論文 / 著書情報
Article / Book Information

題目(和文)	
Title(English)	Chaotic-Amplitude-Controlled Coherent Ising Machines: Extensions to Quadratic Unconstrained Binary Optimisation and Simplified Models
著者(和文)	MASTIYAGEDON SUDEERA HASARANGA GUNATHILAKA
Author(English)	Sudeera Hasaranga Gunathilaka Mastiyage Don
出典(和文)	学位:博士(工学), 学位授与機関:東京科学大学, 報告番号:甲第371号, 授与年月日:2025年3月26日, 学位の種別:課程博士, 審査員:瀧ノ上 正浩,秋山 泰,小野 功,高安 美佐子,小野 峻佑,青西 亨
Citation(English)	Degree:Doctor (Engineering), Conferring organization: Institute of Science Tokyo, Report number:甲第371号, Conferred date:2025/3/26, Degree Type:Course doctor, Examiner:,,,,,
学位種別(和文)	博士論文
Category(English)	Doctoral Thesis
種別(和文)	要約
Type(English)	Outline

This dissertation titled "Chaotic-Amplitude-Controlled Coherent Ising Machines: Extensions to Quadratic Unconstrained Binary Optimisation and Simplified Models" extends the Coherent Ising Machine (CIM), enabling it to solve Quadratic Unconstrained Binary Optimisation (QUBO) problems, and proposes an effective simplified CIM model. The dissertation consists of six chapters.

Chapter 1, "Introduction," describes the background and objectives of this research. First, it introduces combinatorial optimisation problems (COPs) in the context of Ising optimisation and QUBO and outlines the principles of quantum annealers, such as D-Wave. Next, it explains the structure and principles of the CIM, and introduces stochastic differential equations in the Wigner and Positive-P forms, which serve as mathematical models for CIMs. Additionally, it describes how CIMs use soft spins, where the amplitude of each spin varies, and highlights that changes in spin amplitude can cause a mismatch between the coupling term and the Zeeman term, potentially altering the ground state. The chapter then introduces the Inui Model (IM), which addresses this mismatch through chaotic amplitude control (CAC). It also points out that the current IM cannot handle QUBO problems and that Wigner and Positive-P models have high computational costs. Hence, the purpose of this research is stated as to extend the IM for QUBO problems and develop a simplified model with lower computational cost. Finally, the chapter reviews related research and outlines the structure of this dissertation.

Chapter 2, titled "QUBO-Extended IM CIM for Compressed Sensing," extends the IM to QUBO problems and evaluates its performance in L0-regularised compressed sensing (L0RCS), an example of a QUBO problem. First, the IM is extended for solving QUBO problems by leveraging the fact that CAC homogenises the spin amplitude to a target amplitude. Next, building on the CIM-Classical Digital Processor approach proposed by Aonishi et al., the QUBO-extended IM is applied to L0RCS. The model is first evaluated using randomly generated artificial data, demonstrating that it approximates the ground state predicted by statistical mechanics more closely than the model of Aonishi et al., which lacks CAC. Further numerical experiments using magnetic resonance images confirm that the QUBO-extended IM achieves higher reconstruction accuracy than the Aonishi et al. model without CAC, supporting the effectiveness of solution search via CAC.

Chapter 3, titled "Simplified IM CIM with Zeeman Terms," simplifies the IM to a model with reduced computational cost. First, the IM is approximated by neglecting quantum noise, resulting in a mean-field model of the CIM. By leveraging amplitude homogeneity through CAC and appropriately scaling the Zeeman term, the simplified model is constructed. Next, we compare the IM and the simplified IM with Sherrington-Kirkpatrick problem instances and demonstrate that their performances are identical. Additionally, we show that the simplified IM outperforms other methods proposed for controlling the scale of the Zeeman term in previous studies, further supporting the effectiveness of solution search using CAC.

Chapter 4, titled "QUBO-Extension of the Simplified IM CIM for Compressed Sensing," combines the findings from Chapters 2 and 3 to extend the simplified IM to solve QUBO problems. First, the simplified IM is extended to QUBO using the same method as in Chapter 2. This QUBO-extended model is then applied to L0RCS. Using randomly generated artificial data, we demonstrate that both the QUBO-extended IM and the simplified IM achieves the ground state predicted by statistical mechanics in a nearly identical manner. Next, numerical experiments with magnetic resonance images confirm that both models achieve comparable reconstruction accuracy. Hence, the results highlight the superiority of the simplified IM, which has a lower computational cost.

Chapter 5, titled "Overall Discussion and Future Work," explores the applicability of the proposed model to other QUBO problems. It highlights the suitability of the simplified IM for large-scale parallel computing and notes ongoing efforts to implement it on field-programmable gate arrays (FPGAs) and supercomputers. Additionally, the chapter discusses the role of quantum noise in CIMs, comparing with related research. Finally, it discusses the limitations of the proposed model and suggests potential improvements.

Chapter 6, "Dissertation Summary and Conclusion," provides a summary of the dissertation and presents the conclusions.

In summary, this dissertation extends CIM to solve QUBO problems and proposes an effective simplified model, which is then evaluated in the dissertation. The QUBO implementation method for CIM presented here significantly expands its range of applications. Furthermore, the simplified model is well-suited for large-scale parallel computing.