Table 1. Comparison between types of interpretation

Object level interpretation	Meta-level interpretation
Expects clear(A); Observes ¬clear(A) Symptom = contradiction	Expects π; Observes ∅ Symptom = `impasse`
Explanation: on-fire(A) → ¬clear(A)	Explanation: flawed-behavior(∏) → impasse
Goal(g) = ¬on-fire(A)	Goal(g) = ¬flawed-behavior(∏)
Plan(π) = extinguish(A)	Plan = replace(∏)

Related Research

MIDCA is related to other cognitive architectures in that it uses varied levels of abstractions. They differ on how these abstractions are represented. SOAR (Laird 2012) represents different levels of abstraction in a hierarchy. Abstract operators are used to refine abstract goals into increasingly concrete ones. SOAR enables the integration of a variety of knowledge forms than can be triggered by production rules at any level of the hierarchy. ACT-R (Anderson 1993) also uses production levels of varied level of abstraction. They generate new goals when rules are triggered at the lower level of the hierarchy. ICARUS (Langley and Choi 2006) also represents knowledge of different level of abstraction by using Horn clauses that define abstract goals. These clauses are used to learn hierarchies of increasing level of abstraction in a bottom-up matter by using teleo-reactive planning techniques. DISCIPLE (Tecuci 1988; Tecuci *et al.* 2002) uses concept hierarchies to represent knowledge of different levels of abstraction. In contrast to these cognitive architectures, MIDCA distinguishes between meta-level and object-level explicitly in the hierarchy.

Two architectures of note have modeled metacognitive components explicitly. CLARION (Sun, Zhang, and Mathews 2006) has a metacognitive module within its structure, but the mechanism is sub-symbolic as opposed to the higher-level symbolic representation of MIDCA. The ACT-R theory was not developed with specific metacognitive effects in mind, but it has recently modeled metacognitive tasks called pyramid problems. The control of reasoning is actually considered to be part of the cognitive function; whereas monitoring of reasoning is classified as metacognitive (see for example Anderson, Betts, Ferris, and Fincham 2011). In any case, many of the existing cognitive architectures have limitations when modeling metacognitive activity and have been modified on an as needed basis to fit some circumstances.

Other cognitive architectures have explored the issue of explanation. For example, Companions (Forbus, Klenk and Hinrichs 2009) uses truth-maintenance techniques to build justifications of the rationale that led to a decision. These explanations particularly target user interaction settings where the system must justify the reasons for actions taken. As discussed earlier in the paper, explanations play a central role in GDA systems, where the explanation serves as a bridge between discrepancies that the agent encounters during execution and the goal to achieve that addresses those discrepancies. In MIDCA, the Interpret and Evaluate steps help it understand the current situation in the environment (which could include a discrepancy with its own expectations).

An alternative formalism (Roberts *et al*. 2015) treats goal reasoning as *goal refinement*. Using an extension of the plan-refinement model of planning, Roberts models goal reasoning as refinement search over a goal memory M, a set of goal transition operators R, and a transition function delta that restricts the applicable operators from R to those provided by a fundamental goal lifecycle. Roberts proposes a detailed lifecycle consisting of goal formulation, goal selection, goal expansion, goal commitment, goal dispatching, goal monitoring, goal evaluation, goal repair, and goal deferment. Thus many of the differential functionalities in β are distinct and explicit in the goal reasoning cycle. However the model here tries to distinguish between the planning and action side of reasoning (φ and γ) and the interpretation and evaluation components inherent in goal reasoning (β).

Conclusion

This work makes the following contributions: (1) It presents a cognitive architecture that includes a metacognitive as well as cognitive layer to model high-level problem-solving and comprehension in dynamic environments. (2) It marks the public release of a documented implementation of the architecture. Although not as extensive as many existing cognitive architectures, MIDCA represents a new take to modeling aspects of autonomy that so far have received little attention. (3) A novel formalization of goal reasoning using well-defined AI planning concepts. (4) We introduced a new interface between MIDCA and physical robot. (5) We present empirical work demonstrating the dual functionality between the object-level and the meta-level.

Future work includes: (1) the important and non-trivial problem of deciding when to run the metacognitive layer. A possible way to tackle this problem is by running the meta-level and the object level concurrently. However, concurrency introduces many synchronization issues in order to effectively modify the cognitive layer without impeding its performance. (2) Making the best use of the reasoning trace, especially for long-duration missions producing very long traces. (3) Exploring which expectations are needed at the metacognitive level, and how to compute/obtain them.