Enabling Distributed Cognitive Collaborations on the Semantic Web

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ABSTRACT

To date research on improving the state of multi-agent collaboration has only focused on the provision of grounding tools, technologies, protocols, standards and infrastructures that drive the Semantic Web and agent architectures. The basic cognitive and interactional requirements of agents have been neglected leading to the current state-of-the-art development of the Semantic Web whereby its full potential is constrained by the rigid state of multi-agent collaboration. This chapter illustrates and discusses an alternative approach to the development of the agent mediated Semantic Web. The fundamental premise of our approach is that enhancing agents cognitive and interactional abilities is the key to make the digital world of agents more flexible and adaptive in its role to facilitate distributed collaboration. The novelty of this research is that it adapts cognitive models from HCI to develop a heuristic framework called Cognitive Modelling of Multi-Agent Action (COMMAA) for modeling agents’ actions in an attempt to provide an architecture that improves the flexibility of Multi-agent interaction by promoting cognitive awareness. The results of the evaluation show an improved flexibility, interoperability and reusability of agents’ collective behaviours and goals.

INTRODUCTION

Agents may be autonomous and intelligent entities which typically operate in distributed collaborative environments called Multi-Agent Systems (MAS) which allows multiple heterogeneous agents to collaborate by engaging in flexible, high-level interactions (Wooldridge, 2002; Jennings 2000).
Presently, the usability of agent-based applications in a Semantic Web environment is limited due to lack of flexibility in agent’s collaboration with multiple agents including humans. This imposes constraints on the interoperability and reusability of agents’ behaviour that operate in MAS environment. In addition, the inflexibility of the agents’ behaviour does not provide direct mapping to the end user since the end user cannot predict how the agent will behave, thus generating cognitive overload on humans. To date, research on improving the state of multi-agent collaboration has only focused on the provision of grounding tools, technologies, protocols, standards and infrastructures that drive the Semantic Web and agent architectures. Neglect of basic cognitive and interactional requirements are discovered to be the basic reasons for the rigid state of multi-agent collaboration constraining its full potential.

This research presented in this chapter adapts a distributed cognitive view of the agent mediated Semantic Web and argues that enhancing cognition is the key to make the digital world of agents more flexible and adaptive in its role to facilitate distributed collaboration. To this end, work on imparting cognition to improve interaction between multiple agents has been limited. The novelty of this research is that it adapts cognitive models from HCI to develop a heuristic modelling framework for COgnitive Modelling of Multi-Agent Actions (COMMAA) in an attempt to provide an architecture that improves the flexibility of Multi-agent interaction by promoting cognitive awareness. The highlight of the framework is that it identifies architectural and knowledge-based requirements for agents to structure ontological models for cognitive profiling in order to increase cognitive awareness between themselves, which in turn promotes flexibility, reusability and predictability of agent behaviour. The ultimate aim is towards applications which advocate user-centeredness such that as little cognitive overload is incurred on humans.

The Semantic Web is used as an action mediating space, where shared knowledge base in the form of ontological models provides affordances for improving cognitive awareness.

Based on the rationale and concerns described above, the objectives and a brief outline of the chapter presented in the next section.

OBJECTIVES OF THE CHAPTER

The following chapter will serve the following aims and objectives:

- Delineate upon the current limitations in the state of multi-agent collaboration in order to elaborate the rationale, need and the synergistic role of cognitive dimension to the Semantic Web with particular regard to distributed collaborations amongst agents
- Describe the conceptual constituents of a theoretical framework called Cognitive Model of Multi-Agent Action (COMMAA) derived from cognitive models in HCI to improve the state of multi-agent collaboration
- Detail upon the Design and Implementation of Semantic Representational and Ontological Models based on the theoretical principles of COMMAA that allow cognitive processing of an agents action using state of the art Semantic Web technologies
- Describe heuristic reasoning mechanisms that can be derived from cognitive models to enhance the cognition of Semantic Web agents
- Analyze and discuss the impact of using COMMAA to model multi-agent collaborative applications on the Semantic Web

BACKGROUND

The Semantic Web vision of Berners Lee (2001) has enabled the Web applications to move from a
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purely human user community towards a mixed user community consisting of humans as well as of software agents. This imposes certain challenges and brings new requirements towards models for modelling Semantic Web-based systems (Scott et al. 2005; Klein et al. 2004; Neuhold 2003). The foremost issue is that of adaptive collaborative coordination and cooperation for utilizing services and Web information and imposes challenges from the perspective of interaction as well as interoperability amongst both agents and humans (Arai & Ishida 2004). As software agents become more capable and more prevalent, they must be able to interact with a heterogenous collection of both humans and software agents, which can play diverse roles in a system, with varying degrees of autonomy, initiative, and authority across different tasks (Schreckenghost et al. 2002). However, research supporting such interaction with these types of agents has received relatively little attention (Martin et al. 2003a; 2003b).

Limitations in the State of Multi-Agent Interaction

While there has been a significant proliferation of agent architectures and applications in the Semantic Web domain, there is significant separation of concerns from the principles that ensure flexibility of distributed interaction between heterogenous agents. Recently, much effort has been expended on making agents interoperate in the emerging open environments and standards. The Foundation for Intelligent Physical Agents (FIPA), an IEEE Computer Society standards organization, has attempted to facilitate the interoperation and inter-working between agents across multiple, heterogenous agent systems (FIPA, 2007). A variety of FIPA-Compliant platforms have emerged (Luck et al (2005) provide a review). Despite this effort, this goal has still not yet been achieved as Louis and Martinez (2005a) point out. In addition, the Agentcities European project (Willmott, 2003) which resulted in the deployment of a worldwide open testbed environment, underlined the lack of ‘spontaneous’ exchanges between agents running in this environment. In almost all cases, agents can only interact with agents they have been designed to interact with. One reason is that agents are implemented using mechanisms such that they conform to only a limited set of interaction protocols generally resulting in inflexible or rigid agents. It is reported in research and learnt from previous experience (Ahmad et al. 2005, Shafiq et al. 2005, Tariq et al. 2005a, Tariq et al. 2005b) that the agents show unyielding behaviour to messages not specified by the protocol. Efforts such as Louis and Martinez (2005a; 2005b) have attempted to address the issues but the focus has been largely to provide semantic handling of messages.

It is therefore believed that there is still a long way to go before true homogenisation of agent communities can be achieved. This is because the variance of agent communication and functional pragmatics introduces a certain level of mismatch and the need of flexible and adaptive interactions that promote interoperation becomes imperative. This is particularly essential when the agents from diverse platforms intend to co-exist and cooperate in mutual. In addition, most agent-based applications assume pre-defined knowledge of agents’ capabilities and/or neglect basic cognitive and interactional requirements in multi-agent collaboration. Thus the research community is faced with the challenges of improving the limited visibility of agent’s processing ability and behaviours that may be a result of possible mismatches between the agents’ mental and implementation models. In addition, it is claimed that inadequate adjustability of the agent’s autonomy and a basic lack of compatibility between the required capabilities and those provided by an agent impose further research challenges (Martin et al. 2003a; 2003b).
Potential of Cognitive Models to Improve the State of Multi-Agent Interaction

Some interdisciplinary research has stressed the potential of cognitive models studied in cognitive science as substantial means of better probing multi-agent issues, by taking into account essential characteristics of cognitive agents and their various capacities (Sun 2001). The term cognitive models has traditionally been associated with humans as cognition is essentially a human characteristic. Cognition can be thought of as a modelling process which creates a model from which deductions can be drawn (Meredith 1970). Humans are known to continually create and access internal representations of their current situation - referred to as their cognitive model (Saja 1985). It is said that the state of interaction with a system can be greatly improved by design activities that account for and support the emergence of a user’s cognitive model. These models are referred to as mental models in human-computer interaction (Norman 1986; 1988).

Inspired by the potential of cognitive models, the research presented in this chapter investigates the possibility of meeting the above mentioned challenges by bringing cognitive models and theories in the Semantic Web to achieve more robust and effective architectures for agents that facilitate distributed collaboration - be it amongst agents or between agents and humans or vice versa. The premise of the research is based on the hypothesis that if artificial (or software) agents were to be designed to emulate the interactional and cognitive properties of humans in a complementary way, such that they interact with each other and their environment in the manner that humans do, it would increase their functional capability to serve humans. Additionally it would also reduce the cognitive load that humans require in distributed collaborations while viewing it from a distributed cognitive perspective.

