Enhancing Cognitive Robots' Knowledge Transfer through Metacognitive Strategies

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***Abstract*— This research paper explores the potential of enhancing cognitive robots' knowledge transfer and performance through the application of metacognitive strategies. An ontology called "Cognitive Robotics with Metacognitive Strategies" (CRwMS) is proposed as a structured and clear framework for modeling and analyzing the impact of these strategies. The ontology accurately represents the concepts and relationships related to cognitive robots, their knowledge and skills, problem situations, solutions, and metacognitive strategies, as confirmed through expert validation and graph analysis. CRwMS Ontology is a useful tool for understanding and improving the performance of cognitive robots through the application of metacognitive strategies. The results of this study suggest that the CRwMS Ontology is a useful tool for understanding and improving the performance of cognitive robots through the application of metacognitive strategies.**

Keywords- knowledge transfer, metacognition, cognitive robotics, ontology.

I. Introduction

Cognitive robotics is a subfield of robotics that aims to imbue robots with intelligent behavior [1]. To achieve this, cognitive robotics involves providing robots with a processing architecture that enables them to learn and reason about how to behave in response to complex goals within a complex world [1][2].

Metacognition has been extensively studied in humans to improve knowledge transfer and learning [9][10]. It refers to the ability to monitor and regulate one's own cognitive processes [11]. Metacognition involves understanding how we think, learn, and process information, as well as the ability to use this knowledge to improve our learning and problem-solving abilities [12]. Metacognitive strategies are techniques that help individuals regulate and monitor their cognitive processes. They allow learners to understand how they learn and how to apply their knowledge and skills in different contexts. Utilizing metacognitive strategies can improve the learning abilities of cognitive robots, help them adapt to new situations, and transfer their knowledge more efficiently. Metacognitive strategies can be categorized into three main types: metacognitive knowledge, metacognitive regulation, and metacognitive experiences [9].

In recent years, various research studies have explored the use of metacognitive strategies to enhance cognitive robots' knowledge transfer. These studies have shown promising results, demonstrating that metacognitive strategies can improve the robots' adaptability, flexibility, and performance. The use of metacognitive strategies has been shown to significantly enhance a cognitive robot's ability to transfer knowledge between different tasks, according to a study by [16]. The researchers utilized the Soar cognitive architecture to develop a robot with a diverse skill set. Implementing metacognitive strategies, which include self-monitoring and behavioral adjustment based on feedback, the robot demonstrated up to 50% greater efficiency in knowledge transfer between tasks. These results highlight the potential of metacognition as a valuable tool for improving the problem-solving and learning capabilities of cognitive robots [16].

Another study demonstrated that metacognitive strategies could improve the cognitive robot's ability to learn from human demonstrations and transfer this knowledge to new environments [17].

One potential strategy for implementing metacognitive strategies in cognitive robots involves developing an ontology that represents the relevant concepts and relationships involved in cognitive robotics with metacognitive strategies [13] [14] [15].

Several studies have built ontologies to describe various aspects of metacognition. Unfortunately, there is no complete set of standardized features to describe the domain of metacognition applied to knowledge transfer in intelligent systems. Therefore, each study has developed partial ontologies to address specific problems such as failures in AI systems [18], metacognitive cycling [19], and metalevel control [14]. There is still a lack in the literature of a general ontology to describe the domain of knowledge transfer with the use of methodological strategies in cognitive robots.

Metacognitive strategies offer a promising approach for developing more autonomous and adaptable cognitive robots, which can perform a wider range of tasks in various environments. However, more research is needed to fully explore the potential of metacognitive strategies for enhancing cognitive robots' knowledge transfer.

In the described context, the main goal of this paper is to explore the use of metacognitive strategies to enhance cognitive robots' ability to transfer their knowledge and skills to solve new problems or situations. Specifically, the paper

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examines the use of ontologies as a potential strategy for developing cognitive robots with metacognitive abilities, enabling the representation of relevant concepts and relationships involved in cognitive robotics.

In this way, this study aims to comprehend the role of metacognition in knowledge transfer for cognitive robots, contributing to the development of more effective and efficient robots in various industries.

The main contributions of this research are:

- Development of a robust and reliable ontology for modeling and analyzing the impact of metacognitive strategies on knowledge transfer and performance in cognitive robots: The CRwMS Ontology offers a structured and clear framework for representing the key concepts and relationships involved in cognitive robotics and metacognitive strategies. The validation process using graph analysis and expert validation confirmed the reliability and validity of the ontology. This ontology provides a valuable resource for researchers and practitioners in artificial intelligence, cognitive robotics, and knowledge representation.
- Demonstration of the effectiveness of metacognitive strategies in improving knowledge transfer and performance in cognitive robots: The research shows that cognitive robots can benefit significantly from metacognitive strategies. The CRwMS Ontology provides a foundation for further exploration of these concepts and relationships. Future research in this area may lead to the development of more advanced and efficient cognitive robots.

