様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Robust and Adaptive Distributed Control of Discrete-Event Systems: A Supervisor Localization Based Approach

研究課題名（英文）Robust and Adaptive Distributed Control of Discrete-Event Systems: A Supervisor Localization Based Approach

研究代表者
蔡　凱（CAI, KAI）

大阪市立大学・大学院工学研究科・准教授

研究者番号：２０７２８２６６

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研究成果の概要（和文）：This research developed a systematic design framework for robust and adaptive distributed control of multi-agent discrete-event systems. Moreover, this research built a multi-agent experiment platform that tested the validity of the theoretical results.

研究成果の学術的意義や社会的意義
This research has significantly advanced the knowledge in discrete-event systems, by developing new distributed control methods for achieving robust and adaptive behaviors. Further the application of this research would contribute significantly to relieving labor shortage in logistic industries.

研究成果の概要（英文）：This research developed a systematic design framework for robust and adaptive distributed control of multi-agent discrete-event systems. Specifically, (i) distributed controllers were designed for individual agents that are robust against partial event observation and inter-agent communication delay; (ii) scalable controllers were synthesized whose state numbers and computational process are independent of the number of agents; (iii) online controllers were designed to provide adaptive behaviors for the agents. Finally, this research built a multi-agent experiment platform that tested the validity of the theoretical results.

研究分野：制御・システム工学

キーワード：離散事象システム　　分散制御　　オートマトン

1. 研究開始当初の背景

Recently, with rapid technological advances in wireless communication and embedded computing, distributed control of networked multi-agent discrete-event systems has become a cutting-edge research topic, both domestic and international. For this topic, we have pioneered a systematic approach, called supervisor localization, to distributed control synthesis in the framework of supervisory control theory. The essence of localization is the allocation of global control actions in the form of local control strategies among individual component agents, thereby creating a distributed control architecture over networks. Supervisor localization is a general methodology that addresses heterogeneous agent dynamics and arbitrary control specifications; moreover, it guarantees the collective local control performance is equivalent with the global one.

2. 研究の目的

This research aims to develop a systematic design framework for robust and adaptive distributed control of multi-agent discrete-event systems, by extending our previous work on supervisor localization. In particular, the research focuses on synthesizing distributed controllers that are robust against partial event observation and inter-agent communication delay/loss, as well as adaptive to changes in the number of agents and control specifications. To test the validity of the theoretical results, this research furthermore aims to build a multi-agent experiment platform.

3. 研究の方法

The methods used in this research include supervisory control theory, distributed control theory, discrete-event systems theory, automata theory, and computational complexity theory.

4. 研究成果

There are five main accomplishments achieved in this research.

(1) Distributed control with partial observation

Collaborating with Dr. R. Zhang (Northwestern Polytechnical University) and Dr. W.M. Wonham (University of Toronto), we extended supervisor localization to address the issue of partial observation in distributed control of multi-agent discrete-event systems. First, we proposed the combination of supervisor localization with relative observability, which leads to a systematic, computationally effective approach to distributed control of DES under partial observation. In particular, local controllers with only observable state transitions are automatically synthesized, and the collective local controlled behavior is guaranteed to be the same as the global nonblocking behavior. Second, we identified the linguistic essence of partial-observation localization by developing the following key mappings and concepts (as extensions to their full-observation counterparts). Based on these mappings, the new concepts are introduced, including partial-observation control covers and local controllers. In particular, a partial-observation control cover is defined on the state set of the partial-observation supervisor; roughly speaking, the latter corresponds to the powerset of the full-observation supervisor's state set. Moreover, a partial-observation local controller contains only observable state transitions, and uses control functions to determine the existence of selfloops of unobservable controllable events.

We further generalized partial observation supervisor localization to study distributed control of timed discrete-event systems. First, not only was the monolithic supervisor's disabling action localized (as in the untimed case), but also its preemptive action is localized with respect to individual forcible events. Second, the new concepts of partial-observation control cover and partial-observation preemption cover were defined on the powerset of the monolithic supervisor's state set. In this way, in the transition structure of the resulting local controllers/preemptors, only observable events can lead to state changes.