RESEARCH MOTIVATION AND CONTEXT: DISTRIBUTED COGNITIVE VIEW OF THE AGENT MEDIATED SEMANTIC WEB

The view adapted for Semantic Web is that of a world-mediating system as it mediates between users and a part of the world, often by manipulating machine representations of the world (Clark, 2001). At the basis of this research is the idea to view the Semantic Web as a distributed cognitive system, a basic unit of analysis, composed of human and machine agents in a work domain that is delineated by roles, work and communication norms, artefacts, and procedures (Zhang et al, 2002).

According to (Lu, Dong & Fotouhi 2002) the Semantic Web uses ontologies to describe various Web resources, hence, knowledge on the Web is represented in a structured, logical, and semantic way allowing agents to navigate, harvest and utilise this information (Payne, et al., 2002a;2002b). Agents can also read and reason about published knowledge with the guidance of ontologies. Also the collection of Web-services described by ontologies like OWL-S (Ankolekar et al. 2001; Martin et al. 2005;2007) will facilitate dynamic matchmaking among heterogeneous agents: service provider agents can advertise their capabilities to middle agents; middle agents store these advertisements; a service requester agent can ask a middle agent whether it knows of some provider agents with desired capabilities; and the middle agent matches the request against the stored advertisements and returns the result, a subset of the stored advertisements (Sycara et al. 2002;1999).

Based on the analysis of literature and state of the art, agent-mediated distributed computing paradigm for the Semantic Web is viewed as a layered abstract architecture shown in Figure 1 -a lens through which multi-agent collaboration can be viewed. Applying the distributed cognitive view of Semantic Web, the abstract layered model
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revises the traditional view of the Semantic Web by adding cognitively modelled interactions.

The above abstract model of the Semantic Web and agent characteristics requires multi-agent interaction which can consist of three interaction levels: human-human, human-agent, and agent-agent. In each interaction level, both interaction design and interoperability are necessary for mutual accessibility and understanding among them as has also been highlighted by Arai & Ishida (2004). The chapter extends the vision for the need and requirements for modelling these interactions from a distributed cognitive perspective (Basharat and Spinelli, 2008a). By applying the Distributed Cognition perspective Chandrasekharan (2004) this model considers the importance of studying interaction and interoperation amongst multi-agents not in isolation but within the environment agents inhabit. The combination of the Semantic Web inspired by cognitive model can generate a framework where agents and application can better cooperate.

After a review of the available cognitive approaches that model human activities in interaction with any system (artefacts and the environment), the Action Cycle (AC) (Norman 1986; 1992) has been selected as the most promising approach for this research. The aim is to unfold the potential of the AC in an attempt to identify the design and interactional gaps between heterogenous agents on the Semantic Web. The resulting contribution lies in the adoption of the AC to develop a heuristic modelling framework called COgnitive Model of Multi-Agent Actions (COMMAA).

The framework is proposed to model multi-agent actions in a collaborative MAS environment from a cognitive perspective. The framework is intended to aid the designer in modelling the agent behaviour and action through a cognitive cycle. Using the principles of the proposed

Figure 1. Layered Abstract Model for illustrating various levels of Cognitive Collaborations in Agent Mediated Semantic Web

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**Figure 1. Layered Abstract Model for illustrating various levels of Cognitive Collaborations in Agent Mediated Semantic Web**
framework designers can define both functional and non-functional aspects of the design of an agent’s interactive role in a collaborative scenario, especially focusing on the concepts of semantic and articulatory distances, as derived from AC, as mismatch between agents’ goals and its functional capabilities.

Not only this research proposes the theoretical guidelines for cognitive modelling of agents, it also provides design illustration for the architectural elements necessary for realizing these principles in the Semantic Web context. Thus the framework identifies architectural and knowledge-based requirements for agents to structure ontological models for cognitive profiling in order to increase cognitive awareness amongst agents. By cognitive awareness, a term coined within this research, it is intended the ability of the Web agents to diagnose their processing limitations and to establish interactions with the external environment (in the form of other agents including humans and software agents) using the principles derived from the framework for COMMAA. This is with the aim to support users’ goals in a more direct manner by providing agents that can share, discover and access each other’s capabilities in a collaborative manner and are able to function dynamically and adaptively without continuous human intervention.

This brings about a more effective MAS environment; where agents may delegate each other tasks and goals based on each other’s awareness of abilities, behaviours and affordances. The ultimate aim is towards applications which advocate user-centeredness such that as little cognitive overload is incurred on humans. The strength of this framework lies in its robust theoretical foundation that has found validation in a developmental infrastructure that helps realise the theoretical principles.

**THEORETICAL FRAMEWORK AND CONCEPTUAL CONSTITUENTS FOR COGNITIVE MODEL OF MULTI-AGENT ACTIONS (COMMAA)**

The framework developed in this work and presented below is based on these fundamental principles of Agents’ action, borrowed and modified from the Human Action Cycle (Norman 1986) and its elaboration for Direct Manipulation Interfaces by Hutchins et al. (1986). The framework of COgnitive Model of Multi-Agent Actions (COMMAA) is shown in the Figure 2. The primary aim of the framework is to cognitively model the agent’s action in a collaborative MAS environment situated in the Semantic Web such that the limitations in the state of Multi-Agent Interaction can be overcome.

The conceptual constituents of the framework of COMMAA include:

- **Cognitive agent Action Cycle (CogAC):** COMMAA is based on Cognitive agent Action Cycle (CogAC) which serves as the fundamental core of the framework, and is designed to aid the designer elaborate the agent’s functional behaviour using two stages namely Execution and Evaluation, each with its respective steps. The CogAC views agent as the primary entity that interacts and functions in a MAS environment. The stages of an agent interacting with a MAS environment are described such that in order to accomplish a goal, which is in turn delegated to it by a human user, the following steps are traversed by an agent: Goal Formation, Intention formation, Action specification, Execution, Perception, Interpretation and Evaluation.

- **Cognitive Distance Model (CogDM):** The further elaboration of the steps of CogAC leads to the formulation of agent’s semantic and articulatory disposition in each stage of execution and evaluation, described and
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Illustrated by the Cognitive Agent Distance Model CogADM. These dispositions also help to identify the agent’s Gulf of Execution and Evaluation. These two are discussed in the subsections to follow.

- **Cognitive Agent Design Principles:** The principles are derived using the Action Cycle mapped for agents. The principles may serve as heuristic for evaluating the design of agent-based applications. They help to identify the significant mismatches, constraints and affordances. The framework defines CogADPs only at abstract level. These serve as blueprints which may be specialised to a domain specific context by the designer to derive a context specific cognitive profile for an agent. These may be specialised according to the domain knowledge and the specific contexts of application the agent may be operating in. The design principles aid in Cognitive Mismatch (Distance) Analysis, that allow at design time to be made known the possible stages where distance of execution or evaluation may occur. The designer by analyzing whether provision for these principles in made in the agent’s infrastructure can help develop the cognitive profile of the agents, alternatively agents may have the dynamic capability of identifying these distances at runtime and may change, update their profile dynamically.

- **Agent Architectural Elements:** As each sub-stage of agent’s execution and evaluation stages are elaborated, and as distances are identified, it helps in identifying the architectural needs and components required for successful completion of agent action cycle. As these are identified by the designer, they may be cross checked against the environment that the agent in being built using. In other words, it may also be said that provision

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**Figure 2. Conceptual design of Theoretical Framework / Conceptual Constructs of COMMAA – Cognitive Model of Multi-Agent Action**

![Diagram of COMMAA Framework](image-url)
of these capabilities ensure that the agent’s Cognitive Design Principles will be met to some extent. The availability of these elements would ensure that the agent is Cognitively Directed, or Cognitive Directness is exhibited in agent’s action with respect to its interaction with the environment. The Architectural elements identified ensure the minimal design requirements that must be met in order to bridge the agent’s gulfs of execution and evaluation.