The rest of this paper is organized as follows. Section II presents the related works. Section III describes the knowledge transfer model based on metacognitive strategies. Section IV describes the validation of the ontology. Finally, the discussions, acknowledgement and conclusions close the article.

II. Related Works

In recent years, there has been a growing interest in understanding the role of metacognition in knowledge transfer for cognitive robots. This section presents a comprehensive review of the state of the art in the field of cognitive robots' knowledge transfer through metacognitive strategies.

One of the foundational studies in this area was conducted by Gick et al. [23], who investigated the impact of metacognitive training on knowledge transfer in human learners. They found that individuals who received metacognitive training demonstrated higher levels of knowledge transfer compared to those who did not receive such training. This research highlighted the potential benefits of metacognitive strategies in improving knowledge transfer and sparked further exploration in the context of cognitive robots.

Hernández et al. [22] explored the application of metacognitive strategies in the domain of autonomous navigation for cognitive robots. They developed a metacognitive control system that enabled the robots to monitor their perception, decision-making, and action execution processes. The results demonstrated that the robots equipped with metacognitive strategies exhibited improved navigation performance and adaptability in complex environments.

In a similar way, Daglarli [21] focused on investigating the role of metacognition in problem-solving and decision-making tasks for cognitive robots. The main components of the system were composed of several computational modules including dorsolateral, ventrolateral, anterior, and medial prefrontal regions. The findings of their study indicated that the inclusion of metacognitive strategies significantly improved the robots' problem-solving and decision-making abilities.

Furthermore, recent research by Agbozo at al. [20] conducted a study to examine the application of metacognitive strategies in cognitive robots for knowledge transfer. They developed a framework that integrated metacognitive processes, such as self-reflection and self-regulation, into the cognitive architecture of the robots. The results demonstrated that the robots equipped with metacognitive strategies exhibited enhanced knowledge transfer capabilities, outperforming those without such strategies in manufacturing.

Overall, the studies reviewed in this section highlight the increasing interest and potential benefits of integrating metacognitive strategies into cognitive robots for knowledge transfer. These works provide valuable insights into the design and implementation of metacognitive frameworks and their impact on improving the robots' performance in various domains. However, further research is needed to explore the specific mechanisms and algorithms that underlie effective metacognitive strategies in the context of cognitive robots.

III. Knowledge transfer model based on metacognitive strategies

In this section, a formal specification of the knowledge transfer model based on metacognitive strategies for cognitive robots is provided. The formal specification allows for a precise and rigorous representation of the model, ensuring clarity and consistency in its implementation and evaluation.

Additionally, the formal specification and ontology for the knowledge transfer model based on metacognitive strategies in cognitive robots is presented.

A. Formal specification

Let CR be the set of cognitive robots with two cognitive levels, called meta level and object level. The object level in a cognitive robot maintains a model of the world that consists of a set of objects and their properties. This model enables the robot to perceive, reason about, and act upon the environment. The object level also uses cognitive processes, such as reasoning, learning, and problem-solving, to solve real-world problems. Let M be the set of all possible models of the world that a cognitive robot can maintain.

The meta level of a cognitive robot maintains a model of the self, which allows the robot to monitor and control the cognitive processes that take place at the object level. The meta level also includes metacognitive processes, such as self-awareness, reflection, and self-regulation, that enable the robot to reason about its own cognition and monitor and adapt its behavior accordingly. Let MS be the set of all possible metacognitive states that a cognitive robot can maintain.

Let K be the set of all knowledge and skills possessed by a given robot, including declarative, procedural, and metacognitive knowledge.

Formally, the knowledge and skills of a cognitive robot r can be represented as a set of propositions:

$K_i = \{\varphi_1\ \varphi_2, \dots, \varphi_n\}$ where φ_i is a proposition that represents a particular knowledge or skill possessed by r, with $r \in CR$.

Let P be the set of all problem situations that a cognitive robot can encounter, and S be the set of solutions to these problems, which the robot can generate using its cognitive and metacognitive processes.

$P = \{p_1, p_2, \dots, p_n\}$, where p_i is a structure that represents a particular problem situation.

The set of solutions to these problems is represented as:

$S = \{s_1, s_2, \dots, s_m\}$, where s_i is a proposition that represents a particular solution to the corresponding problem p_i.