K. Cai, R. Zhang, and W.M. Wonham, "Relative observability and coobservability of timed discrete-event systems", IEEE Transactions on Automatic Control, vol. 61, no. 11, pp. 3382-3395, Nov. 2016.

R. Zhang, K. Cai, and W.M. Wonham, "Supervisor localization of discrete-event systems under partial observation", Automatica, vol. 81, no. 7, pp. 142-147, Jul. 2017.

K. Cai, R. Zhang, and W.M. Wonham, "Characterizations and effective computation of supremal relatively observable sublanguages", Discrete Event Dynamic Systems, vol. 28, no. 2, pp. 269-287, 2018.

K. Cai, R. Zhang, and W.M. Wonham, "Relative coobservability in decentralized supervisory control of discrete-event systems", International Journal of Control, vol. 92, no. 7, pp. 1481-

1489, Jul. 2019.
R. Zhang and K. Cai, "Supervisor localization of timed discrete-event systems under partial observation", IEEE Transactions on Automatic Control, vol. 65, no. 1, pp. 295-301, Jan. 2020.
R. Zhang and K. Cai, "Supervisor localization for large-scale discrete-event systems under partial observation", International Journal of Control, vol. 93, no. 3, pp. 387-399, Mar. 2020.

(2) Distributed control with communication delay

Collaborating with Dr. R. Zhang (Northwestern Polytechnical University), we extended supervisor localization to address the issue of communication delay in distributed control of multi-agent timed discrete-event systems. A timed channel model which can represent bounded and unbounded communication delays was proposed. This channel model was treated as plant component, and thus the communication delays are integrated into the plant behavior. Timed relative coobservability was adopted to effectively compute decentralized supervisors tolerant of communication delays. The combination of timed relative coobservability and partial-observation supervisor localization was new, and led to a computationally effective solution to delay-tolerant distributed control. Overall, the proposed supervisor localization provided a top-down, computationally effective approach to the distributed control of timed discrete-event systems with inter-agent communication delay.

R. Zhang and K. Cai, "Localization-based distributed control of timed discrete-event systems with communication delay", International Journal of Control, accepted, Apr. 4, 2020.

