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Spatial Information in Instructions and Questions to an Autonomous System

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Abstract

The task of supplying user-friendly access to an autonomous system using natural language is an interesting field of research which can be partitioned into access to autonomous robots and simulated agents. The perceptual information of such a system is to be related to language expressions in order to be able to talk about spatial configurations. The multiplicity of possible utterances is one of the main difficulties with natural language in general. In this paper, we concentrate on spatial expressions in different kinds of instructions and questions using anytime algorithms in order to consider resource limitations.

1 Introduction

Autonomous systems are characterized by their sometimes unpredictable behavior. E.g., their error recovery feature can cause understanding problems for the user: he possibly does not know why the system acts in a certain way. Thus, intelligent systems should also have intelligent man-machine interfaces in order to improve cooperativeness [14]. Talking about the environment of the autonomous system requires connecting its visual-geometric information with natural language expressions.

Flexibility is one of the main advantages of natural language but from the computational point of view it is one of the basic problems. E.g., if we consider instructions: they can either be in imperative, declarative or question form. Since one cannot rely on unique object identifiers the identification must be done by analyzing object descriptions in the utterances.

2 Related Work

Accessing an autonomous system as an interesting research field has already been considered in different ways. Some of the work is about accessing autonomous robots. The well-known SHAKEY system [18], e.g., was able to understand simple natural language commands. Natural language instructions were considered by the work of Sato and Hirai [21], while Torrance [24] developed a simple natural language interface to a mobile robot which was able to move in office rooms. Moratz et al. [16] present a system for the integration of language understanding and visual perception. They aim to give natural language instructions to an assembly robot. Lobin [13] describes some theoretical aspects of natural language communication with robot systems from the view of a computational linguist. Other systems tend to access autonomous agents in simulated 2D or 3D environments. A famous example in this area is the BASIC AGENT of Vere and Bickmore [25], an agent which is moving and acting in an ocean environment. SONJA [5] is an autonomous agent in a video game environment: the instructions given by the player are taken as suggestions for the system which need not to be taken into account. Badler [1] and DiEugenio [7] also have a simulated environment. DiEugenio's work has its focus on the analysis of purpose clauses and their influence on the plans of the autonomous agent.

Research on the connection between perceptual information and verbal expressions has been done in the field of integrated natural language and vision processing [2, 17, 26]. In the VITRA project [12], a reference semantics has been developed to express the relation between visual and verbal space.

3 Accessing an Autonomous System

An autonomous system has its own model of the environment which is the basis for all its activities. Especially in the field of autonomous robots, sensor information plays an important role for the exploration and analysis of the world. Since this information cannot be complete, the system often is not able to get the missing knowledge on its own. Though, a dialog system is more suitable as natural language access component for an autonomous system. In a cooperation between the Saarland University and the University of Karlsruhe we developed the dialog system KANTRA (**K**amro **N**atural Language **TRA**nslator) [23] for the autonomous mobile robot KAMRO (**K**arlsruhe **A**utonomous **M**obile **RO**bot) [15]. It is based on work done in the VITRA Project and can be used for the following four main tasks:

- **Task specification:** Tasks that are to be performed by the robot are given by the user on different levels of abstraction and can be formulated in different ways.
- **Updating and describing the environment representation:** Robot and user exchange information about the environment.
- **Explanation of error recovering:** Recovering from error situations entails the change of plans. Though, a user possibly is no more able to understand what has happened: this should be clarified.
- **Execution monitoring:** An autonomous system does not always work up a plan in the same order. The user should be informed in more or less detail about what is actually done.

4 Processing Spatial Relations

Following Herskovits [11, chapter 1] we distinguish between the "basic meaning" of a spatial preposition and its instantiation according to the characteristics of the object to localize (LO) and one or more reference objects (RO).[1] Looking at a sentence like *The lever is near to the shaft*, the basic meaning of the spatial concept *near* disregards the concrete situation and therefore only depends on a parameter encoding the distance between the objects mentioned. This dependency on such **essential parameters** is defined using cubic spline functions with a value range from 0 to 1, i.e., from *not at all* to *highly* **applicable**. These functions are adjustable to and have already – in part – been validated by the results of cognitive experiments (see [10]). According to instantiation rules depending on the reference object(s) we create a so-called **spatial proposition** for every instance of a spatial concept, represented as follows:

(Relation LO RO^{+})

Together these propositions with the position of the object to localize are associated with a **degree of applicability** (see [8, 23]).