- **Agent Knowledge Elements:** The knowledge requirements are identified by the designer such that at each stage of agent’s execution and evaluation, these are the elements that the agent must possess or must be provided with in order to achieve the successful realisation of the respective stage.

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**Cognitive Agent Action Cycle (CogAC)**

Agents are designed to continually act upon and monitoring the MAS Environment, interacting with it and collaborating with other agents and entities, evaluating its state, and executing actions. The system is a closed loop: when agents act, it is usually done so in response to some prior evaluation of its perceptions or as a result of some goal delegated to it by a human. After an agent acts, it evaluates the impact of the executed act, often modifying the action as it carries it out. In MAS environment the fundamental unit of agent’s social ability is its interaction with other agents using messages in Agent Communication Language (ACL). Agent’s Interaction is modelled to have two stages as shown in Figure 3. The Interaction will have some Goal i.e. the objective that needs to be achieved using the interaction. In order to achieve this goal, agent will need to go through the two stages namely Execution and Evaluation.

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**Figure 3. High-level conceptual design of CogAC in relation to other constructs of COMMAA**
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in order to successfully achieve the goals of the interaction respectively.

The stages of an agent interacting with a MAS environment are described such that in order to accomplish a goal, which is in turn delegated to it by a human user, the following steps are traversed by an agent: Goal Formation, Intention formation, Action specification, Execution, Perception, Interpretation and Evaluation (as shown in Figure 3.). The essential concepts are the Gulfs of Evaluation and Execution, each arising as a result of semantic and articulatory distances (cognitive distances in general). The relevance of these concepts to the agent domain is formally described in the next sections in the form of Cognitive Agent Distance Model, which are detailed further.

The inter-relationship between the CogAC, its stages of execution and evaluation, the semantic and articulatory dispositions and other elements of COMMAA is schematically shown in Figure 3. In Table 1 and Table 2 these stages are elaborated.

In addition, a generic view of the corresponding CADPs, Knowledge Requirements and architectural needs are also identified. Together with these main components, the three additional components are identified to help the designer model agents’ behaviour in a more robust manner. Cognitive Agent Design Principles, Agent Architectural Elements and Agent Knowledge Elements are all identified, as each stage of the agent’s execution and evaluation are elaborated upon.

Cognitive Agent Distance Model (CogADM)

On the Semantic Web, Knowledge is invisible and intangible. While meanings are essential to knowledge, they cannot get across to an agent without some kind of representational form. Knowledge representation has two aspects: the meaning of the information, named semantics, and the physical form or appearance, named syntax.

Table 1. Steps of CogAC in Execution Stage (Agent’s Gulf of Execution) cross referenced with design principles, Knowledge elements and Architectural requirements

<table>
<thead>
<tr>
<th>Steps of CogAC</th>
<th>Description</th>
<th>Cognitive Agent Design Principle (CADP)</th>
<th>Agent Knowledge Elements</th>
<th>Agent Architectural Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Execution Stage (Agent’s Gulf of Execution)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Step 1: Form Goal</strong></td>
<td>An Agent’s Goal is the state the agent wishes to achieve</td>
<td><em>Compatible goal formation</em></td>
<td><em>Task Knowledge</em>; <em>Intention formation</em></td>
<td><em>Goal Representation</em>; <em>Intention Formulator</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Agent must have the capability to express goals to desired intentions</em></td>
<td><em>Appropriate Situation</em>; <em>Intention formation</em></td>
<td><em>Task Representation</em>; <em>Intention Representation</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Semantic Distance Occurs if the capability is not provided to the agent</em></td>
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<tr>
<td></td>
<td></td>
<td><em>Agent is being required to work at lower level of detail resulting in greater semantic distance</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Step 2: Form/Specify Intention</strong></td>
<td>The decision to act as to achieve the goal</td>
<td><em>Exhibit Semantic Directives of Interaction with the Environment</em> (Characteristics of Agent is Semantically Directing its execution of its intentions in the given environment)</td>
<td><em>Task Knowledge</em>; <em>Intention details</em></td>
<td><em>Content Representing the Intentions, as rules or some contract</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Functional Capability for Intention formation</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Step 3: Action Specification</strong></td>
<td>The process involved in determining the logical representation of the actions that are to be executed by the agent on the multiagent system (MAS environment)</td>
<td><em>Conclusion Imposed by the environment or the world of the agent (may be taken into account)</em></td>
<td><em>Task Knowledge</em>; <em>Action Details</em></td>
<td><em>Actions Represented as a set of protocols</em> of Interaction/Interactions/Mechanisms</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Articulatory Directiveness</em> (Plans of Agent is does not pass any articulatory distance even to execution of its actions in the given environment)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Affordance for Action</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Step 4: Execution</strong></td>
<td>Agent executes the plans formulated as a result of action specification</td>
<td>Using the MAS Environment and the middleware to execute its actions</td>
<td><em>Knowledge of Execution/Interaction Mechanisms</em></td>
<td><em>MAS Middleware  Execution Framework</em>; <em>Control Mechanism for Agent’s Execution</em></td>
</tr>
</tbody>
</table>
When an agent interacts with a knowledge representation, it interacts with both the semantics and the syntax.

There is often, however, a gap, known as Cognitive Distance, between the knowledge an agent needs and the manner in which this is represented in its environment, as shown in Figure 4. This manner of representation also includes the mechanisms with which the knowledge is accessed and reasoned about.

The prospective relevance of the cognitive distances is highly relevant to Communication, collaboration and interactions taking place between agent application residing on the Semantic Web - since the basis of interaction is the communication language and its vocabulary represented as knowledge on the Semantic Web.

Cognitive Distance in this context is taken to be a measure of the gulfs of execution and evaluation

—the conceptual gap, or mismatch between the agent’s goals and intentions, and the way in which they are in cohesion to, or represented by, the multi-agent system environment. A large distance is representative of a large gulf in the execution or evaluation stages, signifying that a lot of cognitive load is incurred in translating the agent’s intentions into the system’s representations, or vice versa.

That is, a large distance of execution means it is relatively difficult or not possible for the agents to express their query or desires to the system, and

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Table 2. Steps of CogAC in Evaluation Stage (Agent’s Gulf of Evaluation) cross referenced with design principles, Knowledge elements and Architectural requirements

<table>
<thead>
<tr>
<th>Steps of CogAC</th>
<th>Description</th>
<th>Cognitive Agent Design Principle (CADP)</th>
<th>Agent Knowledge Elements</th>
<th>Agent Architectural Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 5: Perception</td>
<td>• Perceive the output, response of an event: a trigger or a message</td>
<td>• Affordance for perceiving the state of the environment</td>
<td>• MAS/Platform Knowledge: Constructs, Content, Protocols</td>
<td>• Means of Feedback Specification</td>
</tr>
<tr>
<td>Step 6: Interpretation</td>
<td>• The relationship between the state of the MAS environment and the goals of the agent can only be determined by first translating the environment state into psychological states for the agent then interpreting the perceived environment state in terms of agent’s variables of interest.</td>
<td>• Articulatory Directedness (Disposition of Agent does not exhibit Articulatory distance wrt to evaluation of its actions and the response of the environment) • Affordance for Reasoning • Affordance for extracting the required meaning from interaction output • Affordance for Interpretation of Feedback of the Interaction</td>
<td>• Domain Knowledge: Expected effects</td>
<td>• Means of Interpretation • Reasoning Mechanism for Interpretation • Logic Mechanism • Feedback Means • Means to Recognize and Interpret Feedback • Interpretable effects</td>
</tr>
<tr>
<td>Step 7: Evaluation</td>
<td>• Evaluation of the environment state requires comparing the interpretation of the environment state with the desired goals. This often leads to a set of new goals and intentions.</td>
<td>• Agent’s Functional Capability for Evaluating the Outcome to determine if the goal has been achieved and to determine if it possesses the means to predict the outcome • Semantic Directedness (Disposition of Agent is Semantically Direct wrt to evaluation of its actions and the response of the environment)</td>
<td>• Task Knowledge: expected effects • Expected feedback</td>
<td>• Logics based on which Evaluation is to be carried out • Heuristic Logics • Representational Logics • Expectation Means • Predictability</td>
</tr>
</tbody>
</table>
a large distance of evaluation indicates mismatch of some form within the agent’s infrastructure to interpret or evaluate the system’s output or response as a result of some interaction with it.