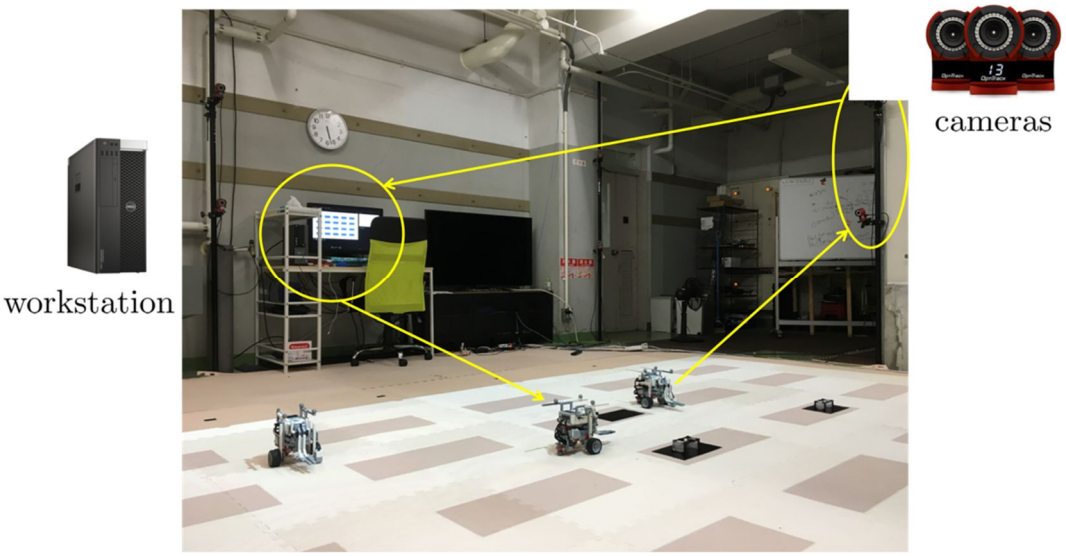
(3) Scalable distributed control

Collaborating with Dr. Y. Liu and Dr. Z. Li (Xidian University), we exploited the modular characteristic of multi-agent discrete-event systems, and thereby designed a scalable supervisor whose state number and computational process are independent of the number of agents. The contributions of our work are threefold. First, our designed centralized supervisor was scalable with respect to the number of agents in the system. This scalability was a desired feature of a supervisor for multi-agent systems, inasmuch as it allows the supervisor to remain invariant regardless of how many agents are added to or removed from the system (which may occur frequently due to productivity/reliability concerns or malfunction/repair). Second, the local controllers we designed for individual agents enjoyed the same scalability feature, and are guaranteed to collectively achieve identical controlled behavior as the centralized supervisor does. With the local controllers 'built-in', the agents became autonomous and made their own local decisions; this was particularly useful in applications like multi-robot systems. Finally, the computation of the scalable supervisor and local controllers was based solely on template structures and was thus independent of agent numbers as well. As a result, the computation load remained the same even if the number of agents increased; this was advantageous as compared to the existing supervisory synthesis methods.

Y. Liu, K. Cai, and Z. Li, "Scalable supervisory control of multi-agent discrete-event systems", Automatica, accepted, Jul. 2019.

(4) Application to multi-robot based warehouse logistic automation

Collaborating with my students and Dr. Z. Lin (Hangdian University), we adapted the online supervisory control approach to the case of multi-agent discrete-event systems to not only cope with computational efforts but also address time-varying specifications, and applied the approach to warehouse automation systems served by multiple mobile robots. First, we presented a key modification to the existing online supervisory control approach such that the approach is amenable to multi-agent discrete-event systems. In particular, we proposed to first generate limited-step-ahead projections of each agent model, and then compute the synchronous product of the projected agent models. This is computationally more efficient than the existing approaches in the literature. Second, we showed how a warehouse automation system served by multiple robots could be modeled as a multi-agent discrete-event systems, and demonstrated through a case study the effectiveness of applying the adapted online supervisory control approach to control the automation system. Finally, we built a testbed, consisting of multiple LEGO MINDSTORMS EV3 robots, that served to experimentally test the validity of our proposed online supervisory control approach for multi-agent discrete-event systems. The experiment testbed is shown below.



Y. Tatsumoto, M. Shiraishi, K. Cai, "Application of Supervisory Control Theory with Warehouse Automation Case Study", Transactions of the Institute of Systems, Control and Information Engineers (ISCIE), Special Issue on Event-Driven Approach to System Design -- Application and Development, vol. 62, no. 6, pp. 203-208, 2018.
Y. Tatsumoto, M. Shiraishi, K. Cai, Z. Lin, "Application of online supervisory control of discrete-event systems to multi-robot warehouse automation", Control Engineering Practice, vol. 81, pp. 97-104, Dec. 2018.
K. Cai, "Warehouse automation by logistic robotic networks -- a cyber-physical control approach", Frontiers of Information Technology & Electronic Engineering, vol. 21, pp. 693-704, 2020.

(5) Contributions to education

Collaborating with Dr. W.M. Wonham (University of Toronto) and Dr. Rudie (Queen's University), we summarized a brief history of the 'supervisory control of discrete-event systems' as it had evolved in the period 1980–2017. Overall, the trend had been from centralized or 'monolithic' control to more structured architectures, and from 'naive' to symbolic computation. We also provided tutorial material on the supervisory control theory and the supervisory localization theory. These papers provided entry-level education of graduate students and young researchers for doing research in this field.