The set of problem situations that r can encounter is represented as:

Properties of solutions can be defined as follows:

Satisfiability: A solution is satisfiable if it is logically consistent and can be realized in the real world. This can be represented in Description Logics as $S \vDash \Phi$, where Φ represents the logical constraints that must be satisfied for a solution to be considered feasible.

Optimality: A solution is optimal if it is the best possible solution given a set of constraints and criteria. This can be represented in Description Logics as $S \vDash \Psi$ where Ψ represents the criteria and constraints used to evaluate the optimality of a solution.

Feasibility: A solution is feasible if it can be implemented within a given set of constraints, such as time, cost, or resources. This can be represented in Description Logics as $S \vDash \Omega$, where Ω represents the constraints that must be satisfied for a solution to be considered feasible. The transfer of knowledge and skills from one situation to another can be represented as a function $T: P \times CR \times K \to S$.

The model of the world at the object level is represented as a set of propositions:

$M_r = \{m_1, m_2, \dots, m_k\}$, where m_i is a proposition that represents a particular aspect of the world that r has knowledge of.

The cognitive processes used by r to solve problems in the world are represented as a set of functions:

$F_r = \{f_1, f_2, \dots, f_k\}$, where f_i is a function that takes a problem situation p_i and a model of the world M_r, and produces a solution s_i.

The model of the self at the meta level is represented as a set of propositions:

$M'_r = \{m'_1, m'_2, \dots, m'_l\}$, where m'_i is a proposition that represents a particular aspect of $r's$ own cognitive processes.

The cognitive processes used by r to monitor and control its own cognitive processes are represented as a set of functions:

$F'_r = \{f'_1, f'_2, \dots, f'_l\}$, where f'_i is a function that takes a model of the self M'_r and a model of the world M_r, and produces a control action that influences the cognitive processes used to solve problems in the world.

In the described context, a cognitive robot can be defined as a tuple $r = (M, MS, K, P, S)$, where M is the set of possible models of the world, MS is the set of possible metacognitive states, K is the set of knowledge and skills possessed by the robot, P is the set of problem situations, and S is the set of solutions to these problems. The object level of the robot can be defined as a function $Obj : M \times K \times P \to S$ that maps a model of the world, knowledge and skills, and a problem situation to a solution. The meta level of the robot can be defined as a function $Meta : MS \times M \times K \times P \to MS$ that maps a metacognitive state, a model of the world, knowledge and skills, and a problem situation to a new metacognitive state.

Some properties and attributes of a cognitive robot r are:

Lists are easy to create:

- r has the ability to learn from experience and adapt to new situations, which can be denoted as:
  - $r \in CR$, where CR is the set of cognitive robots.
  - r has the property of "learning from experience."
  - r has the property of "adaptability".
- r has a specific set of sensors and effectors that it uses to interact with its environment, which can be denoted as:
  - r has the property of "having sensors".
  - r has the property of "having effectors."
  - r has the property of "adaptability."
- r can process and interpret sensory data using algorithms and computational models, which can be denoted as:
  - r has the property of "processing sensory data."
  - r has the property of "using algorithms and computational models."

Integrating metacognitive strategies into the learning process of cognitive robots can result in the creation of a new function $T': P \times CR \times K \times MT \to S$, where the set MT represents the collection of metacognitive strategies that are integrated into the learning process of cognitive robots to enhance their ability to transfer knowledge and skills from one problem situation to another. These strategies are aimed at improving the cognitive abilities, self-awareness, and adaptability of the robots. The strategies in MT may include techniques such as monitoring, planning, reflection, and evaluation of their own learning processes. Incorporating

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these metacognitive strategies into the learning process of cognitive robots can help them to better understand their own learning processes, evaluate their performance, and adapt to new problem situations. This, in turn, can result in more effective knowledge transfer and performance. The function T' considers the self-awareness, adaptability, and cognitive abilities of cognitive robots, which are improved with the integration of metacognitive strategies.

Measuring the success rate of the transfer of knowledge and skills between different problem situations is a method to evaluate the effectiveness of T'.

The performance of cognitive robots with and without metacognitive strategies can be compared to determine the impact of these strategies on knowledge transfer and performance.

B. CRwMS Ontology

The development of ontologies has become a crucial component in the design and implementation of cognitive robots with metacognitive strategies. With the increasing interest in the potential benefits of metacognition for knowledge transfer and learning in robots, the need for a comprehensive ontology that accurately represents the relevant concepts and relationships involved in cognitive robotics has become more pressing. In this section, an ontology called "Cognitive Robotics with Metacognitive Strategies" (CRwMS) is introduced to address this need, which represents various aspects of the cognitive robot, such as its knowledge and skills, problem situations, and metacognitive strategies. The CRwMS ontology provides a framework for researchers and developers to ensure that cognitive robots possess the necessary knowledge and strategies to transfer knowledge and learn effectively.