**Directness of Agent’s Interaction with MAS Environment**

Using the directness of interactions as usability measures would involve understanding the agent’s problem solving strategies, approaches and intentions as now well the MAS environment supports the agent’s functional needs. A design and evaluation methodology that assesses directness requires cognitive basis because understanding the user’s mental processes is key to assessment. The concept of directness as suggested by (Hutchins et.al, 1986), and later by (Cuomo 1993) is adapted here to refer to the degree of capacity of an agent to bridge the Gulfs of Execution and Evaluation.

The concept of multi-agent interaction is virtually an unexplored area in terms of operationally defining and assessing the directness of interactions an agent engages in with its MAS environment to a degree that can be applied in practice and measured using qualitative or quantitative tools. Directness of an Agent’s Interaction with its environment may be used as a qualitative indicator of the amount of cognitive processing needed to carry out a successful interaction. Directness is inversely proportional to the amount of cognitive processing it takes to manipulate and evaluate the results of agents’ interaction with its MAS environment. Moreover the cognitive processing required for an agent is a direct result of the gulfs of execution and evaluation the agent has to deal with. The better the agent’s architecture, the less cognitive processing needed and the more direct the resulting interaction between agents.

Thus Distances are complementary to Directness; the lower the distances, the greater the directness, and vice-versa. The two terms distance and directness may be alternatively used, depending on the nature of mismatch or the extent of gulf in the stages of agent action. It would be subsequently shown in the later sections how these concepts are encoded into the profile of agents and how the concepts are important to derive heuristic mechanisms for agents’ reasoning.

**Applying the Gulfs of Execution and Evaluation in Multi-Agent Environment**

In order to identify gaps that separate agents mental states from execution ones, the agent’s gulfs of execution and evaluation must be detailed as below:

**Agent’s Gulfs of Execution:** The gulf of execution arises as a result of cognitive distances of execution between the agent and its interaction with the environment (multi-agent, open). The gulf can be identified by elaborating the cognitive distances of execution – which result due to the
difference or mismatch between the intentions and the allowable, available actions, capabilities and affordances in its environment. One indicator representing this gulf is to determine how well the agent is able to do the intended actions directly, without extra effort: is the agent able to fulfil its goals delegated to it by humans? Do the actions provided by the agent match those intended by the person? Does the environment/infrastructure (internal infrastructure and/or external environment) provide affordances that allow for the intentions of the agent? If there is a limitation, then there is a gulf of execution in the state of agent’s interaction which must be bridged, either with collaborative effort with other agents in the environment or eventually by the human, who would incur cognitive overload or processing. The ultimate aim is to design agents that are able to readily identify and bridge/overcome such a gulf to efficiently achieve the goals set up for them.

Agent’s Gulfs of Evaluation: The gulf of evaluation arises as a result of cognitive distances of evaluation between the agent and its interaction with the environment (multi-agent, open); the possible mismatches between agents reasoning capabilities and its representation mechanisms. The Gulf of Evaluation reflects the amount of effort that the agent must exert to interpret the state of its interaction with the system and to determine how well the expectations and intentions have been met. The gulf is smaller when the system provides information about its state in a form that is easy to get, is easy to interpret and matches the manner in which agents’ affordances allows these to be perceived.

Bridging the Gulfs and the Cognitive Distances

Directness is inversely proportional to the amount of cognitive effort/processing it takes to manipulate and evaluate the state of interaction with MAS Environment and, moreover, the cognitive effort is a direct result of the gulfs of execution and evaluation. The better the architecture and the environment of the agent helps the agent bridge the gulfs, the less cognitive processing needed and the more directed the resulting interaction. For this, the architecture should facilitate some means of identify, through some indicators, the possible distances and also identify the capabilities and affordances available and not-available corresponding to these indicators.

Agents’ Capabilities and Affordances

The concept of affordance is here explored and exploited. It is believed that an affordance inspired agent architecture and environment will help to bridge the gulfs of execution and evaluation. By interfacing perception and action in terms of capabilities and affordances for agents, the aim is to provide a new way for reasoning about agent’s capacities and bring about cognitive awareness amongst the agents about each others capacities and constraints, when interacting in a collaborative environment. In Cognitive Science, an affordance is a resource or support that the environment offers an agent for action, and that the agent can directly perceive and employ (Gibson, 1979). Although, this concept has only rarely been used in Semantic Web agent architectures, it offers an original perspective on coupling perception, action and reasoning, differing notably from standard reactive and hybrid architectures. Taking it literally as a means or a metaphor for coupling perception and action directly, the potential that affordances offer for designing new powerful and intuitive agent-based Semantic Web architectures is obvious (Vugt et al. 2006).

The term affordance is adapted for COMMAA to refer to the agent’s capacity of action. At each stage of the agent action cycle the agent’s corresponding affordance is determined and accounted for. Any constraint in any of the agent’s capacities, being the ability to achieve the goal, to formulate the intention or to interpret the consequences of
its action, may result in a cognitive distance being introduced. Usually the term affordance is linked to a machine or an application (Norman 1992). In the context of this research affordance is the ability of one agent (the sender) to behave in a way that the other agents in the MAS environment (the receiver) can understand, such that they both have a shared mental model and can trigger, complement or facilitate each other’s action/behaviour; therefore these affordances need to be ensured. The affordances are provided by the cognitive artefacts that form part of the agent’s internal infrastructure/architecture and its external environment.

Affordances are the opposite concept to distances, so they are complimentary. For instance, an agent’s affordance for intention formation will ensure there is no semantic distance of execution and a semantic distance of execution will mean that agent has no affordance for forming an intention. The psychologist Gibson was the first to frame affordances as unified relations between the environment and an actor (Gibson, 1979, p. 127). Affordances can be explained as action possibilities that actors have in the environment. That is, an affordance exists relative to (1) properties of the environment and (2) the action capabilities of an actor (McGrenere & Ho, 2000). For example, a chair has the affordance of ‘sitting’, because of its shape, height and carrying capacity and because of the humans’ ability to sit, the length of their legs, and their weight. The concept of affordances is of particular interest in the field of HCI, which primarily concerned is studying how properties of computers (the environment) and humans (actors) influence their interaction with each other.

Extending the affordance concept to the Semantic Web, it is believed that by semantically identifying and encoding the affordances of an agent will help achieve cognitive directness of interactions amongst the agents. This will contribute to making agents more interoperable in open and heterogenous environments. Some considerations that must be taken into account include the relationship of goals with respect to agents. Goals are central in affordance evaluations. It is important to understand that an affordance does not change as the needs and goals of the person change (McGrenere & Ho, 2000 interpreting Gibson, 1979). Similarly, for an agent, an affordance must be identified irrespective of what the agent’s eventual goals are. E.g. if an agent affords Message translation from FIPA-ACL into FIPA-SL, it is independent of whether another agent will eventually participate in such interaction where this translation is required. However, agent’s actions do depend on the goal context. Agents will typically need to act within the environment (they use an affordance) because of a goal they want to achieve for example, performing a task (Vugt et al. 2006, Kakazu & Hakura 1996).

**Semantic and Articulatory Distances in Multi-Agent Interaction Model**

Following is a detailed account of how may the components of cognitive distance namely: the Semantic and the Articulatory distances occur in the execution and the evaluation cycles. It is also important to illustrate how the cognitive distances are identified with the help of agents’ capabilities and affordances. A conceptual high-level view is shown in Figure 5. Identifying these distances, along with agents’ capabilities and affordances is of primary importance in highlighting the possible gulfs of evaluation and execution.