The **applicability distribution** evoked by the spatial proposition *(near lever shaft)* is shown in Fig. 1 with the lever as object to localize on the right hand side.

The presented approach for the evaluation of spatial relations can be used for both, two- and three-dimensional domains. We distinguish the following classes of static spatial relations:

- **Topological relations:** These relations only depend on the parameters **local distance**, i.e., the distance between LO and RO scaled by the extent of the reference object. Relations of this type are, e.g., *near*, *at*, *in*.
- **Projective relations:** Relations like *to the left of*, *above*, *in front of*, a.s.o., primarily depend on the **scaled local deviation angle** compared to their canonical direction. Following Retz-Schmitt [19] this **frame of reference** is either implied by the *prominent front* of the object considered (**intrinsic view**) or by an explicitly mentioned (**extrinsic view**) or commonly known (**deictic view**) point of view.
- **Combined relations:** In German, combining elementary relations is often used in more precise describing localizations. There are different subclasses:
  - **Topological/projective:** Possible combinations are {*to the left of, to the right of, in front of, behind*}x{*at, close to*}. The relation *on* is represented as combination of *over* and *at*, the latter expressing contiguity.
  - **Projective/projective:** Here, we can combine different elements of the following sets {*to the left of, to the right of, in front of, behind*}x{*in front of, behind, over, under*}.
- **Special relations:** Some relations do not really match into the classes mentioned before
  - **between:** We consider only the case with two reference object RO-1 and RO-2. Then, *'between'* can be interpreted as combination of *LO in front of RO-1 seen from RO-2* and vice versa.
  - **<Projective> + 'on':** In terms like *links auf*, in English this could be expressed by *left on top*, a projective relation is combined with *on*, a combination itself.

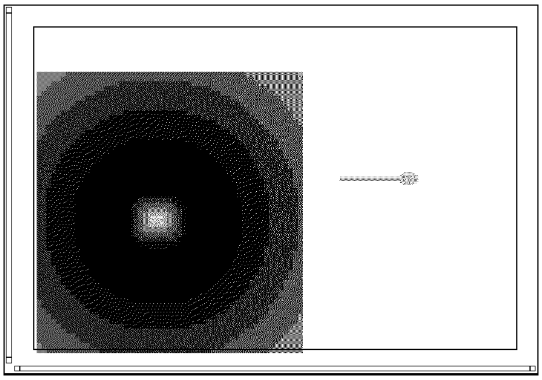

Figure 1: Graphical representation of the degrees of applicability for *the lever near to the shaft* (darker regions correspond to higher applicability)

[1] As people often are not concerned with too many details we can use idealizations for the objects in question (see [8]).

5 Task Specification

A task specification for the robot can appear in different ways: in imperative form, e.g., *Pick the left spacer!*, in declarative form *The left spacer should be picked* or even in form of a question *Would you please pick the left spacer?* They all have to be interpreted in order to produce a command which can be used as input for the autonomous system.

5.1 Natural Language Instructions

Here, we concentrate on the two implicit robot commands *pick* and *place* and different kinds of utterances which can be related to them. For imperative sentences, we distinguish between:

- **simple instruction:** *<action> <patient>!*
- **instruction with goal information:** *<action> <patient> <goal>!*
- **combined instruction:** consisting of two instructions of the named types combined by *and* or comma.

<action> refers to a verb which can be related to the robot action itself, *<patient>* is the object which is to be manipulated, and *<goal>* is a position to be specified in *place* operations. We can suppose that the autonomous system is always in the agent position. As mentioned above, we cannot assume that the user always verbalizes unique object identifiers, e.g., only the name of the object type is often used together with an indefinite article. Accordingly, one of the most difficult problems in this context is the object identification. Following Herskovits [11, chapter 3], spatial expressions are often used to identify an object by describing its location. Therefore, we can concentrate on forms of spatial object descriptions, i.e., expressions which can be related to spatial relations in the actual context. Another problem is the search for the goal position in a *place* action, i.e., a certain location has to be identified and not an object. This is in many cases done by a prepositional phrase describing the desired position in relation to another object, e.g., *Place the spacer in front of the sideplate!*[2]

Declarative sentences can mediate the same information as imperative sentences, e.g., instructions can be given in form of passive forms *The spacer will be placed near the sideplate* or with the help of modal verbs *The spacer should lie near the sideplate / The spacer should be placed near the sideplate*. Utterances like *The spacer is near the sideplate* realize object identification, they are often combined with instructions in imperative or declarative form in order to give further information.

