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Linguistic Formalism for Semi-Autonomous Reactor Operation

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1. Introduction

The ultimate goal of our work is to develop a novel, integrated system for semi-autonomous reactor operation by introducing an interfacing language shared by human reactor operators and artificially intelligent service agents (e.g., robots). We envision that human operators and artificially intelligent service agents operate the reactor cooperatively in the future. For example, an artificially intelligent service agent carries out a human reactor operator's command or reports the result of a task commanded by the human reactor operator. Since, perhaps, the most natural communication means for humans is language, it would be convenient for human operators to communicate with artificially intelligent service agents with the language that both human operators and the service agents can understand [1, 2]. This work presents a preliminary work towards the goal. The main contribution of this work is to present a unified linguistic formalism for efficient human-robot interaction (HRI) for reactor operation, adopting a lexicalized grammar formalism called combinatory categorial grammar (CCG) and hybrid logic dependency semantics (HLDS).

2. Reactor Operator Communication Protocol

Jang *et al*. [3] has proposed a reactor operator communication protocol based on the dialogue scripts collected from real nuclear power plant operations. The protocol defines a small language used for reactor operation. Even though the language is restricted, less expressive than the natural language used in human daily lives, it is suitable for reactor operation as a domain-specific language. This section briefly summarizes the reactor operator communication protocol [3].

3.1 Scope of the Communication Protocol

By analyzing previous works on speech act coding schemes, the scope of the communication protocol for reactor operation is narrowed down to 11 types, covering essential parts of reactor operation, represented by shaded area in Table I [3].

Table I: Scope of the Protocol

Speech act Type \ Task Type	Monitoring/ Detection	Situation Assessment	Response Planning & Coordination
Inquiry	■	■	
Command	■		■
Suggestion	■		■
Report	■	■	
Judgment	■	■	
Announcement		■	

3.2 Categories in the Communication Protocol

The collected dialogue scripts were hierarchically categorized, and 169 standard communication expressions were selected (Table II).

Table II: Categories in the Communication Protocol

Category	Sub-Category	# of Expressions
Alarm/Status	Alarm	6
	Component Status	9
	Operation Mode	3
	Condition/Schedule	5
	Parameter Status	12
	Safety Function	2
Manipulation/ Control	Component Manipulation	7
	MCR Interface	2
	Local Request	8
	Local Work	5
	Parameter Control	4
	Task Performance	7
	Task Proceeding	3
Abnormality	Failure/Abnormality	16
	Leak/Rupture	5
Condition	Operator Position	4
	Time/Timing	7
	Manipulation Possibility	4
	Work Status	19
Reference	Procedure/Tech. Spec.	16
	Parameter Criteria	5
Etc.	Call/Confirmation	11
	Emphasis	8
	Emergency	1

The following is an example of the protocol in Alarm/Status category [3]:

(a) Purpose: Directing alarm status check
(b) Sample Expression:
"LEE, check secondary radiation alarms."
(c) Generalization rule:
[Name], "check" + ([alarm location] + alarms / [alarm name])

3. Linguistic Formalism for Semantic Parsing

Artificially intelligent agents cannot process (i.e. understand) a human language directly. They need a formally defined language. A formal language is a set of strings of symbols with a set of rules that are specific to the language [4]. Similar to human languages, a grammar defines syntactic structure of a formal language, and a formal logic is used to add semantics (i.e. meaning) to the language.

In this section, a linguistic formalism that provides syntax and captures the semantics of the communication protocol is proposed. First, the syntax is introduced using a lexical grammar formalism. Then, the hybrid logic dependency semantics [8] concept is adopted for semantic parsing.

3.1 Lexical Grammar

In this work, we propose to build structures for the communication protocol based on a particular lexicalized grammar formalism called the combinatory categorial grammar (CCG). This section serves as a brief introduction to CCG, summarizing previous works [5,6,7].

In CCG, elements like verbs are associated with a syntactic "category" which identifies them as functions, and specifies the type and directionality of their arguments and the type of their results. CCG uses a small set of combinatory rules (i.e., combinators) to combine rich lexical categories of 'words'. Categories in CCG are either atomic or complex:

(i) Atomic categories: A finite set of basic action categories C (i.e., $A, B, \dots \in C$).

(ii) Complex categories: Complex categories are functions that take a set of arguments$\{W, X, \dots\} \subset C$ and produce a result $Z \in C$.