- **Semantic distance**: The degree to which the semantic concepts used by the agent are (1) compatible with those of the other agents (including humans if the interaction is being carried out with a human) and, (2) can be used to easily accomplish the agent’s goals
- **Articulatory distance**: The degree to which the form of communication between an agent and its environment reflects the application objects and tasks involved
Articulatory distance concerns the actual form that communication takes between say two agents; for example, the choice of Message Encoding, Message Content, Content Type, Interaction Protocol used/employed for the communication. A small articulatory distance results when the input techniques and output representations used are well suited to conveying the required information. Articulatory distance is also decreased when the form of inputs and outputs relate to the semantic concepts used of the underlying conceptual model.

Semantic distance involves the capability of agents required to express desired actions within the concepts of the system. It deals with the possibility to express the concepts of interest concisely using the available capabilities. Semantic distance also involves a measure of how closely the agent’s conception of the task domain matches that of the environment. The two distances that compose the Cognitive Distance in Agent’s Behaviour are the Semantic Distance and Articulatory Distance. These can be considered as subsets of each of the gulfs, but in reference to input behaviour (initiator’s behaviour in communication/interaction) and output behaviour (Respondent’s behaviour in communication/Interaction). These are illustrated and discussed in depth below.

An Illustration of Semantic Distance of Execution

Semantic Distance relates to the relationship between an agent’s intentions and the meaning of expressions, required to convey the agents’ intention such that its meaning is interpretable by the intended recipients in the environment. Semantic distance is related to the ‘nouns’ and ‘verbs’ or objects’ and ‘actions’ provided by an agent’s infrastructure and its environment. For execution, forming an intention is the activity that spans semantic distance. The intention specifies the meaning of the input expression that is to satisfy or reach the agent’s goal or sub-goal.

If semantic indirectness of execution existed, agents would not be able to express their intentions directly, or at all in order to achieve the goal delegated to them. Lack of capabilities or affordances would be indicators of this condition. Agent is programmed at lower level of functionality than desired by the human user. The agent or the human may need to carry out more actions...
then would be expected to accomplish the same goal or intention. E.g. Agent may need to collaborate or request another agent to achieve the goal on its behalf. This requires agent to have desired affordances and capabilities defined. The semantic distance of execution is illustrated in more detail in Figure 6.

An Illustration of Articulatory Distance of Execution

Whereas semantic distance relates to relationships between Agents’ formulated intentions and the meanings of expressions/functional capabilities available, articulatory distance in an agent context is defined to relate to relationships between the meanings of expressions/capability and the agent has the affordance to realise the capability in action, or whether agent affords the actions that are essential in achieving the desired intentions. A mismatch of such a form will cause an articulatory distance of execution to exist. The articulatory distance of execution is illustrated in more detail in Figure 7.

An Illustration of Semantic Distance of Evaluation

Semantic distance also occurs on the evaluation side of the interaction cycle. Semantic distance of evaluation is proportional to the amount of processing required by the agent to determine whether the goal has been achieved. The semantic distance of evaluation is illustrated in more detail in Figure 8.

An Illustration of Articulatory Distance of Evaluation

Articulatory distance or indirectness of evaluation would be indicated by errors in interpretation and having to take extra actions to correctly interpret the state of communication or the result of interaction. An agent’s inherent articulateness is closely tied to its level of technology. The articulatory distance of evaluation is illustrated in more detail in Figure 9.

Figure 6. An illustration of agent’s semantic distance of execution
Enabling Distributed Cognitive Collaborations on the Semantic Web

Figure 7. An illustration of agent’s articulatory distance of execution

Figure 8. An illustration of agent’s semantic distance of evaluation
Enabling Distributed Cognitive Collaborations on the Semantic Web

Figure 9. An illustration of agent’s articulatory distance of evaluation

DESIGN AND IMPLEMENTATION OF COMMAA INSPIRED AGENT ARCHITECTURE

Design Goals for Cognitive Profiling of Agents

The theoretical foundations of Cognitive Models such as the Action Cycle (AC) bring about important implications in the current Semantic Web architectures. Traditional Web-service agent architectures only allow agents to discover about each others services. However this research claims that an architecture that is inspired from cognitive models would allow the agents to develop a cognitive awareness about each other which could bring to a more effective MAS environment. To validate this claim, a lower-level classification of design goals which provide the basis upon which the Cognitive Profiling Architecture is devised upon includes: (a) Enhanced Negotiation and Collaboration based on Cognitive Awareness (b) Flexibility and Reusability (c) Adaptive Interaction and Interoperability (d) Discovery based on Heuristic reasoning and (e) Minimization of cognitive load on humans.

In an attempt to realise the above design goals, which are direct implications of COMMAA, some important considerations are taken into account. Firstly, some mechanism is needed that enables the agents to discover and find out about each others cognitive distances, semantic and articulatory dispositions, capabilities, affordances and constraints. Secondly, dynamic and built in mechanisms are needed for heuristic reasoning and invoking/developing learning, adaptive measures for these constraints and distances to be bridged. These considerations are considered rudimentary to enable agents to be aware of these limitations and Guls that may limit their functionality or the extent of services they can provide. As minimal architectural consequences, the elements necessary in COMMAA inspired semantic-Web agent architecture are implemented in a cognitive profiling architecture described in Basharat and Spinelli, (2008b). The Cognitive Profile of Agents is detailed next.
A Semantic Representation Model for Cognitive Profile of Agents

A possible way of implementing the cognitive profile is by associating an ontology with an agent, i.e., agent is given knowledge about its constraints and affordances, its semantic and articulatory disposition. At the heart of the framework is the adoption of ontology to drive the cognitive profile of agents. From a philosophical perspective, ontology can be defined as a set of things whose existence is acknowledged by a particular theory or system (Honderich, 1995 cited in Bell et al. 2007). Such ‘things’ include both types (such as the class of Agents) and individual elements (such as the agent TravelAgent). The adoption of such a definition is important because, when compared with more computationally orientated definitions of ontology (for example, (Gruber 1993); p.1) states that “an ontology is a specification of a conceptualisation”), there is an explicit reference to a system’s ontic commitment (i.e., things whose existence is acknowledged or recognised). This leads to representations that are more closely mapped to real world objects.

The use of ontology is also prospective in the Semantic Web action space, since the emerging standards enable reasoning to be carried out effectively on such models. An ontology based reasoner could be invoked on the ontology to carryout reasoning using the heuristic reasoning rules defined; agent could then be made to reason about its state of processing according to CogAC. Architectures that facilitate the sharing of ontologies would enable the agents to discover each other cognitive dispositions thus improving the manner in which they interact. The issue at stake is to be able to represent the cognitive profile adequately and in a manner that can be shared among agents. The Cognitive profile is therefore implemented as an Ontology in OWL, with OWL-DL (Description Logics) as basis of representation of the profile parameters and properties. Being an emergent standard, OWL-DL ensures that the model caters for a more open community. Ontologies have been recognised by the research community as a –model of expressing the knowledge model for agents e.g. by the recent research of (Laclavík et al. 2006).

Figure 10. Conceptual Model of Ontological Knowledge Model for Cognitive Profile of Agents
Conceptual Model for Agents’ Cognitive Profile Ontological Model

Figure 10 shows a generic conceptual model, with objects and properties (shown by labels on associations between concepts) of the ontological model to be implemented in order to enable shared cognitive profiling of agents.

