Publication about robotic mind's eye reasoning for verification in lab environments

Deliverable 5.4

Deliverable Title	D5.4 Publication about robotic mind's eye reasoning for verification in lab environments
Deliverable Lead:	University of Bremen (UOB)
Related Work Package:	WP5: Traceable Semantic Twin: Planning, reasoning, Audit Trail
Related Task(s):	T5.2: Replication of medical lab environments into Traceable Semantic Twin Knowledge Bases for Reasoning T5.3: Traceability-aware process (re-)planning, reasoning and regulatory digital audit trail
Author(s):	Prof. Michael Beetz
Dissemination Level:	Public
Due Submission Date:	28/02/2025
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Project Number	101017089
Instrument:	Research and innovation action
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Duration:	51 months
Abstract	This deliverable provides information about a novel approach for mind's eye reasoning in the context of lab environments. The method can be used to verify the task outcome visually by exploiting the Traceable Semantic Twin technology developed in the TraceBot project.

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Versioning and Contribution History

Version	Date	Modified by	Modification reason
v.01	11.02.2025	Prof. Michael Beetz (UOB)	Ready for internal revision
v.01r	17.02.2025	Anthony Remazeilles (TECN)	Internal revision
v.02	18.02.2025	Prof. Michael Beetz (UOB)	Revised version ready for submission

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1 Executive Summary

This deliverable presents a publication on robotic mind's eye reasoning for verification in lab environments, produced within the scope of the TraceBot project's Work Package 5 (WP5). Specifically, it aligns with Task 5.2, which focuses on replicating medical lab environments into Traceable Semantic Twin Knowledge Bases for reasoning, and Task 5.3, which extends this reasoning capability to process (re-)planning and regulatory digital audit trails. The publication behind this deliverable has recently been accepted at the ICRA 2025 conference for publication. Given the constraints of copyright, the full paper cannot be included in this deliverable; however, its key contributions are summarized here to highlight its relevance to the project objectives.

In this research, we explore an imagination-enabled perception framework that integrates cognitive artificial intelligence with semantic digital twins. This approach empowers medical robots to simulate task outcomes, compare them with real-world results, and autonomously verify task success, ensuring compliance with regulatory requirements. Our work specifically addresses the challenges associated with handling small and transparent objects in medical laboratory settings, such as sterility testing kits. By enhancing our perception system with parthood-based reasoning, we improve the robot's ability to verify actions with fine-grained object analysis. Experimental results indicate that this method significantly enhances verification accuracy without requiring extensive retraining, demonstrating its potential to improve reliability in automated laboratory processes.

The paper contributes to WP5 by providing a systematic approach to reasoning over subsymbolic information, leveraging the Traceable Semantic Twin environment developed in Task 5.2. This environment allows the robot to realistically envision task outcomes and supports semantic traceability of its verification actions. Furthermore, the developed framework integrates with Task 5.3's process reasoning and regulatory audit trail mechanisms, ensuring that verification processes are both transparent and compliant with relevant standards. These contributions support the overarching project goals by enhancing robotic adaptability and regulatory compliance in high-precision environments.

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2 Description

The automation of medical laboratory processes presents significant challenges, particularly in ensuring precision, reliability, and compliance with strict regulatory requirements. Autonomous robots deployed in such environments must not only execute complex tasks with high accuracy but also be capable of verifying task success in real time. Traditional approaches to robotic verification rely heavily on object recognition and predefined success criteria, which may not be robust enough to handle intricate laboratory tasks, especially when working with small, transparent, or composite objects.

To address these challenges, our research introduces an innovative framework that integrates cognitive AI with semantic digital twins, enabling robots to simulate task outcomes before execution. This capability—referred to as robotic mind's eye reasoning—allows the system to predict, compare, and verify task success dynamically. By incorporating parthood-based reasoning into the perception system, we enhance the robot's ability to analyze object subparts, leading to a more precise and adaptable verification process.

The paper associated with this deliverable presents the theoretical foundation and experimental validation of this framework. It demonstrates how integrating a digital twin environment with high-level reasoning mechanisms enhances robotic perception and verification capabilities. The findings contribute directly to the objectives of Task 5.2 and Task 5.3 by reinforcing the role of traceable semantic twin knowledge bases in real-time robotic reasoning and regulatory compliance. Additionally, the framework lays the groundwork for future research on autonomous process planning and digital audit trails, ensuring a robust and verifiable execution of laboratory tasks.

Due to copyright restrictions, the full text of the paper is not included in this deliverable. However, its abstract and key insights have been summarized to ensure alignment with the project's objectives and to provide a comprehensive understanding of its relevance.

The paper has been accepted for Publication at the 2025 IEEE International Conference on Robotics & Automation in January 2025. It is expected that the paper is published around August 2025 on IEEE Xplore, based on the experience from ICRA 2024.

The reference to the paper is:

Mania, Patrick, Neumann, Michael, Kenghagho Kenfack, Franklin and Beetz, Michael, "Towards Autonomous Verification: Integrating Cognitive AI and Semantic Digital Twins in Medical Robotics", In 2025 International Conference on Robotics and Automation (ICRA), 2025. Accepted for publication.

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3 Deviations from the workplan

No major deviation has been detected, and the document has been delivered on time.

4 Conclusion

This deliverable presents the contributions of a novel robotic mind's eye reasoning framework for verification in medical lab environments. By integrating cognitive AI with semantic digital twins, we provide a robust solution for autonomous task verification, addressing key challenges in handling complex and transparent objects. The results of our research demonstrate significant improvements in verification accuracy.

Our approach has been described in a paper which has been accepted in a highly ranked, peer-reviewed conference on robotics and lays a strong foundation for further advancements in robotic reasoning for laboratory scenarios.

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5 References

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