For example, the complex category $Z\backslash\{W, X, \dots\}$ is a functor category that takes an unordered set of arguments $\{W, X, \dots\} \subset C$ and produces a result Z where the slash indicates where the function looks for its arguments. Complex categories specify the type and direction of the arguments and the type of the result. Here, we use the "result leftmost" notation in which a rightward-combining functor over a domain B into a range A are written A/B, and leftward-combining functor is written A\B.

To parse sentences a number of combinators are required:

•Forward & Backward application:

$$\frac{A/B \;\; B}{A} >, \frac{B \;\; A\setminus B}{A} <$$

•Forward & Backward composition:

$$\frac{A/B \;\; B/C}{A/C} > \mathbf{B}, \frac{B\setminus C \;\; A\setminus B}{A\setminus C} < \mathbf{B}$$

CCG also allows one category to be "type-raised" into another category. For example,

•Forward & backward type raising:

$$\frac{A}{B/(B\setminus A)} > \mathbf{T}, \frac{A}{B\setminus(B/A)} < \mathbf{T}$$

Steedman[5] noticed that combinators contribute to the additional expressive power of CCG (over traditional context-free grammars, CFGs).

An instance of a CCG combinatory is obtained by substituting CCG categories for variables. To parse a sentence is to apply instances of CCG combinators so that the final category is derived at the end. For example,

$$\cfrac{\cfrac{\frac{LEE}{NP}}{NP}> \quad \cfrac{check}{(S\backslash NP)/NP}> \quad \cfrac{\frac{secondary}{NP/N} \quad \frac{radiation\ alarm}{N}}{NP}>}{S}<$$

3.2 Hybrid Logic Dependency Semantics

Hybrid logic enables us to logically capture two essential aspects of meaning in a clean and compact way, (a) ontological richness and (b) the possibility to refer [7]. Logically, we can represent an expression's linguistically realized meaning as a conjunction of modalized terms, anchored by the nominal that identifies the head's proposition:

$$@_h(\mathbf{proposition} \wedge \langle\delta_i\rangle(d_i \wedge \mathbf{dep}_i)) \quad (1)$$

In (1), dependency relations are modeled as modal relations $\langle\delta_i\rangle$, and with each dependent we associate a nominal d_i , representing its discourse referent. Technically, (1) states that each nominal d_i names the state where a dependent expressed as a proposition $\mathbf{dep}_i$ should be evaluated and is a δ_i successor of h, the nominal identifying the head. The following exemplary sentence can be represented as in (2)

"Secondary radiation alarm occurred."

$$@_{h1}(\mathbf{occur} \wedge \langle ACT\rangle(d_0 \wedge \mathbf{radiation\ alarm} \wedge\langle GR\rangle\mathbf{secondary})) \quad (2)$$

,where modal relations ACT and GR stand for the dependency relations Actor and General Relationship, respectively.

As seen above, Hybrid logic's flexibility makes it amenable to representing a wide variety of semantic phenomena in a propositional setting [8].

By coupling CCG to HLDS, we can parse the sentence more efficiently, and relate syntactic and semantic features perspicuously using unification. Furthermore, we can also syntactically account in detail the realization of information structure.

To link syntax and semantics in derivations (i.e. argument/dependent binding), since we work in a lexicalist setting, we can compile the effects of the linguistic linking theory directly into category assignments. Firstly, arguments express only their own nominal, not the nominal of a head as well. For example, proper nouns receive categories such as (3)

$$radiation\ alarm \vdash n : @_{d_1}\mathbf{radiation\ alarm} \quad (3)$$

This entry highlights the relaxation of the strict connection between syntactic and semantic types traditionally assumed in categorial grammars. The semantic portion of a syntactic argument in CCG-HLDS system does not declare the role it is to take and does not identify the head it is to be part of. Instead it identifies only its own referent. (4) is an example of the kind of head category needed.

$$occurs \vdash s : @_{h_2}(\mathbf{occur} \wedge \langle ACT\rangle(i \wedge p))\backslash n : @_i p \quad (4)$$

To derive "radiation alarm occurs", (3) and (4) combine via backward application to produce (5),

$$radiation\ alarm \vdash n : @_{d_1}\textbf{radiation alarm}\ \backslash$$
$$occurs \vdash s : @_{h_2}(\textbf{occur} \wedge \langle ACT\rangle(i \wedge p))\backslash n : @_i p$$
$$\rightarrow s : @_{h_2}(\textbf{occur} \wedge \langle ACT\rangle(d_1 \wedge \textbf{radiation alarm}))\ (5)$$