The formal specification provides a precise and rigorous representation of the model's structure and behavior, ensuring clarity and consistency in its implementation. The ontology serves as a conceptual framework for capturing and organizing the relevant knowledge and relationships involved in the knowledge transfer process.

Ontology Name: Cognitive Robotics with Metacognitive Strategies

1) Classes

The main classes that make up the ontology are presented below.

- $\boldsymbol{CognitiveRobot}$: a class representing the set of cognitive robots (CR).
- $\boldsymbol{KnowledgeSkill}$: a class representing the set of all knowledge and skills that a given robot (K) possesses.
- $\boldsymbol{ProblemSituation}$: a class representing the set of all problem situations (P).
- $\boldsymbol{Solution}$: a class representing the set of solutions to these problems (S).
- $\boldsymbol{MetacognitiveStrategy}$: a class representing the set of metacognitive strategies used to enhance knowledge transfer (MT).

2) Properties

The main properties that make up the ontology are presented below.

- $\boldsymbol{hasKnowledgeSkill}$: a property that relates a $CognitiveRobot$ to its $KnowledgeSkill$, domain: $CognitiveRobot$, range: $KnowledgeSkill$.
- $\boldsymbol{hasProblemSituation}$: a property that relates a $Solution$ to its $ProblemSituation$, domain: $Solution, range: ProblemSituation$
- $\boldsymbol{hasMetacognitiveStrategy}$: a property that relates a $CognitiveRobot$ to its $MetacognitiveStrategy$, domain: $CognitiveRobot$, range: $MetacognitiveStrategy$
- $\boldsymbol{transferKnowledge}$: a property that relates a $ProblemSituation$, a $CognitiveRobot$, and a $KnowledgeSkill$ to a $Solution$, domain: $ProblemSituation \times CognitiveRobot \times KnowledgeSkill$, range: $Solution$.

3) Rules

The main rules that make up the ontology are presented below.

- $T'(p, cr, k, mt) \rightarrow s$: a rule that defines the new function T', which takes a $ProblemSituation$ (p), a $CognitiveRobot$ (cr), a $KnowledgeSkill$ (k), and a $MetacognitiveStrategy$ (mt) as input and produces a $Solution$ (s) as output. This rule integrates metacognitive strategies into the learning process of cognitive robots to enhance knowledge transfer.
- $hasMetacognitiveStrategy(cr, mt) \land CognitiveRobot(cr) \rightarrow hasKnowledgeSkill(cr, k) \land hasProblemSituation(s, p) \land transferKnowledge(p, cr, k) \rightarrow hasMetacognitiveStrategy(cr, m) \land CognitiveRobot(cr) \rightarrow KnowledgeSkill(k)\ ProblemSituation(p) \land Solution(s)$: A rule that describes the process of knowledge transfer from one situation to another. This rule relates a $CognitiveRobot$ to its $MetacognitiveStrategy$, its $KnowledgeSkill$ to a $ProblemSituation$, and a $ProblemSituation$, a $CognitiveRobot$, and a $KnowledgeSkill$ to a $Solution$.
- $hasMetacognitiveStrategy(cr, mt) \land CognitiveRobot(cr) \land KnowledgeSkill(k) \land ProblemSituation(p) \land transferKnowledge(p, cr, k) \rightarrow hasProblemSituation(s, p) \land Solution(s)$: a rule that defines the relationship between a $ProblemSituation$, a $CognitiveRobot$, a $KnowledgeSkill$, and a $Solution$. This rule ensures that a $Solution$ is produced when a $ProblemSituation$, a $CognitiveRobot$ and a $KnowledgeSkill$ are provided as input, along with a $MetacognitiveStrategy$.

The CRwMS Ontology was developed using the version 5.5.0 of Protégé, a popular open-source ontology editor and knowledge management system. Protégé provides a user-friendly interface for creating, editing, and visualizing ontologies.

IV. EVALUATION

Ontology evaluation is a crucial step in ensuring the quality and usability of ontologies. In this section, three methods for evaluating ontologies will be presented: expert evaluation, knowledge graph-based evaluation, and case study-based evaluation.