In many cases, the user will refer to the situational or dialog context, i.e., the relations between different utterances must be considered in order to get a sensible and fully instantiated instruction. Some utterances are **under-specified** if they are seen separately. In the example *The spacer is near the sideplate. Pick it up!*, the first sentence will identify the spacer which should be picked whereas the second is the instruction which should be performed with the specified object in the patient position. **Temporal relations** can give a kind of linearization of the tasks *Before you pick up the lever place the sideplate on the table!* while possible parallelizations lie in charge of the planning component of the autonomous system. Other purpose clauses which are responsible for causal relations between plans also are important but not to be considered here.

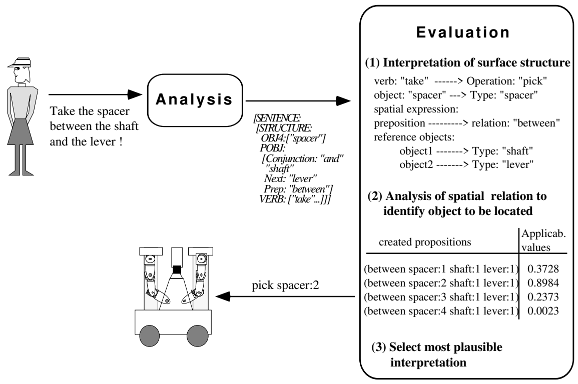

Figure 2: Object identification by a prepositional object

5.2 Interpretation of Spatial Expressions

For the task of object identification, we allow several forms of spatial object descriptions:

- **Prepositional phrases:** *the spacer between the shaft and the lever*
- **Relative clauses:** *the spacer which is in front of the sideplate*
- **Adjective:** *the left spacer*
- **Adverb:** *the spacer on the left*

Here, relative clauses can be considered as a special (extended) form of prepositional phrase and can therefore be treated in the same way as the description of the location where the object can be found. The prepositional object must again be identified: either by a unique name or again by an object description.[3] The use of several types of spatial expressions for one object is also possible and sometimes necessary in order to find an unambiguous description. Considering the example *Pick the spacer between the shaft and the lever!*, the object of type *spacer* is specified by the expression *between the*

[2] Supposed that this object again can be identified by the agent.

[3] People normally do neither understand nor use more than two or three recursions.

shaft and the lever: an unambiguous identification of the related instance is in many cases possible by interpreting the semantics of the prepositional phrase supposed that the named reference objects *shaft* and *lever* can also be identified.

Figure 2 shows how this expression is evaluated: after the natural language utterance has been processed by a parser the produced surface structure is analyzed by the evaluation component. The operation (*pick*) and the object type (*spacer*) are identified and the spatial expression (*between the shaft and the lever*) is decomposed (in spatial relation and reference objects). Now, it is important to know for which of the four instances of type *spacer* existing in the domain the relation mostly holds. For every instance, a spatial proposition is created in order to compute its applicability degree and select the best interpretation possible – spacer:2 has the highest value – for the generation of the command: `pick spacer:2`.

As mentioned above, spatial adjectives and adverbs can also be utilized in order to identify an object: *Take the left spacer!* or *Take the spacer on the left!* We suppose that the speaker is referring to the leftmost spacer seen from his position.[4] Here, in contrast to the evaluation of prepositional phrases and relative clauses, we do not consider the relation of every instance of the named type to another object but to each other of the same type. We can therefore check the validation of the corresponding relation *left* pair-wisely for all instances of type *spacer*. For every LO-instance, the algebraic average of the applicability values of its spatial propositions is taken as a measure for the evidence of the considered adjective or adverb, in this case *left*, in the actual context.