Cognitive Profile of Agent

The framework’s correct implementation calls for maintaining a cognitive profile of Semantic Web agent. Following are the elements to be maintained in the cognitive profile:

- Agents Cognitive Mental States
- Capabilities
- Affordances
- Semantic Disposition (Semantic Distances of Evaluation and Execution)
- Articulatory Disposition (Articulatory Distances of Evaluation and Execution)
- Goals, Intentions, Perceptions, Evaluations

Cognitive Mental State of an Agent

An agent modelled along the lines of the CogAC requires various cognitive mental states corresponding to the various steps in the execution and evaluation stages of the action cycle. These mental states of the agent facilitate the agent’s behaviour in both its execution and evaluation cycles. It provides provision for state modelling, representation and tracking an agent’s state of execution. In addition representing these states agents may have the dynamic capability of identifying these distances at runtime and may change and update their profile dynamically. The conceptual model is developed using the Protégé Ontology editor to generate OWL Ontology.
Table 3. Description of Activities in processing agents’ action through COMMAA with input and output artefacts

<table>
<thead>
<tr>
<th>Activities</th>
<th>Description</th>
<th>Input Artefact</th>
<th>Output Artefacts</th>
</tr>
</thead>
</table>
| Cognitive Modelling of Agent Behaviour | ▪ Model Agent’s Action using the CogAC  
▪ The agent’s behaviour is programmed according to the stages described in the CogAC  
▪ Elaborate Agent’s Action with the help of Seven Stages of CogAC  
▪ Identify agent’s knowledge requirements and elements  
▪ As the knowledge elements needed by the agent are identified, it is ensured that the architecture of the agent provides for these knowledge elements to ensure a successful completion of the CogAC  
▪ Program agent’s behaviour according to available architecture | ▪ Agents Functional Requirements  
▪ Agents Knowledge and Representational Constraints  
▪ Cognitive Agent Design Principles. The CADPs are used as heuristics to evaluate the design at each stage | ▪ Knowledge Requirements |
| Scoping the Agent’s Cognitive Profile | ▪ Identify Agents capabilities capacities and affordances  
▪ Identify agents cognitive distances  
▪ Identify known possible agent’s gulf of execution and evaluation  
▪ Each of the components of the Agent Profile are interpreted such that they represent its Ontic Commitment | ▪ Knowledge Requirements  
▪ Agents Functional Requirements  
▪ Agents Knowledge and Representational Constraints | ▪ Individual Agent Cognitive Profile (Ontic Commitment Model) |
| Encoding of Cognitive Profile     | ▪ Encode Agent’s Cognitive Profile parameters in the ontology  
▪ The Disposition of Agent (Semantic and Articulatory) in both stages of execution and evaluation is encoded at design time | ▪ Profile Parameters  
▪ Agents Semantic Disposition  
▪ Agent’s Articulatory Disposition | ▪ Cognitive Profile (Ontic Commitment Model) |
| Sharing the Cognitive Profile     | ▪ Registering or Publishing the profile | ▪ Cognitive Profile | ▪ Shared Cognitive Profile Repository populated with Cognitive Profile of Agent |

Modelling Agents Using COMMAA

In order to utilise COMMAA in practice to process and analyse the interactions and tasks of an agent, the process shown in Figure 11 is used during the design and development process of an agent-based application. The figure also summarises the components and principles that contribute to the agents state modelling, based on the principles of COMMAA. The process is described in detail in Table 3.

Abstract Heuristic Reasoning Mechanism for Agents

To bridge the guls of execution and evaluation, agent must have some heuristic reasoning mechanism built into its architecture, such that given a shared cognitive profile is available, it should be
able to reason on the knowledge present in it to aid the agent’s processing and help bridge the gulfs of execution and evaluation through collaboration or other means. The important considerations are with regards to the representation, discovery and reasoning of the cognitive distances. Rules generate advice by defining the combination of agent knowledge, action stages, distances, abilities/capabilities, and affordances, typically with the generic format shown in Figure 12.

### Heuristic Reasoning Mechanism for Agents Execution Stage

The encoding of agents cognitive distances requires a reasoning mechanism. The reasoning is carried out based on the Semantic and Articulatory disposition of agents encoded in their Cognitive Profile. A reasoning mechanism for the execution stage in the form of pseudo-code is given in Figure 13. This is generic given that the action

---

**Figure 12. Generic Format for Rule-based reasoning of agents’ cognitive mental states**

![Generic Format for Rule-based reasoning of agents’ cognitive mental states](image)

**Figure 13. Abstract Mechanism for Heuristic Reasoning of the Cognitive Profile Model (Execution Stages)**

```plaintext
startCogAC(Goal g0al){
    While (!goalFulfilled)
        {
            - Assert Cognitive Profile
            - Reason
            //Analyze semantic profile
            if (hasSemanticDistance)
                {
                    reviseGoal(g);
                    startCogAC(g);
                }
            else {
                IntentionSet = getIntentionFromGoal(Goal g);
                //Analyze Articulatory Disposition of Execution
                if (hasArticulatoryDistance)
                    {
                        attempt to overcome/bridge using available affordances
                    }
                else
                    search Shared CognitiveModel
            }
        }
    }
```
cycle is applied in a generic context. It may be specialised according to the agent application being developed.

**Heuristic Reasoning Mechanism for Agent Evaluation Stage**

A reasoning mechanism for the evaluation stage in the form of pseudo-code is given in Figure 14.

**DEMONSTRATION OF AGENTS’ ENHANCED COGNITIVE CAPABILITIES**

In order to give a flavour of how the framework presented above enhances the agents’ cognitive capabilities by imparting improved cognition, the framework was applied to a simulated multi-agent based distributed collaborative application with the aim of testing, improving and evaluating the framework. The purpose of this distributed collaborative multi-agent application is as follows:

- To show how the framework is applied to design of MAS based applications operable on the Semantic Web
- To show how application of COMMAA helps build the cognitive profile of the Agent
- Show how sharing the cognitive Profile improves the collaboration between Agents

**High-Level Architecture of Distributed Collaborative Multi-Agent Application**

**Travel Planning Scenario**

The high-level architecture of the travel planning scenario developed to demonstrate the enhanced cognitive abilities of agents is shown in Figure 15 is a customised adaptation from the vision of travel planning agents presented by Hendler (1999).

---

*Response r = getSystemResponse();
PerceptionSet P = convertResponseToPerceptions();
//assert Perceptions
//Perform Cognitive Profile Check;
If(hasArticulatoryDistance)
{
    attemptBridgeGulfEvaluation (P);
}
Else{
    interpretPerception(P);
    if(hasSemanticDistance){
        Goal g = reviseGoal(P);
        g.start();
    } else
    evaluateGoal(G);
}
The top level functional goals of the demonstration application are as follows: The Multi-Agent based application is aimed to use cognitively modelled agents to solve travel problems given by a user. The user can propose to the user Agent his desired travel, and it will obtain a complete plan that includes information about transport, lodging, etc. The agents will extract, filter and store information automatically from the Semantic Web using other agents. The system aims to use the same information that the user could find if he wish planning the travel himself. Cognitive Sharing of different kinds of abilities is to be demonstrated to gain efficiency in the problem solving task. The agents are simulated to reuse each others capacities, behaviours and offer affordances to each other. Agents closely work according to the user’s characteristics, and functions based on the ultimate goals obtained from the user profile and adapt their functional behaviour according to the learned user preferences.

Roles Defined for Agents

Table 4 shows the Roles and Responsibilities defined for Agents involved in Travel Planning Collaboration Scenario. The Collaborative scenario aims integrate the abilities of a set of heterogenous agents. The system is made by a set of agents that can communicate and cooperate among them to reach the problem solution. All the agents in the application use FIPA Based Agent Communication Language for standardization purposes.

Cognitive Profiles of Agents in TPA

The cognitive profile ontology is central to representing the knowledge for agents. The elements of the cognitive profile ontology serve to represent the shared knowledge base of agents through which agents’ cognitive awareness will be enhanced. The cognitive profiles are designed to simulate an environment such that some agents are limited in certain capabilities, while others are equipped...
### Enabling Distributed Cognitive Collaborations on the Semantic Web