In addition, we can mark the informativity of dependents as contextually bound (CB) and contextually nonbound (NB). In unification-based approaches such as CCG, the transferal of feature information into semantic representations is standard practice. We thus employ the feature inf and mark informativity in logical forms with values resolved syntactically.

$$radiation\ alarm \vdash n_{inf=CB} : @_{d_1}\textbf{radiation alarm}\ (6)$$
$$occurs \vdash s : @_{h_2}([NB]\textbf{occur} \wedge [q]\langle ACT\rangle(i \wedge p))\backslash n_{inf=q} : @_i p\ (7)$$

Combining these entries using backward application gives the following result for "radiation alarm occurs":

$$s : @_{h_2}([NB]\textbf{occur} \wedge [CB]\langle ACT\rangle(d_1 \wedge \textbf{radiation alarm}))$$

A major benefit of having nominal in HLDS representations comes with adjuncts. We consider the prepositional verbal modifier in the sentence "radiation alarm occurs in the reactor hall" as an optional Locative dependent of occurs. To implement this, we compile into the category for the adjunct.

$$in \vdash (s : @_i(p \wedge [r]\langle LOC\rangle(j \wedge q))\backslash s : @_i p)/n_{inf=r} : @_j q$$

To derive the sentence "radiation alarm occurs in the reactor hall", we need the following additional entries:

$$the \vdash n_{inf=CB} : p/n_{inf=NB} : p$$
$$reactor\ hall \vdash n_{inf=NB} : @_{d_3}\textbf{ractor hall}$$

This approach allows adjunct to insert their semantic import into the meaning of the head.

Syntactically, a CCG grammar tells us which string of words are grammatical and which are not, and it also assigns derivational structure to the grammatical strings. Then what about semantics? By combining CCG and HLDS, we can interprete (i.e. relating the grammtical sentences with their HLDS), and generate grammatical sentences (i.e. realize sentences from HLDS.)

We can add HLDS to our lexicon in two steps:

(i) Add a nominal to each atomic category symbol, for example

$$\mathrm{LEE} : -\mathrm{NP_x}$$
$$\mathrm{radiation\ alarm} : -\mathrm{NP_x}$$
$$\mathrm{reactor\ hall} : -\mathrm{NP_x}$$
$$\mathrm{occurs} : -\mathrm{S_e}\backslash\mathrm{NP_x}$$
$$\mathrm{secondary} : -\mathrm{N_x}/\mathrm{N_x}$$
$$\mathrm{the} : -\mathrm{NP_x}/\mathrm{N_x}$$
$$\mathrm{in} : -\mathrm{S_e}\backslash\mathrm{S_e}/\mathrm{NP_x}$$

(ii) Add a set of elementary predications of hybrid logic to each lexical category

$$\mathrm{LEE} : -\mathrm{NP_x} : @\mathrm{x\ LEE}$$
$$\mathrm{radiaton\ alarm} : -\mathrm{NP_x} : @\mathrm{x\ radiation\ alarm}$$
$$\mathrm{reactor\ hall} : -\mathrm{NP_x} : @\mathrm{x\ reactor\ hall}$$
$$\mathrm{occurs} : -\mathrm{S_e}\backslash\mathrm{NP_x} : @\mathrm{e\ occur}, @\mathrm{e} < \mathrm{ACT} > \mathrm{x}$$
$$\mathrm{secondary} : -\mathrm{N_x}/\mathrm{N_x} : @\mathrm{e\ secondary},$$
$$@e < \mathrm{IMPORTANCE} > \mathrm{x}$$
$$\mathrm{the} : -\mathrm{NP_x}/\mathrm{N_x}$$
$$\mathrm{in} : -\mathrm{S_e}\backslash\mathrm{S_e}/\mathrm{NP_x}$$

Then the combinatories (i.e. unification) take care of the rest. We can combine words both:
(i) Syntactically (derivations, unification), and
(ii)Semantically (set union of elementary predications).

4. Conclusions

This work presents preliminary work towards a unified linguistic formalism for cooperative, semi-autonomous reactor operation. Application of the proposed formalism to reactor operator communication domain shows that the formalism effectively captures the syntax and semantics of the domain-specific language defined by the communication protocol [3].

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