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論文の内容の要旨

Over history, games have served multiple purposes. It serves as a fun activity for players who need entertainment to become test-beds for artificial intelligence. Solving games is beneficial in providing a better understanding of how information is progressing throughout the game. Applying search algorithms to solve games divides the game-tree into two areas: ``explored nodes'' and ``unexplored nodes'', each signifies certainty and uncertainty value in the game respectively. A game typically progresses from uncertain state to certain state. Currently, a game progress can be observed using two different approaches. The first approach is by monitoring its game progress pattern using a certain indicator while the second approach is by analyzing and observing the game information progress model. Previous works have interpreted uncertainty in the game progress through various means, but there has been no clear links among those interpretations. Observing the effect of uncertainty in the game may lead to the linking between those definitions.

In this thesis, the probability-based proof number search and single conspiracy number, which derived from the idea of Conspiracy Number (CN), were used to analyze how uncertainty affects various elements of games. The probability-based proof number search is a domain-independent best-first search algorithm which main purpose is to solve games. %that is introduced with the purpose of solving games. It exploits information from both areas of a game-tree by combining certain and uncertain information to reach convergence. The single conspiracy number is an indicator used to evaluate the difficulty of the current state of the game. It is useful to evaluate progress patterns and long-term positions, as well as to evaluate game playing positions.

This thesis focuses on understanding the influence of uncertainty in the best-first search game computation along with its impact on game entertainment. To achieve it, we are guided by three purposes: (1) To find the optimal difficulty ordering procedure for game solver for different game-tree structures. To see how the uncertainty affects ordering process in best-first search, the probability-based proof number search is deployed into several games with notably distinct structures. Results from the experiment on a total of 1000 Othello positions from different stages

of the game revealed that information coming from uncertainties affects the result differently in each stage. It expedites the convergence of solved positions, reaching 100% in the end-game positions. Later, the framework is expanded into a single-player game.; (2) To define the indicator for entertainment using a game-tree search framework, and (3) To define the link between the game-tree search result and entertainment indicator in different game environments. Using the single-conspiracy number as a game position evaluation indicator based on expert play demonstrates that it can show progress continuity. Furthermore, the indicator is expanded into a single-player game. The expansion result shows the game progress related to simulated players' ability. Finally, the result is used to find the momentum and potential energy of a single-player game using the motion in mind concept. The experiment demonstrates the link between the search indicator of a game-tree and the measure of entertainment. In the end, it is concluded that uncertainty plays an important part in game computation as well as game entertainment. Even more, it has become a requirement in both computation and entertainment measure, as it impacts both the quality of games' computation result and also how the game-playing experience is perceived.

Keyword: *game solver, game progress pattern, probability-based proof number search, single conspiracy number, motion in mind*

論文審査の結果の要旨

本学位論文の重要な学術的貢献を 3 つの部分に分類できる．(1) 2 人ゲームのソルバである AND/OR 木探索の探索アルゴリズム Probability-based Proof Number Search（PPNS）を完成度の高いアルゴリズムとして発展させた上で，1 人ゲームに適用可能なアルゴリズムとして一般化し，既存ソルバで最高性能であることを検証した．(2) 局面の複雑さを表す指標 Single Conspiracy Number（SCN）を用いて，2 人ゲームを題材として試合展開の長期的視点での優劣判断法を提案し, その有効性を示した上で, 1 人ゲームへの拡張法とその有効性を検証した．(3) SCN が Motion in Mind モデルにおける mass に対応することを仮定し，試合中の SCN の時間推移を解析することで, 試合展開とエンターテインメント性質としてのプレイヤの遊戯体験との関連性を示し，一人ゲーム 2048 を題材としてその有効性を示した．

上述した 3 つの方面での貢献の共通点は，共謀数（Conspiracy Number）の概念である．共謀数は，ミニマックス木探索での解の安定性を表す指標である．共謀数が十分に大きい場合，そのときにミニマックス解は十分に安定しており, さらに探索を続けても更新される可能性は十分に低いことを意味する．逆に，共謀数が小さい場合，解は安定していないため，探索を続けることで解が更新される可能性が高い．これらの性質を統合した，即ち，ミニマックス解が十分に安定するまで探索を続ける最良優先探索アルゴリズム Conspiracy Number Search（CNS）を出発点として，本論文では，2 人ゲームおよび 1 人ゲームにおける最高性能ソルバの開発へと発展させ，同時に，試合の優劣判断の指標として発展させ，さらには，ゲームの不確定性の概念に基づき，遊戯性の定量化との橋渡しへとなる指標を導出した．当該分野の研究をより深め，かつ，拡げる

貢献と言える.

以上，本論文は，ゲームを題材として不確定性の探索面とエンターテインメント性の橋渡しを実現したものであり，学術的に貢献するところが大きい。よって博士（情報科学）の学位論文として十分価値あるものと認めた.