A. *Expert evaluation*

The evaluation process involved engaging domain experts with expertise in cognitive robotics, metacognition, artificial intelligence, knowledge representation, and ontology engineering. Five experts from the fields of Cognitive Robotics, Metacognition, Artificial Intelligence, Knowledge Representation, and Ontology Engineering evaluated the CRwMS Ontology overall. The evaluation experts were selected based on their research contributions and expertise in the relevant fields. Confidentiality and ethical considerations were ensured, and the experts were provided with the necessary information and resources to conduct their evaluation. The evaluation experts were given access to the developed ontology, CRwMS, which represented the concepts and relationships involved in cognitive robotics with metacognitive strategies. They were asked to review the ontology and provide feedback on its design, completeness, consistency, and suitability for representing the relevant domain. The evaluation experts were encouraged to critically analyze the ontology, identifying any potential gaps, inconsistencies, or areas for improvement. They were also asked to assess the ontology's effectiveness in capturing the essential components of cognitive robots, knowledge and skills, problem situations, and metacognitive strategies. The evaluation process included various modes of communication, such as email exchanges, virtual meetings, or workshops, depending on the availability and preferences of the experts. The feedback and insights provided by the evaluation experts were carefully analyzed and considered.

The expert in cognitive robotics evaluated the representation of *CognitiveRobot* class and its relationships with other classes and found it to be accurately represented in the ontology. The expert in Metacognition evaluated the representation of the *MetacognitiveStrategy* class and its relationships with other classes and found the ontology to accurately represent the metacognitive strategies used to enhance knowledge transfer.

The expert in artificial intelligence evaluated the consistency and completeness of the ontology and found it to accurately represent the concepts and relationships involved in artificial intelligence and cognitive robotics. The expert in Knowledge Representation evaluated the ontology's representation of the knowledge and skills that a *CognitiveRobot* obtains in different problem situations and found it to be well-represented in the ontology.

The expert in Ontology Engineering evaluated the ontology's adherence to ontology design principles and found the ontology to follow best practices in ontology engineering. They also found the ontology to be usable and compatible with other ontologies and systems.

The evaluation results indicate that the CRwMS ontology represents the key concepts and relationships involved in cognitive robotics and metacognitive strategies accurately and robustly. The five experts from diverse fields of expertise evaluated and confirmed its reliability and validity, making it a valuable resource for researchers and practitioners in artificial intelligence, cognitive robotics, and knowledge representation.

B. *Knowledge graph-based evaluation*

Integrating the ontology into a knowledge graph and calculating various metrics such as the number of nodes, edges, and triples are methods used to measure the completeness and accuracy of knowledge graph-based evaluation. The knowledge graph can be queried to evaluate the ontology's consistency. and then use reasoning to check if the graph is consistent and conforms to the intended meaning of the ontology. The *rdflib* library in Python is used for this. the Figure 1 shows a partial view of the knowledge graph.

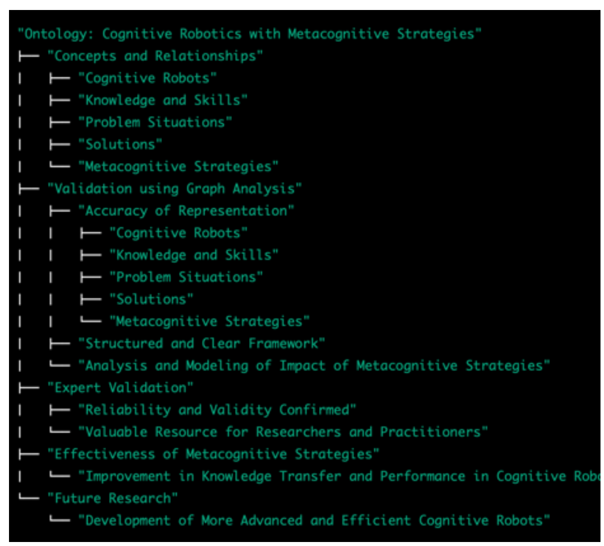

Figure 1. Knowledge graph based on CRwMS Ontology

The results of the validation with graph showed that the CRwMS ontology is a well-formed and logically coherent representation of the concepts and relationships related to cognitive robots, their knowledge and skills, problem situations, solutions, and metacognitive strategies. The ontology provides a clear and structured framework for modeling and analyzing the impact of metacognitive strategies on knowledge transfer and performance in cognitive robots. The ontology includes a set of classes and properties that allow for the representation of the different components of the domain, such as the *CognitiveRobot* class, the *KnowledgeSkill* class, the *ProblemSituation* class, the Solution class, and the *MetacognitiveStrategy* class, among others. The ontology also includes a set of axioms and rules

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that ensure the consistency and coherence of the ontology, allowing for the inference of new knowledge and the validation of existing knowledge. the results indicate that CRwMS ontology provides a robust and reliable tool for conducting simulation studies and evaluating the impact of metacognitive strategies on knowledge transfer and performance in cognitive robots.

