1版

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） Sampling-guided symbolic control framework under changing environments

研究課題名（英文） Sampling-guided symbolic control framework under changing environments

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研究成果の概要（和文）： この研究プロジェクトでは、外乱が発生する可能性のある環境に対する安全な制御フレームワークを検討しました。このプロジェクトの目標は、非決定性と不確実性の下でシステムを処理するのに十分な堅牢性を備えた、安全で効率的な記号構造ベースの制御および検証手法を開発することです。研究期間中、時相論理仕様の下での安全性の検証と制御のための効率的な記号制御アルゴリズムが開発され、非ホロノミックロボットのシミュレーションによってその性能が実証されました。また、離散記号構造を利用した安全な学習アプローチが探求されました。さらに、システムの安全性の検証に使用できる確率多項式システムのモーメント近似法が開発されました。

研究成果の学術的意義や社会的意義
Our research project provides safe system verification and control approaches that are suitable for managing safety-critical systems.

研究成果の概要（英文）： This research project studied safe control frameworks for semi-controlled environments in which some disturbance may occur. The overall goal of the project is to develop safe and efficient symbolic-structure-based control and verification techniques that are robust enough to handle systems under some nondeterminism and uncertainties. Throughout the research period, we developed efficient symbolic control algorithms for safety verification and control under temporal logic specficiations, and demonstrated their performances by simulations on nonholonomic robots. We studied a safe learning approach utilizing discrete symbolic structures. We also developed a moment approximation method of a stochastic polynomial system, which can be used for system safety verification.

研究分野： system control

キーワード： symbolic control　control theory　motion planning　robotics

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Symbolic control is a powerful controller synthesis approach as it can synthesize correct-by-design controllers for complex specifications such as temporal logic, a powerful language that can express not only traditional goals like stability and reach-avoid (reaching a target while avoiding obstacles) but also more intricate requirements such as the order of different tasks over time. One of the key strengths of symbolic controllers is their correctness-by-design: if the synthesis algorithm generates a controller, it's mathematically proven that all behaviors of the controlled system will meet the specified requirements. This makes symbolic control particularly suitable for controlling safety-critical systems.

One major drawback of symbolic control is its scalability. Synthesizing a symbolic controller for large systems with complex specifications can take several minutes or even hours. Therefore, symbolic control is primarily suitable for offline controller synthesis in stable and fully controlled environments. The approach struggles with dynamic environments because it requires recomputation of new abstractions whenever changes occur.

On the other hand, sampling-based and learning-based controllers are recognized for their strong performance, especially in terms of adapting to changing environments. These methods utilize numerical sampling, often incorporating techniques like neural networks, to determine appropriate control inputs. However, they can only offer asymptotic guarantees: the likelihood of controller failure decreases to zero as the number of samples increases indefinitely. The fact that these approaches are not inherently correct-by-design raises concerns about safety and reliability, especially for systems that are not fully deterministic. For instance, passengers may find it difficult to trust autonomous vehicles if their actions cannot be guaranteed to be safe.

２．研究の目的

This research project focuses on developing safe control frameworks for semi-controlled environments where disturbances can occur. The primary objective is to create robust and efficient control and verification techniques based on symbolic structures. These techniques are designed to handle systems that exhibit non-deterministic behavior and uncertainties while ensuring safety.

３．研究の方法

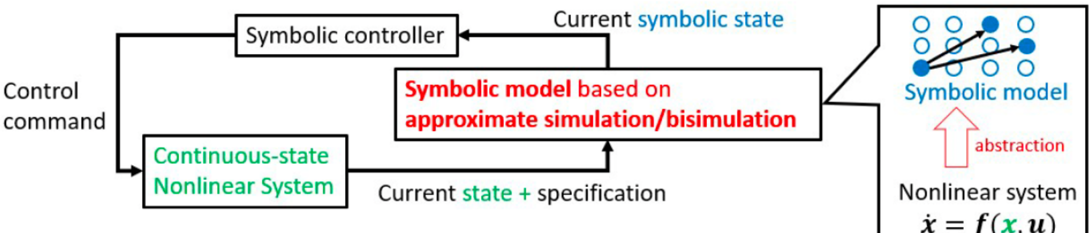

Fig. 1: Symbolic control framework

First, this research project investigates the symbolic control approach. As depicted in Figure 1, symbolic control involves three primary steps: (1) constructing a discrete-state system, known as a symbolic model, which abstracts the continuous-state systems using approximate simulation, (2) solving the discrete control problem to derive a control strategy, and (3) refining the control strategy to control the continuous-state system. This method can synthesize controllers that are correct-by-design, making it appropriate for controlling safety-critical systems. However, the main drawback of symbolic control is its scalability.

Fig. 2: A motivating example of a simple path planning problem. The objective is to control the red car to avoid the green car.

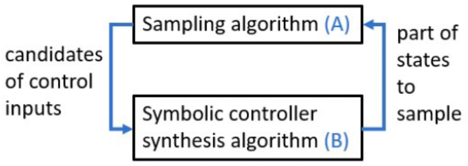

Fig. 3: Sampling-guided symbolic controller synthesis

Therefore, in this project, we studied a fast symbolic control synthesis approach that leverages numerical samplings as guides. We proposed a heuristic method aimed at reducing computation time. Figure 2 illustrates an example scenario: a problem to control the red car to avoid colliding with the green car. Traditional symbolic controller synthesis algorithms would typically construct a symbolic model across the entire state space, resulting in all red and gray circles representing symbolic states. However, we may a smaller state space such as the part with red circles, from each of which we have a suitable control input to control the red car to avoid the green car. Building on this concept, we investigated sampling-guided symbolic control synthesis, as depicted in Fig. 3. Our proposed method incorporates heuristic techniques and reachability analysis, leading to a significant reduction in computation time.