#### Table 4. Roles and Responsibilities defined for Agents involved in Travel Planning Collaboration Scenario

<table>
<thead>
<tr>
<th>Agent</th>
<th>Functional Role of Agent in the Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>User Agent</td>
<td>This agent handles a user query and returns the solution. To do so, it analyzes the problem and obtains an abstract representation. Subsequently, it requests a Travel Planner Agent solution to that problem. The User Agent has different skills like communication with Travel Planner Agents and users, or learning the user's profile necessary to customize the system answer. The User Agent also has a set of interfaces to allow input and output information and the user evaluation of the solutions found.</td>
</tr>
<tr>
<td>Travel Planner Agent</td>
<td>The main Travel Planner Agent's goal is reasoning about User Agents and other Travel Planner Agents' problems, and find out a set of possible solutions. Travel Planner Agents have different skills like communication (with different agents in the system), planning (its main reasoning module) and learning.</td>
</tr>
<tr>
<td>Transport Broker Agent</td>
<td>This is a mediator agent, who has the ability of directly communicating with a transport agent and may provide services to some other agent which may not be able to directly communicate with a transport agent thus acting as an intermediary.</td>
</tr>
<tr>
<td>Transport Agent</td>
<td>This agent has the capability of finding desired transport options from the web service providers and provides this information to other agents.</td>
</tr>
<tr>
<td>Translator Broker Agent</td>
<td>This is a mediator agent, who has the ability of directly communicating with a translator agent and may provide services to some other agent which may not be able to directly communicate with a translator agent thus acting as an intermediary.</td>
</tr>
<tr>
<td>Translator Agent</td>
<td>This agent mediates a functionality computational agent on the semantic web which has the capability of performing translation services upon request from one language to another e.g. English to Italian.</td>
</tr>
<tr>
<td>Currency Converter Agent</td>
<td>The role of this agent is to retrieve up to date currency conversion rates from the web and provide currency conversion services to other agents upon request.</td>
</tr>
<tr>
<td>Airline Service Providers</td>
<td>These are agents belonging to organization such as Airlines which maintain up to date information about the accommodation availability, rates etc. and can carry out automated bookings on behalf of their owners.</td>
</tr>
<tr>
<td>Accommodation Service Providers</td>
<td>These are agents belonging to organization such as Hotels etc. which maintain up to date information about the accommodation availability, rates etc. and can carry out automated bookings on behalf of their owners.</td>
</tr>
<tr>
<td>Cognitive Broker Agent</td>
<td>This agent also plays a central role in the collaboration scenario by acting as an index of facilitator for other agents to access other agent's cognitive profile.</td>
</tr>
</tbody>
</table>

#### Table 5. Capabilities and affordances defined for agents in the Travel Planner Application

<table>
<thead>
<tr>
<th>Agent</th>
<th>Goals and Capabilities</th>
<th>Behaviours (Actions)</th>
<th>Affordances</th>
</tr>
</thead>
<tbody>
<tr>
<td>User Agent</td>
<td>Communication Capability</td>
<td>sendMassage, receiveMessage, requestInteractionProtocol, interactionProtocolFIPA-request</td>
<td>hasNo OntologicalAffordance</td>
</tr>
<tr>
<td>Travel Planner Agent</td>
<td>Collaboration Capability, Conversational Capability, canAchieveGoal(GetTravelDetails)</td>
<td>InteractionProtocolFIPA-Contractor</td>
<td>hasNo ComputationalAffordance</td>
</tr>
<tr>
<td>Translator Broker Agent</td>
<td>Conversational Capability, canAchieveGoal(BrokersTranslation)</td>
<td>InteractionProtocol-BrokersTranslation</td>
<td>ComputationalAffordance, CognitiveProfileAffordance</td>
</tr>
<tr>
<td>Cognitive Mediator Agent</td>
<td>Conversational Capability, canAchieveGoal(TravelFacts)</td>
<td>InteractionProtocolFIPA-Request</td>
<td>ComputationalAffordance, CognitiveProfileAffordance</td>
</tr>
<tr>
<td>Transport Broker Agent</td>
<td>Brokage Capability, canAchieveGoal(BrokersTransport)</td>
<td>InteractionProtocol-BrokersTransport</td>
<td>ComputationalAffordance, CognitiveProfileAffordance</td>
</tr>
<tr>
<td>Translator Agent</td>
<td>Computational Capability, canAchieveGoal(TranslateEnglishToFrench)</td>
<td>InteractionProtocolFIPA-Request</td>
<td>ComputationalAffordance, CognitiveProfileAffordance</td>
</tr>
<tr>
<td>Currency Converter Agent</td>
<td>Computational Capability, canAchieveGoal(ConvertPoundsToDollars)</td>
<td>InteractionProtocolFIPA-Request</td>
<td>ComputationalAffordance, CognitiveProfileAffordance</td>
</tr>
<tr>
<td>Transport Agent</td>
<td>Computational Capability, canAchieveGoal(TranslateEnglishToFrench)</td>
<td>InteractionProtocolFIPA-Request</td>
<td>ComputationalAffordance, CognitiveProfileAffordance</td>
</tr>
<tr>
<td>Airline/Hotel Service Provider Agent</td>
<td>canAchieveGoal(ProvideService)</td>
<td>InteractionProtocolFIPA-Contractor</td>
<td>ComputationalAffordance, CognitiveProfileAffordance</td>
</tr>
<tr>
<td>Flight Search Agent</td>
<td>Computational Capability, canAchieveGoal(FindFlight)</td>
<td>InteractionProtocolFIPA-Contractor</td>
<td>ComputationalAffordance, CognitiveProfileAffordance</td>
</tr>
</tbody>
</table>
with them in a complementary manner to facilitate interoperability, reuse and adaptive collaboration based on enhanced cognitive awareness. The cognitive profiles of the agents in the prototype application are shown in Table 5.

Reuse Mechanisms Employed

The Behaviour API and Interaction Protocol API of JADE (Bellifemine et al., 2001; 1999; JADE 2004) are used to model the Agent’s Actions, or an action Plan. ACL Messages are used as representations for Intentions and perception. An agent is simulated in such a way that it is given runtime capability to change its behaviour, and dynamically change profile so as to demonstrate the power and potential of the Ontological Model.

Cognitive Modelling of Agent Interactions and Communication Scenarios Through CogAC

Table 6 shows an example of how the agents collaboration is modelled through the CogAC.

Illustration of Improved Cognitive Awareness

The provision of cognitive profile as shared knowledge base serves as means to increase the cognitive awareness for agents since they can not only reason about their own cognitive distances, they can also access and query other agents’ cognitive profiles allowing them to adaptively refine their interactions in attempt to achieve their goals in a collaborative manner. An illustration of how this proves so is shown in Figure 16.

| Table 6. Cognitively Modelled Agent Communication Scenario for Travel Planner Agent |
| --- | --- | --- | --- |
| **Stage** | **Description** | **Capabilities/ Affordances/Behaviours** | **Inferred Distances Rules for Inference** |
| Goal | • hasGoal Converge Currency Pounds to Dollars (G) | • G requires Capability (C) | • Semantic Distance G requires Capability C Agent hasNoCapability C Therefore hasSemanticDistance |
| Agent’s Gui of Execution | | | |
| Intention | • If ( hasNoSemanticDistance Stage(exection)) Proceed (Go to Next Step) | • hasNoCapability(C) | • Articulatory Distance G requiresCapability A Agent hasNoAffordance A Therefore hasArticulatoryDistance |
| Action Specification | • If ( hasNoArticulatoryDistance Stage(exection)) Proceed (Go to Next Step) | • hasNoAffordance(A) | |
| Execution | • Performing the actions Send the Request, Wait for Response | | • Semantic Distance G requiresCapability C Agent hasNoCapability C Therefore hasSemanticDistance |
Cognitive Profile as an Affordance

The cognitive profile in the form of ontology serves as an affordance for the agent to be cognitively aware of its environment and make adaptive decisions about it. Following is a scenario in Figure 17 that illustrates how this proves so.

EVALUATION AND FUTURE TRENDS

The application of the COMMAA to the application was found very useful in structuring the agents’ interaction and collaborations in an MAS environment. An attempt to assess the directness of engagement using the distances in the multi-agent interaction scenario offered useful results. As shown by the demonstration that the Cognitive Modelling of agents give a powerful boost and shows great potential in the manner that agent utilise each other’s capabilities to support each other functional execution and in return facilitate and reduce cognitive overload of humans. The increased cognitive awareness promotes interop-eration amongst agents and results in behaviour sharing and reuse. The high visibility into each other’s mental models increases the mapping of agent’s functional and execution models. The 7 stages of CogAC ensure that enough feedback is received to ensure successful fulfilment of goals through multi-agent collaboration. The Cognitive Profile Ontological Model serves as an essential artefact for agents which, continually provides for both sides of the CogAC: execution and evaluation.