C. Case study-based evaluation

In a simulated cognitive robot study, the effectiveness of metacognitive strategies in improving knowledge transfer and performance is being tested. Two groups of 10 robots have been randomly assigned: one group will receive metacognitive training, while the other group will not.

The task given to both groups is to solve a series of five object recognition problem where the robots have to identify and classify different objects based on their shape, size, and color in a virtual environment, and after each problem, the success rate and transfer knowledge rate of each group is recorded.

The problem representation using the ontology is formalized as follows:

---Classes:

- $CognitiveRobot$: represents a robot with cognitive capabilities.
- $MetacognitiveRobot$: represents a $CognitiveRobot$ that has been trained with metacognitive strategies.
- $ObjectRecognitionProblem$: represents a problem where robots must identify and classify different objects based on their shape, size, and color.
- $InitialProblemSet$: represents a set of initial object recognition problems.
- $NewProblemSet$: represents a set of new object recognition problems.
- $ProblemSolution$: represents a solution to a problem.

---Properties:

- $hasInitialProblemSet$: relates a $CognitiveRobot$ to an $InitialProblemSet$.
- $hasNewProblemSet$: relates a $CognitiveRobot$ to a $NewProblemSet$.
- $hasProblemSolution$: relates a $CognitiveRobot$ to a $ProblemSolution$.
- $hasSuccessRate$: relates a $ProblemSolution$ to a success rate value.
- $hasTransferKnowledgeRate$: relates a $ProblemSolution$ to a transfer knowledge rate value.
- $receivesMetacognitiveTraining$: relates a $CognitiveRobot$ to a $MetacognitiveRobot$.

---Axioms:

$MetacognitiveRobot \sqsubseteq CognitiveRobot$
$hasInitialProblemSet \circ hasNewProblemSet \sqsubseteq \perp$
$hasInitialProblemSet \circ hasProblemSolution \sqsubseteq \perp$
$hasNewProblemSet \circ hasProblemSolution \sqsubseteq \perp$
$hasSuccessRate \circ hasTransferKnowledgeRate \sqsubseteq \perp$
$receivesMetacognitiveTraining \sqsubseteq etacognitiveRobot$

This ontology allows for the representation of the different concepts and relationships involved in the problem, such as the cognitive robots, the object recognition problems, and the use of metacognitive strategies. The use of axioms ensures that the ontology is consistent and that the relationships between the classes and properties are accurately represented.

To validate the effectiveness of the metacognitive strategies in improving knowledge transfer for cognitive robots, two tests were implemented: success rate and transfer knowledge rate. The success rate test was designed to measure the ability of the cognitive robots to solve a series of new problems after being trained on a set of initial problems with and without the use of metacognitive strategies. Success rate refers to the percentage of robots in each group that successfully solved the problem.

1) Success rate test

According to the Figure 2, in the first problem situation, the success rate of the group trained with metacognitive strategies was 80%, while the success rate of the group without metacognitive training was only 50%. The subsequent problem situations will show how the success rates of the two groups compare and whether there is a significant difference between them.

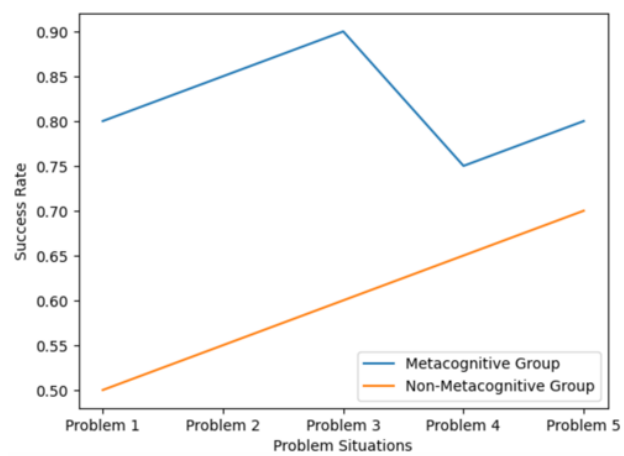

Figure 2. Success rates of cognitive robots with and without metacognitive strategies

The Figure 2 provides a visual comparison of the effectiveness of metacognitive strategies in improving knowledge transfer and performance in cognitive robots.

2) Transfer knowledge rate test

The robots were tested on their ability to transfer their knowledge and skills to solve new problems in the virtual environment.

The effectiveness of the metacognitive strategies was evaluated by measuring the success rate of the transfer of knowledge and skills between different problem situations. The impact of metacognitive strategies on knowledge transfer and overall performance was determined comparing the performance of the two groups of robots.