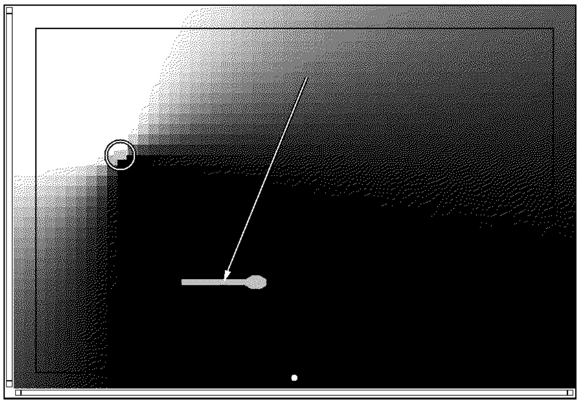

Figure 3: Localization of *in front of the shaft*

A *place*-operation normally requires the statement of a goal position of the patient. In the example *Place the lever in front of the shaft!*, the prepositional phrase *in front of the shaft* describes the location where the instance of type *lever* has to be placed. In order to interpret such an utterance it is necessary to know what the instructor wants to express. Following [22], a maximal typical position of the object can be found by applying the hill-climbing algorithm on the applicability distribution (see section 4). I.e., we use the degree of applicability as a measure for the typicality of an expression in the actual context. In our example, the applicability distribution is expanded from the reference object *shaft* to the viewpoint (see figure 3). The computed goal position is used in the generated robot command for instruction. Inaccuracies can be corrected by the error recovery component of the autonomous system.

[4]This is the default view. Other views, e.g., seen from the autonomous system, are also possible.

6 Questions on the Communication Environment

6.1 Questions and Instantiations of Propositions

As mentioned in section 5.1 spatial expressions can be used for identifying objects as well as searching a (goal) position. Furthermore, questions on the environment are often employed if the user has doubts about something, especially in the case of error statements of the autonomous system. To be able to help the system recovering from errors the user may have to get some information about what the system did last or which subtasks have already been done: *Are the spacers already placed in the sideplate?* During error recovery he may ask for object locations. After an error recovery the user will perhaps verify special aspects and query for it. This leads us to different types of questions. (1) The most important question, of course, is the so-called **'Where'-Question**: *Where is spacer:1?* asks for a locative description of the position of spacer:1, i.e., the answer requires a spatial relation together with a reference object, in most cases the LO will be repeated: *Spacer:1 is left to the sideplate:2*. Using the formalism introduced in section 4 a 'where'-question can be represented as follows:

(?Relation? LO ?RO?$^+$)

(2) A question simpler to compute only asks for one item of the proposition. Then, mostly the LO will be queried, as in *Which object/what is left to sideplate:2?*:

(Relation ?LO? RO$^+$)

(3) We can also ask *How is spacer:1 placed in relation to sideplate:2?* in search for a relation applicable between two objects:

(?Relation? LO RO$^+$)

(4) Finally, e.g., looking for a better reference object, we may ask *To which object is spacer:1 placed left?*, resulting in

(Relation LO ?RO?$^+$)

(5) Another kind of question takes a fully instantiated proposition and queries for its applicability (in natural language usually expressed by 'yes', 'no', or expressions like 'more or less', 'very', etc.): *Is spacer:1 left to sideplate:2?*

(Relation LO RO$^+$)

Table 1: Degrees of instantiation of spatial propositions

Type	Relation	LO	RO	Response
(5)	known	known	known	Applicability
(3)	?	known	known	(**Relation** LO RO)
(2)	known	?	known	(Relation **LO** RO)
(4)	known	known	?	(Relation LO **RO**)
(6)	known	?	?	Set of Propositions
(1)	?	known	?	Set of Propositions
(7)	?	?	known	Set of Propositions
(8)	?	?	?	Set of Propositions

(6) Even more complex than type (1) are questions like *Are there objects close together?*, because normally the set of objects is larger than the set of relations. This question would be represented as

(Relation ?LO? ?RO?$^+$)

Table 1 resumes the possible types of queries according to the degrees of instantiation of their spatial position.

While type (7) seems rather unusual, (8) can be interpreted as *What are the relations between all the objects?*, requiring a complete description of the situation.

In types (2)-(5) the answer will consist of a single information but in the cases with more than one proposition item not instantiated the response will be a (may be large) set of propositions.