４．研究成果

(1) We developed an efficient symbolic self-triggered control framework for non-deterministic continuous-time non-linear systems without stability assumptions under right-recursive LTL specifications. These specifications are more expressive than those typically studied in previous work. We addressed two control objectives: a right-recursive LTL specification and a threshold for the average control signal length. Apart from extending the class of specifications, we proposed a heuristic method to shorten the computation time. Furthermore, we introduced a heuristic pruning algorithm to speed up the computation time by disabling some control signals based on expected rewards in a Büchi automaton generated from the specification.

(2) We studied a safe learning approach utilizing discrete symbolic structures. Our work focuses on minimizing undesired behaviors during learning without the need for prior knowledge of the system. Specifically, we introduced dynamic shielding, an enhancement of a model-based safe reinforcement learning technique known as shielding, which integrates data-driven automata learning.

(3) We developed a moment approximation method of a stochastic polynomial system, which can be used for system safety verification. Our approach involves estimating the moments of a stochastic polynomial system with finitely many states. This is achieved using Carleman linearization with truncation to derive a finite-dimensional linear system. We also investigated efficient online computation methods for implementing this scheme, along with several error bounds for the approximation. To validate our method, we conducted simulations on systems including a logistic map with stochastic dynamics and vehicle dynamics affected by stochastic disturbances, demonstrating its effectiveness.

5．主な発表論文等

〔雑誌論文〕　計5件（うち査読付論文　5件／うち国際共著　5件／うちオープンアクセス　0件）

1．著者名 Pruekprasert Sasinee、Dubut Jeremy、Takisaka Toru、Eberhart Clovis、Cetinkaya Ahmet	4．巻 160
2．論文標題 Moment propagation of polynomial systems through Carleman linearization for probabilistic safety analysis	5．発行年 2024年
3．雑誌名 Automatica	6．最初と最後の頁 111441～111441
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.automatica.2023.111441	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 Waga Masaki、Castellano Ezequiel、Pruekprasert Sasinee、Klikovits Stefan、Takisaka Toru、Hasuo Ichiro	4．巻 13505
2．論文標題 Dynamic Shielding for Reinforcement Learning in Black-Box Environments	5．発行年 2022年
3．雑誌名 Lecture Notes in Computer Science	6．最初と最後の頁 25～41
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/978-3-031-19992-9_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 Eberhart Clovis、Haydon James、Dubut Jeremy、Cetinkaya Ahmet、Pruekprasert Sasinee	4．巻 -
2．論文標題 Logic for Timed Agent Network Topologies	5．発行年 2022年
3．雑誌名 Proceedings of the 61st Conference on Decision and Control (CDC)	6．最初と最後の頁 2870～2877
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/CDC51059.2022.9992550	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 Pruekprasert Sasinee、Eberhart Clovis、Dubut Jeremy	4．巻 -
2．論文標題 Fast Synthesis for Symbolic Self-triggered Control under Right-recursive LTL Specifications	5．発行年 2021年
3．雑誌名 2021 60th IEEE Conference on Decision and Control (CDC)	6．最初と最後の頁 1321-1328
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/CDC45484.2021.9683328	査読の有無 有
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1．著者名 Pruekprasert Sasinee、Cai Kai	4．巻 -
2．論文標題 Local Opacity Verification for Distributed Discrete Event Systems	5．発行年 2021年
3．雑誌名 2021 60th IEEE Conference on Decision and Control (CDC)	6．最初と最後の頁 7022-7027
掲載論文のDOI（デジタルオブジェクト識別子） 10.1109/CDC45484.2021.9683017	査読の有無 有
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〔学会発表〕　計4件（うち招待講演　0件／うち国際学会　4件）

1．発表者名 Waga Masaki、Castellano Ezequiel、Pruekprasert Sasinee、Klikovits Stefan、Takisaka Toru、Hasuo Ichiro
2．発表標題 Dynamic Shielding for Reinforcement Learning in Black-Box Environments
3．学会等名 Automated Technology for Verification and Analysis (ATVA 2022)（国際学会）
4．発表年 2022年

1．発表者名 Eberhart Clovis、Haydon James、Dubut Jeremy、Cetinkaya Ahmet、Pruekprasert Sasinee
2．発表標題 Logic for Timed Agent Network Topologies
3．学会等名 2022 IEEE 61st Conference on Decision and Control (CDC)（国際学会）
4．発表年 2022年

1．発表者名 Pruekprasert Sasinee
2．発表標題 Fast Synthesis for Symbolic Self-triggered Control under Right-recursive LTL Specifications
3．学会等名 2021 60th IEEE Conference on Decision and Control (CDC)（国際学会）
4．発表年 2021年

１．発表者名 Pruekprasert Sasinee
２．発表標題 Local Opacity Verification for Distributed Discrete Event Systems
３．学会等名 2021 60th IEEE Conference on Decision and Control (CDC)（国際学会）
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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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

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関