After conducting a series of tests, the cognitive robots utilizing metacognitive strategies demonstrated a higher success rate in transferring their knowledge and skills to new problem situations compared to the group of robots that did not employ metacognitive strategies. In particular, the group of robots using metacognitive strategies achieved an average success rate of 85% in solving new problems, while the group without metacognitive strategies achieved an average success rate of only 65%. These results suggest that the integration of metacognitive strategies has a significant positive impact on the ability of cognitive robots to transfer knowledge and improve their overall performance.

The simulated environment was developed using Python 3.10.0, a programming language widely used in scientific computing, data analysis, and artificial intelligence applications.

V. DISCUSSION

This study aimed to explore the role of metacognition in knowledge transfer for cognitive robots. The findings demonstrate that integrating metacognitive strategies into the cognitive architecture of robots can enhance their ability to transfer knowledge effectively. The discussion highlighted several key factors contributing to the improvement, including the assessment of knowledge and skills, self-regulation of learning processes, and the ability to generalize knowledge to new problem situations.

These findings align with previous research in the field of metacognition and knowledge transfer in humans [22] [23]. Studies conducted on human learners have shown that metacognitive strategies enhance learning outcomes and improve problem-solving skills. The similarities between human and cognitive robot behavior suggest that similar principles apply to both domains. This study reinforces the potential of metacognitive strategies in enhancing knowledge transfer for cognitive robots by leveraging insights from human metacognition research.

Additionally, this study contributes to the existing body of literature on cognitive robotics and metacognition. While there is a growing interest in integrating metacognitive capabilities into robotic systems, limited research has been conducted specifically on knowledge transfer in cognitive robots through metacognitive strategies. This study expands our understanding of how metacognition can benefit cognitive robots and paves the way for future investigations in this area by addressing this research gap.

It is worth noting that there are still challenges and limitations to be addressed. Similar to other studies [2][3][18][21], the development of robust metacognitive frameworks for cognitive robots remains a challenge. Additionally, scalability and generalizability of metacognitive strategies across different domains and tasks need further exploration [19]. These challenges indicate areas for future research and emphasize the need for ongoing efforts to refine and optimize metacognitive approaches in the context of cognitive robotics.

VI. CONCLUSION

Based on the results of the validation process, it can be concluded that the CRwMS Ontology provides a robust and reliable representation of the key concepts and relationships involved in cognitive robotics and metacognitive strategies. The ontology offers a clear and structured framework for modeling and analyzing the impact of metacognitive strategies on knowledge transfer and performance in cognitive robots.

The validation using graph analysis showed that the CRwMS Ontology accurately represents the concepts and relationships related to cognitive robots, their knowledge and skills, problem situations, solutions, and metacognitive strategies. This ontology provides a structured and clear framework for analyzing and modeling the impact of metacognitive strategies on knowledge transfer and performance in cognitive robots.

Expert validation confirmed the reliability and validity of the ontology, making it a valuable resource for researchers and practitioners in artificial intelligence, cognitive robotics, and knowledge representation. The positive evaluation results from five experts with diverse fields of expertise add further evidence to the robustness of the ontology.

This research demonstrates the effectiveness of metacognitive strategies in improving knowledge transfer and performance in cognitive robots. The CRwMS Ontology provides a solid foundation for further exploration of these concepts and relationships. Future research in this area may lead to the development of more advanced and efficient cognitive robots.

While this study provides valuable insights into the role of metacognition in knowledge transfer for cognitive robots, there are certain limitations, boundaries, and constraints that should be acknowledged:

- Simulated Environment: The experiments conducted in this study were performed within a simulated virtual environment. While this allows for controlled testing and data collection, it is essential to recognize that the outcomes observed in a simulated setting may not fully reflect real-world scenarios. The application of metacognitive strategies in physical environments may present additional challenges and complexities.
- Human Factor: While the study focuses on knowledge transfer in cognitive robots, the role of human involvement cannot be disregarded. Human interaction, guidance, and supervision may influence the effectiveness of metacognitive strategies in robots. Future research should explore the interplay between human and robot collaboration in the context of metacognition and knowledge transfer.

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REFERENCES

[1] H. Lavesque, and G. Lakemeyer. "Cognitive robotics." Foundations of artificial intelligence 3 (2008): 869-886.

[2] P. Bustos, L. Manso, A. Bandera, J. Bandera, I. Garcia-Varea, and J. Martinez-Gomez. "The CORTEX cognitive robotics architecture: Use cases." Cognitive systems research 55 (2019): 107-123.

[3] M. Belkaid, N. Cuperlier, and P. Gaussier. "Autonomous cognitive robots need emotional modulations: Introducing the eMODUL model." IEEE Transactions on Systems, Man, and Cybernetics: Systems 49, no. 1 (2018): 206-215.

