

Peer Review

Review of: "A Review of Formal Methods in Quantum Circuit Verification"

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Summary.

This paper presents a review of formal methods applied to the verification of quantum circuits. It surveys several major verification paradigms, including barrier certificates, abstract interpretation, model checking, theorem proving, and runtime verification, and discusses their application across different domains such as quantum error correction, compiler verification, and quantum algorithms. The review aims to summarize the state of the art, highlight challenges, and outline future research directions in quantum circuit verification.

Strengths.

- The paper addresses a relevant topic, as formal verification is becoming increasingly important with the scaling of quantum hardware.
- The manuscript collects a large number of references and covers multiple verification paradigms within a single article.
- The high-level organization into verification techniques and application domains is potentially useful for newcomers to the field.

Weaknesses.

- The motivation for conducting this review is not clearly articulated. While the need for quantum system verification is discussed, the paper does not justify why a new review is necessary given the existence of [17].
- The selection of verification techniques (barrier certificates, abstract interpretation, model checking, theorem proving, runtime verification) is not justified, and no rationale is provided for excluding other relevant formal methods.

- The hybrid methods are claimed as part of the review's scope in the abstract and introduction, but they are not surveyed as existing work and are instead treated only as future research directions.
- The depth of analysis is unbalanced: barrier certificates and abstract interpretation are treated in detail, while model checking, theorem proving, and runtime verification receive comparatively shallow coverage.

Novelty.

Although the paper addresses an important topic that could benefit from a review of the current state of the art, its novelty is not clearly established, as it does not position itself with respect to [17] or clarify what additional perspective or synthesis it provides beyond existing surveys.

Soundness.

Many claims and statements between Sections 3, 4, and 5 are not supported by the corresponding citations; it is not clear which papers concluded which statement regarding the discussed approaches.

The imbalance in treatment among verification methods further affects the overall soundness: barrier certificates and abstract interpretation and their application domains are discussed in more detail, while the other techniques are summarized at a much higher level.

Furthermore, runtime verification seems to be largely absent after its introduction; it only appears again in Table 2 as a method used for quantum hardware, despite this application domain (quantum hardware) not being discussed in Section 6. This makes it unclear how runtime verification is meant to support that application domain within the review's narrative.

Quality of Presentation.

The manuscript contains several presentation issues that affect clarity:

- The following acronyms are introduced without definition: VLSI in the introduction, SMT in Section 5.2.
- Important background topics (e.g., VQCs, quantum error correction, compilers) are introduced abruptly and only briefly in technical sections, instead of being framed more coherently in the background.
- Table 2 also depicts the quantum hardware application domain, which is not introduced earlier.

Suggestions to the Author.

The manuscript would benefit from substantial revision. The author should:

- Clearly justify the need for this review by positioning it with respect to existing surveys and identifying a concrete gap in the literature.
- Explicitly explain the rationale behind the selection of verification techniques.
- Resolve the inconsistency regarding hybrid approaches, either by properly reviewing existing hybrid methods or by narrowing the initial claims.
- Rebalance the coverage of verification techniques to ensure a more consistent depth of analysis.
- Reorganize the discussion so that each claim, assessment, or conclusion is stated in close proximity to the specific references that support it, both in the technique-focused sections and in the application section. This would make it clearer which papers provide the evidence for each reported finding and would improve traceability throughout the manuscript.
- Improve presentation quality by fixing the minor issues and restructuring the background material for better coherence.

Declarations

Potential competing interests: No potential competing interests to declare.