Based on the above evaluation of the application, The CogAC can come to be considered as a fundamental part of the functioning of agent’s actions in interaction with its MAS environment. Thus agent modelled along lines of COMMAA exhibit strong principles of user-centred design
and advocate ease of use, efficiency and reuse and interoperation. Although, the model is used to model software agents, similar model can be used for classifying user roles and capabilities and for maintaining and sharing user profiles and roles. The proof-of-concept application has also demonstrated the feasibility of implementing the constructs of COMMAA using the combination of Multi-Agent Platform and the Semantic Web middleware.

In addition, the COMMAA takes a holistic view of agent’s action and its processing in the stages of execution and evaluation. It increases the cognitive awareness amongst agents by elaborating the action infrastructure, its limitations, constraints (Distances) and its capabilities and affordances. In this way it facilitates the architecture for the agents that are designed to work or be programmed to work more adaptively on the Semantic Web. This was made sufficiently evident using the implementation of the Travel Planning scenario. Similarly, agents can use the semantic information, share it, yet can communicate using ACL languages, programmed according to the Agent principles and do not need to rely on the Web service interfaces and profiles.

The results of the application are validated against the design goals presented earlier in Table 7.

**Future Directions**

The abstract architecture opens new doors of research. With the core framework in place the natural next step in its expansion is the specialised enhancement towards a more rigorous definition of different levels and variations of cognitive profile.
Table 7. Improvements achieved as a result of application of COMMAA

<table>
<thead>
<tr>
<th>Design Goals</th>
<th>Evaluation</th>
</tr>
</thead>
</table>
| **Cognitive Awareness:**                         | ▪ Agents profile has shown to be encoded using OWL ontology and published. Thus Agents are able to cognitively describe, publish and access each others capabilities, affordances and distances/constraints by Querying the ontology using SPARQL based mechanism. More dynamic and adaptive behaviour of agents has been shown. Thus the implementation shows cognitively aware modelling agents interaction.  
▪ Agents can carry out cognitively aware communication and collaboration with each other  
▪ Through Cognitive awareness, agents help each other identify and bridge the gulfs of execution and evaluation |
| **Enhanced Negotiation and Collaboration**        | ▪ As shown by the collaboration scenarios, agents negotiation abilities are enhanced as a result of improved cognitive awareness                                                                                                                                 |
| **Flexibility and Reusability:**                 | ▪ As shown, through cognitive profiling, JADE Behaviour API and Interaction protocols have been used with much more flexibility and their reuse is promoted by agents sharing cognitively their goals and abilities.  
▪ Agents are equipped with reasoning mechanism to dynamically reason about their semantic and articulatory disposition. This allows them to adapt to the required interaction scenario, thus providing intrinsic support for more flexible interaction. |
| **Adaptive Interaction and Interoperability:**    | ▪ Heterogenous agents in different roles including Transport Agents, Transport and Translator Brokers, Currency Convertors etc. have been shown to participate in adaptive collaborative scenarios through dynamic sharing of their cognitive profiles in order to help each other bridge cognitive distances of execution and evaluation. In doing so, they help each other achieve their goals.  
▪ Interoperability is promoted through the sharing of cognitive profiles, dynamic publish and access mechanisms.  
▪ Reasoning through SWRLJess based rules enhances cognitive awareness, thus improving interoperability. |
| **Discovery based on Heuristic reasoning:**       | ▪ Agents dynamically reason about their profiles using SWRL Rules and DIG reasoners that classify ontology. This allows dynamic discovery of cognitive distances and other agents’ profiles improving agents cognitive awareness of itself and the environment. |
| **Minimisation of cognitive load:**              | ▪ User has been shown to be relieved of much cognitive overload since agent through all of the above functionalities is able to perform much more. It is able to meet all the preferences in the user profile. If the case was otherwise, the distribution of tasks would shift from the agent to the user. E.g. if the agent was unable to meet the goal of converting dollar to pound, given it was not able to find any other agent to achieve the goal, the user would have the added cognitive overload of meeting the desired goal on its own.  
▪ Thus human information processing has shown to be reduced as a result of increased cognitive awareness and improvement in the flexibility and adaptability of agents’ collaborative abilities. |

and its parameters. Identifying the best level of detail for functionally decomposing each task or intention and applying it consistently is difficult. The application highlights that in order to make this model fully implementable or workable in the real world, there needs to be taxonomy of distances, directness measures, capabilities and affordances defined. This study initiates this activity by identifying the rudimentary picture of the basic Cognitive profile of agents e.g. at present the capabilities were identified as high level constructs. They can be made much more elaborate e.g. that of OWL-S. However to make it reach such a state of maturity where it could be utilised in practice will take some more effort. A taxonomy could be appealing because it would allow a generic to specific discussion of cognitive distances across different agent applications. Although some subset of cognitive distances will always be generic, it can be suspected that a fairly
large subset will need to be specialised across limited applications.

Ontology Learning, Alignment and Mapping: A serious issue in making this model work on a larger scale will be ensuring the standardization for the interoperability. Issues of Ontology learning (Maedche & Staab 2001), Ontology alignment and mapping (as highlighted in works by Laera et al. 2006, Mocan, Cimpian & Kerrigan 2006; Sampson & Lanzenberger 2006) also become important for standardization and homogenization purposes. Standardization of cognitive profile for agents will be another issue foreseen if this model were to work successfully, but with rich semantic model of OWL and RDF will allow for standardization to be achieved. However it provides substantial stimulus for future research.

Enhanced Learning and Reasoning Mechanisms: Furthermore, an idea that will add immense value to the further development of agents’ cognitive model is enhanced Reasoning and learning mechanisms. It would also be worth investigating how the principles of COMMAA plays a useful role in Interface characteristics i.e. investigation into role of cognitive models applied to model interface agents and their activities and management of user profiles. Another issue is with respect to the extent to which agent’s knowledge model or cognitive profile is to be shared. The notion of Public, Private profile could be considered. The extent of autonomy given to the agent moving towards Autonomous Semantic Web services (Paolucci & Sycara 2003) is also highly relevant.

CONCLUSION

The Semantic Web community has recognised the advantages of an agent-based approach to building deployable solutions in a number of application domains comprising complex, distributed systems. The chapter targeted some of the key challenges faced when developing autonomic and autonomous entities in the domain of Multi-Agent Collaborations. By applying cognitive models to model agents’ behaviour on the Semantic Web, a reasonably successful attempt has been made at coupling cognitive science principles of user-centred design with features of agent base systems and architectures.

This research took into account the emergent standards in both agents and Semantic Web in order to render the framework principles presented. The principles and design of COMMAA have also been used to demonstrate agents’ improved capabilities through an evaluation of a multi-agent collaborative scenario to illustrate the adaptive coordination of different agents acting as owners in heterogeneous and dynamically changing environments. The results of the evaluation show an improved flexibility, interoperability and reusability of agents’ collective behaviours and goals. Thus, it establishes COMMAA as a step forward in providing the next generation of Semantic Web, a successful framework of multi-agent collaboration, which is inevitably required for generating robustly engineered agents able to carry out spontaneous and adaptive collaboration based on cognitive awareness of their environment and infrastructure.

REFERENCES


Enabling Distributed Cognitive Collaborations on the Semantic Web


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**KEY TERMS AND DEFINITIONS**

**Affordance:** An affordance is a resource or support that the environment offers an agent for action, and that the agent can directly perceive and employ.

**Agent:** Agents are defined as autonomous, problem-solving computational entities capable of effective operation in dynamic and open environments.

**Capability:** The functional ability possessed by an agent to achieve some given goal or requirement.

**Cognitive Awareness:** It refers to the ability of the Web agents to diagnose their processing limitations and to establish interactions with the external environment (in the form of other agents including humans and software agents).

**Cognitive Model:** Internal representations of the current situation created by either a human and agent to assess their state with respect to the environment.

**Cognitive Profile:** It is a semantic representation model which includes information about the cognitive states of an agent, its functional capacities and affordances.

**COMMAA (Cognitive Model of Multi-Agent Action):** A framework for modeling agents’ actions and interactions in its environment in an attempt to provide an architecture that improves the flexibility of Multi-agent interaction by promoting cognitive awareness.

**Multi-Agent System:** Multi-Agent System (MAS) is a distributed collaborative environment which allows a number of agents to cooperate and interact with other agents (including both people and software) that have possibly conflicting aims, in a complex environment.