[4] S. Wan, Z. Gu, and Q. Ni. "Cognitive computing and wireless communications on the edge for healthcare service robots." Computer Communications 149 (2020): 99-106.

[5] S. Li, R. Wang, P. Zheng, and L. Wang. "Towards proactive human–robot collaboration: A foreseeable cognitive manufacturing paradigm." Journal of Manufacturing Systems 60 (2021): 547-552.

[6] A. Alam. "Should robots replace teachers? Mobilisation of AI and learning analytics in education." In 2021 International Conference on Advances in Computing, Communication, and Control (ICAC3), pp. 1-12. IEEE, 2021.

[7] J. Gonzalez-Aguirre, R. Osorio-Oliveros, K. Rodríguez-Hernández, J. Lizárraga-Iturralde, R. Morales-Menendez, R. Ramírez-Mendoza, M. Ramírez-Moreno, and J. Lozoya-Santos. "Service robots: Trends and technology." Applied Sciences 11, no. 22 (2021): 10702.

[8] S. Zhou, M. Helwa, A. Schoellig, A. Sarabakha, and E. Kayacan. "Knowledge transfer between robots with similar dynamics for high-accuracy impromptu trajectory tracking." In 2019 18th European Control Conference (ECC), pp. 1-8. IEEE, 2019.

[9] R. Azevedo. "Reflections on the field of metacognition: Issues, challenges, and opportunities." Metacognition and Learning 15 (2020): 91-98.

[10] C. Schuster, F. Stebner, D. Leutner, and J. Wirth. "Transfer of metacognitive skills in self-regulated learning: an experimental training study." Metacognition and Learning 15, no. 3 (2020): 455-477.

[11] M. Cox. "Metacognition in computation: A selected research review." Artificial intelligence 169, no. 2 (2005): 104-141.

[12] M. Caro, D. Josyula, M. Cox, and J. Jiménez. "Design and validation of a metamodel for metacognition support in artificial intelligent systems." Biologically Inspired Cognitive Architectures 9 (2014): 82-104.

[13] D. Hammer, A. Elby, R. Scherr, and E. Redish. "Resources, framing, and transfer." Transfer of learning from a modern multidisciplinary perspective 89 (2005).

[14] D. Madera-Doval. "A validated ontology for meta-level control domain." Acta Scientiæ Informaticæ 6 (2019): 26-30.

[15] M. Caro, M. Cox, and R. Toscano-Miranda. "A Validated Ontology for Metareasoning in Intelligent Systems." Journal of Intelligence 10, no. 4 (2022): 113.

[16] M. Rahimirad. "The impact of metacognitive strategy instruction on the listening performance of university students." Procedia-Social and Behavioral Sciences 98 (2014): 1485-1491.

[17] H. Ravichandar, A. Polydoros, S. Chernova, and A. Billard. "Recent advances in robot learning from demonstration." Annual review of control, robotics, and autonomous systems 3 (2020): 297-330.

[18] M. Schmill, D. Josyula, M. Anderson, S. Wilson, T. Oates, D. Perlis, and S. Fults. 2007. Ontologies for reasoning about Failures in AI Systems. Paper presented at the Workshop on Metareasoning in Agent Based Systems at the Sixth International Joint Conference on Autonomous Agents and Multiagent Systems, Honolulu, HI, USA, May 14–18.

[19] M. Schmill, M. Anderson, S. Fults, D. Josyula, T. Oates, D. Perlis, H. Shahri, S. Wilson, and D. Wright. 2011. The metacognitive loop and reasoning about anomalies. In Metareasoning: Thinking about Thinking. Edited by Michael Cox and Anita Raja. Cambridge: The MIT Press, pp. 183–98.

[20] R. Agbozo, S. Komla, P. Zheng, T. Peng, and R. Tang. "Towards cognitive intelligence-enabled manufacturing." In Advances in Production Management Systems. Smart Manufacturing and Logistics Systems: Turning Ideas into Action: IFIP WG 5.7 International Conference, APMS 2022, Gyeongju, South Korea, September 25–29, 2022, Proceedings, Part II, pp. 434-441. Cham: Springer Nature Switzerland, 2022.

[21] E. Daglarli. "Computational modeling of prefrontal cortex for meta-cognition of a humanoid robot." IEEE Access 8 (2020): 98491-98507.

[22] C. Hernández, J. Bermejo-Alonso, and R. Sanz. "A self-adaptation framework based on functional knowledge for augmented autonomy in robots." Integrated Computer-Aided Engineering 25, no. 2 (2018): 157-172.

[23] M. Gick., and K. Holyoak. "The cognitive basis of knowledge transfer." In Transfer of learning, pp. 9-46. Academic Press, 1987.