W.M. Wonham, K. Cai, and K. Rudie, "Supervisory control of discrete-event systems: a brief history", Annual Reviews in Control, vol. 45, pp. 250-256, 2018.
K. Cai, "Supervispr localization", Wiley Encyclopedia of Electrical and Electronics Engineering, Nov. 2019.
K. Cai and W.M. Wonham, "Supervisory control of discrete-event systems", Encyclopedia of Systems and Control, 2nd ed., Springer, 2020.

５．主な発表論文等

〔雑誌論文〕　計14件（うち査読付論文　13件／うち国際共著　11件／うちオープンアクセス　0件）

１．著者名 Y. Tatsumoto, M. Shiraishi, Kai Cai, Z. Lin	４．巻 81
２．論文標題 Application of online supervisory control of discrete-event systems to multi-robot warehouse automation	５．発行年 2018年
３．雑誌名 Control Engineering Practice	６．最初と最後の頁 97-104
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.conengprac.2018.09.003	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 R. Zhang, Kai Cai	４．巻 93
２．論文標題 Supervisor localization for large-scale discrete-event systems under partial observation	５．発行年 2020年
３．雑誌名 International Journal of Control	６．最初と最後の頁 387-399
掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/00207179.2018.1471220	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 R. Zhang, Kai Cai	４．巻 65
２．論文標題 Supervisor localization of timed discrete-event systems under partial observation	５．発行年 2020年
３．雑誌名 IEEE Transactions on Automatic Control	６．最初と最後の頁 295-301
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TAC.2019.2912008	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 R. Zhang, K. Cai, and W.M. Wonham	４．巻 81
２．論文標題 Supervisor localization of discrete-event systems under partial observation	５．発行年 2017年
３．雑誌名 Automatica	６．最初と最後の頁 142-147
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1016/j.automatica.2017.03.018	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Y. Tatsumoto, M. Shiraishi, K. Cai	4．巻 62
2．論文標題 Application of Supervisory Control Theory with Warehouse Automation Case Study	5．発行年 2018年
3．雑誌名 Transactions of the Institute of Systems, Control and Information Engineers (ISCIE)	6．最初と最後の頁 203-208
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

1．著者名 K. Cai, R. Zhang, and W.M. Wonham	4．巻 28
2．論文標題 Characterizations and effective computation of supremal relatively observable sublanguages	5．発行年 2018年
3．雑誌名 Discrete Event Dynamic Systems	6．最初と最後の頁 269-287
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1007/s10626-017-0250-0	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 K. Cai, R. Zhang, and W.M. Wonham	4．巻 92
2．論文標題 Relative coobservability in decentralized supervisory control of discrete-event systems	5．発行年 2019年
3．雑誌名 International Journal of Control	6．最初と最後の頁 1481-1489
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1080/00207179.2017.1397754	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 W.M. Wonham, K. Cai, and K. Rudie	4．巻 45
2．論文標題 Supervisory control of discrete-event systems: a brief history	5．発行年 2018年
3．雑誌名 Annual Reviews in Control	6．最初と最後の頁 250-256
掲載論文のDOI（デジタルオブジェクト識別子） https://doi.org/10.1016/j.arcontrol.2018.03.002	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Renyuan Zhang, Kai Cai, Yongmei Gan, W.M. Wonham	4．巻 89
2．論文標題 Delay-robustness in distributed control of timed discrete-event systems based on supervisor localization	5．発行年 2016年
3．雑誌名 International Journal of Control	6．最初と最後の頁 2055-2072
掲載論文のDOI（デジタルオブジェクト識別子） 10.1080/00207179.2016.1147606	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Kai Cai, Renyuan Zhang, W.M. Wonham	4．巻 61
2．論文標題 Relative observability and coobservability of timed discrete-event systems	5．発行年 2016年
3．雑誌名 IEEE Transactions on Automatic Control	6．最初と最後の頁 3382-3395
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/TAC.2015.2513370	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Kai Cai	4．巻 -
2．論文標題 Supervisor localization	5．発行年 2019年
3．雑誌名 Wiley Encyclopedia of Electrical and Electronics Engineering	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1002/047134608X.W8402	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 -