Until now, we only considered *totally* known or unknown items. But in natural language it is also possible to cope with incomplete information. This can, e.g., be expressed by using type specifiers or class names, compare *Is spacer:1 left to a sideplate?* to (4): *To which object is spacer:1 placed left?* This effect is often expressed by the use of indefinite article, see section 5.1.

6.2 Time-dependent Generation of Responses

As we have seen in section 6.1, the complexity of analyzing questions (and their answers) obviously varies a lot. Of course, the importance of this problem depends on the domain and the number of objects in it as well as on the number of objects belonging to identical classes and other factors. The algorithm for the computation of responses to all kinds of the above mentioned questions, reflects this possible combinatoric explosion as well: The top level query expects three sets, possible relations, possible objects to localize, and possible reference objects, of mostly unknown cardinality.[5] Only in type (5), we know a priori that exactly one (in this case: given) proposition has to be evaluated. Normally, the number of propositions to analyze can not be predicted without meta knowledge about the sets of relations and objects in the domain.

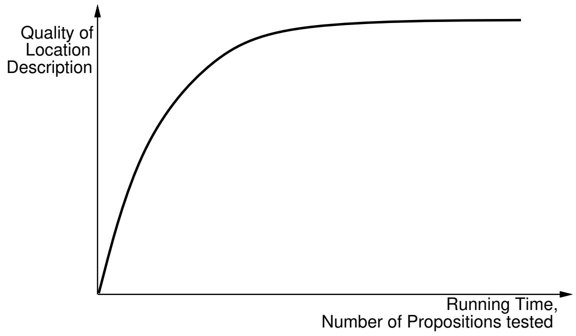

Figure 4: Sketch of a performance profile

Hitherto, in Artificial Intelligence the relations between visual and verbal space have mostly been examined assuming unlimited computational and natural resources and complete perceptual information. But considering dynamic environments like dialog situations, we find that response times are usually limited. Therefore, we should be able to generate some answer even before a perhaps complex computation has finished with the best possible result. These responses necessarily are suboptimal but by applying intelligent algorithms and architectures their quality will increase with the amount of time, the main resource in this case. In [4] we introduced a first approach of time-dependent generation of minimal sets of spatial descriptions using anytime algorithms. Now, we want to extent this approach from "where"-questions to all kinds described in section 6.1. First, a short reminder of the definition of anytime algorithms: Dean [6] characterizes anytime algorithms as a special class of interruptible algorithms, which can be suspended and restarted with negligible overhead and terminated at any time returning some answer. These answers increase monotonously over time. The last point has been worked out in [20] introducing **Performance Profiles** for anytime algorithms as functions $Q_A(t)$ from time allocation to output quality (cf. Fig. 4). [6]

Answers to queries in our algorithm can be retrieved *at any time*. According to the computational time elapsed, the quality of the response improves. To facilitate this information retrieval, the resulting fully instantiated propositions are split in different groups corresponding to the classes of spatial relations described in section 4 and sorted according to their degrees of applicability. This allows a quick and easy answer, if the questions are of the simpler types (2)-(5) where only one information is required. In the other cases, generating a response is in general more complicated. There may be, e.g., more than one LO, which implies (at least) the same number of answers. Often it is not sufficient to verbalize only one

[5] We restrict the set of possible spatial relations to those presented in section 4. Therefore the second reference object is not always required.

[6] Additionally, in [4] we claimed that the strongest improvement of the resulting locative description should take place at the beginning of the process.

spatial expression because more information is needed to enable the user to identify an object or a position.[7] The answer to a "where"-question, then, can be improved by combining some applicable propositions to get a better spatial description. The number of propositions that can be combined in a German natural language utterance is highly restricted to at most three elementary propositions, e.g., *left* and *near*, *at* and *between* (see [9]). The task of intelligently combining propositions has to be solved using an anytime architecture parallel to the construction of propositions.

7 Conclusion

In this article, we described the use of spatial relations for accessing an autonomous system. In the first part, the task specification, we showed how the reference problem is handled for the object identification in instructions. This is important because the patient of an action and – if necessary – its goal must be known in order to make an execution by the autonomous system possible. Furthermore, we classified different types of questions according to the degree of instantiation. Intelligent man-machine communication has to consider resource limitations such as time restrictions for the generation of answers. This lead to the implementation of an anytime algorithm competent for the calculation of sets of spatial expressions representing responses to both identification of objects and exchange of environment information.

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