model of the exosystem and thereby achieves perfect output regulation. This approach leverages methods from internal model based controller synthesis, multi-agent consensus over directed networks, and stability of time-varying linear systems; the derived result is an adaptation of the (centralized) internal model principle to the distributed, networked setting.

This work is reported online at http://arxiv.org/abs/1604.05481, and its journal version to be submitted. The figure below shows that four agents cooperatively tracks a sinusoidal signal generated by an exosystem.



５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計　1　件）
① Kai Cai, B. Anderson, C. Yu, and G. Mao, "Local average consensus in distributed measurement of spatial-temporal varying parameters: 1d case", Automatica, 査読有, vol. 52, no. 2, pp. 135-145, 2015.
DOI:10.1016/j.automatica.2014.11.002

〔学会発表〕（計　3　件）
① Kai Cai and T. Motoyama, "Eigenstructure assignment for synthesis of multi-agent consensus algorithms", 第 58 回自動制御連合講演会, ID 2B1-2, 兵庫県神戸市神戸大学六甲台第 2 キャンパス（工学部）, 2015 年 11 月 14 日～2015 年 11 月 15 日.

② Y. Xu, T. Han, Kai Cai, Z. Lin, "A fully distributed approach to resource allocation problem under directed and switching topologies", in Proceeding of the 10th Asian Control Conference, Sutera Harbour Resort, Kota Kinabalu, Malasia, 2015 年 05 月 31 日～2015 年 06 月 03 日.

③ K. Cai, "On reliable surplus-based averaging and optimization algorithms under communication constraints", 第 59 回システム制御情報学会研究発表講演会(SCI'15), ID 311-6, 大阪府大阪市中央電気倶楽部, 2015 年 05 月 20 日～2015 年 05 月 22 日.

〔その他〕
ホームページ等
Technical report online at:
http://arxiv.org/abs/1604.05481

６．研究組織
(1)研究代表者
蔡　凱　　（ CAI, Kai ）
大阪市立大学・都市研究プラザ・特任准教授
研究者番号：20728266