1．著者名 Kai Cai, W.M. Wonham	4．巻 -
2．論文標題 Supervisory control of discrete-event systems	5．発行年 2020年
3．雑誌名 Encyclopedia of Systems and Control, 2nd ed., Springer	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/978-1-4471-5102-9_54-2	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Y. Liu, Kai Cai, Z. Li	4．巻 -
2．論文標題 Scalable supervisory control of multi-agent discrete-event systems	5．発行年 2019年
3．雑誌名 Automatica	6．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.automatica.2019.06.012	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Kai Cai	4．巻 21
2．論文標題 Warehouse automation by logistic robotic networks -- a cyber-physical control approach	5．発行年 2020年
3．雑誌名 Frontiers of Information Technology & Electronic Engineering	6．最初と最後の頁 693-704
掲載論文のDOI（デジタルオブジェクト識別子） 10.1631/FITEE.2000156	査読の有無 無
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

〔学会発表〕　計10件（うち招待講演　4件／うち国際学会　9件）

1．発表者名 Y. Liu, Kai Cai, Z. Li
2．発表標題 On scalable supervisory control of multi-agent discrete-event systems
3．学会等名 Workshop on Discrete Event Systems（国際学会）
4．発表年 2018年

1．発表者名 R. Zhang, Kai Cai
2．発表標題 Supervisor localization of discrete-event systems with infinite behavior
3．学会等名 Workshop on Discrete Event Systems（国際学会）
4．発表年 2018年

１．発表者名
R. Zhang, Kai Cai

２．発表標題
Localization-based distributed control for large discrete-event systems under partial observation

３．学会等名
Chinese Control and Decision Conference（国際学会）

４．発表年
2018年

１．発表者名
M. Shiraishi, Y. Tatsumoto, Kai Cai, Z. Lin

２．発表標題
Online supervisory control of multi-agent discrete-event systems with warehouse automation case study

３．学会等名
SICE Annual Conference（招待講演）（国際学会）

４．発表年
2018年

１．発表者名
S. Matsui, Kai Cai

２．発表標題
Secret securing with minimum cost

３．学会等名
Japan Joint Automatic Control Conference

４．発表年
2018年

１．発表者名
W.M. Wonham, Kai Cai, K. Rudie

２．発表標題
Supervisory control of discrete-event systems: a brief history -- 1980-2015

３．学会等名
20th IFAC World Congress（招待講演）（国際学会）

４．発表年
2017年

１．発表者名
R. Zhang, Kai Cai

２．発表標題
Supervisor localization of timed discrete-event systems under partial observation

３．学会等名
IEEE Conference on Decision and Control（国際学会）

４．発表年
2016年

１．発表者名
R. Zhang, Kai Cai

２．発表標題
On supervisor localization based distributed control of discrete-event systems under partial observation

３．学会等名
American Control Conference（国際学会）

４．発表年
2016年

１．発表者名
Kai Cai, A. Giua, C. Seatzu

２．発表標題
On consistent reduction in discrete-event systems

３．学会等名
15th IEEE International Conference on Automation Science and Engineering（招待講演）（国際学会）

４．発表年
2019年

１．発表者名
S. Matsui, Kai Cai

２．発表標題
Secret securing with multiple protections and minimum costs

３．学会等名
58th IEEE Conference on Decision and Control（招待講演）（国際学会）

４．発表年
2019年

〔図書〕　計1件

１．著者名 W.M. Wonham, Kai Cai	４．発行年 2019年
２．出版社 Springer	５．総ページ数 600
３．書名 Supervisory Control of Discrete-Event Systems	

〔産業財産権〕

〔その他〕

Warehouse Automation by Robotic Networks https://control.eng.osaka-cu.ac.jp/experiment

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考