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Carl: from Situated Activity to Language Level Interaction and Learning

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Transverse Activity on Intelligent Robotics
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Abstract

Carl is a prototype of an intelligent service robot, designed having in mind such tasks as serving food in a reception or acting as a host in an organization. The approach that has been followed in the design of Carl is based on an explicit concern with the integration of the major dimensions of intelligence, namely Communication, Action, Reasoning and Learning. Although different communities have thoroughly studied these dimensions in the past, their integration has seldom been attempted in a systematic way. This paper describes the software architecture of Carl as well as the main modules, from sensor fusion and navigation to language-level communication and learning.

1. Introduction

In recent years, robotics-related technologies have reached such a level of maturity that, now, researchers are feeling the next step is the development of personal robots, meaning, intelligent service robots capable of performing useful work in close cooperation/interaction with humans.

It will be necessary for robots of this new generation to comply with three criteria [15]. First, these robots must be *animate*, meaning that they should respond to changing conditions in their environment. This requires a close coupling of perception and action.

Second, personal robots should be *adaptable* to different users and different physical environments. One of the basic capabilities in this respect is to be able to make decisions at the task-level. The development of task-level robot systems has long been a goal of robotics research [1,9]. It is of crucial importance if robots are to become consumer products. The idea, that was already present in automatic robot programming languages since the 1970's, has been taken up in recent years by other researchers [11]. This is a central topic, since future robots are expected to be modular and reconfigurable, from a hardware point of view, and act in unstructured environments, which means that the number of action alternatives at the task-level will increase significantly, with respect to current robots.

The *adaptable* criterion also implies the need for learning capabilities [3,10,11]. Learning is important for robots to adapt to new environments, new users and new tasks. Learning should take place both at the perception & action level and at the task level.

Finally, robots should be *accessible*, meaning that they should be able to explain their beliefs, motivations and intentions, and, at the same time, they should be easy to command and instruct. In most cases, accessibility will imply the use of spoken language communication [8,14]. Furthermore, the combination of linguistic communication (not only with humans but also with other artificial agents) with learning capabilities seems to be essential for addressing the symbol grounding problem [5,14,17].

In order to meet the *animate*, *adaptable* and *accessible* criteria for intelligent service robots, it is, therefore, necessary to include in their design such basic capabilities as linguistic communication, reasoning, reactivity and learning. "Integrated Intelligence" is an emerging keyword that identifies an approach to building intelligent artificial agents in which the integration of all those aspects of intelligence is considered. Recent research works explore a variety of alternative paths, leading to architectures in which different functionalities are combined in different ways [15].

Given the progress obtained in sub-domains of AI and the maturity of the produced technologies, the "integrated intelligence" challenge seems to be the real challenge to face next. This is the focus of a national-funded project, CARL [1], led by the author.

Artificial intelligence is often taken as a discipline aiming to develop artificial agents with a human level of intelligence. In the CARL project, we believe that it is more reasonable to develop useful robotic systems with hardware and intelligence tailored for specific applications. This will provide experience on how to integrate different technologies and execution capabilities and, eventually, will enable us to scale up to more general robot architectures.

[1] "CARL - Communication, Action, Reasoning and Learning in Robotics", FCT PRAXIS/P/EEI/12121/1998.

This paper describes Carl, a prototype of an intelligent service robot developed by the project. Section 2 describes the hardware configuration and software architecture of the robot. Section 3 describes the basic capabilities developed for Carl to support situated behavior and interaction. Section 4 describes the global management system of the robot. Section 5 describes the learning module. Sections 6 and 7 conclude the paper with references to demonstration and lessons learned.

2. Carl, the robot

2.1. Hardware configuration

Carl is the name of the robot of the CARL project. It is based on a Pioneer 2-DX indoor platform from ActivMedia Robotics, with two drive wheels plus the caster. It includes wheel encoders, front and rear bumpers rings, front and rear sonar rings and audio I/O card. A Sony EVI pan-tilt camera was added. The platform configuration that was acquired also includes a micro-controller based on the Siemens C166 processor and an on-board computer based on a Pentium 266 MHz with PC104+ bus, 64 Mb of memory and a 3.2 Gb hard drive. The operating system is Linux.

On top of this mobile platform, we added a fiber glass structure that makes Carl approximately 85 cm high (see Fig. 1). This fiber structure carries a DA-400 v2 directional microphone from Andrea Electronics and a speaker. In a normal stand-up position near the robot, the mouth of a person is at a distance of 1 m from the microphone array. This is enough for enabling speech recognition in a quiet environment. This was, actually, the main motivation for adding the fiber structure: with the microphone installed directly in the Pioneer 2-DX base, the speech signal coming from a person in normal stand-up position would not be recognizable. For robust navigation, a set of 10 IR sensors was added to the fiber structure. The structure also includes a recipient for small objects, equipped with an IR sensor for detecting the presence of objects.

Figure 1*: Current look of Carl*

With this platform, we are developing an autonomous robot capable, not only of wandering around, but also of taking decisions, executing tasks and learning.

2.2. Software architecture

The control and deliberation architecture of Carl (Fig. 2) reflects the goals of our project. Human-robot communication is achieved through spoken language dialog. A set of Linux processes, making up the *speech processing* module, handle speech recognition, natural language parsing and speech synthesis. Another Linux process handles general perception and action, including navigation. High-level reasoning, including inductive and deductive inference, is mostly based on the Prolog inference engine (we use a freeware implementation with a good C-language interface, SWI Prolog). Another module of the architecture provides Carl with learning capabilities. A central manager coordinates the activities at the high level. All these modules are described in special sections below. All computation is done on board.

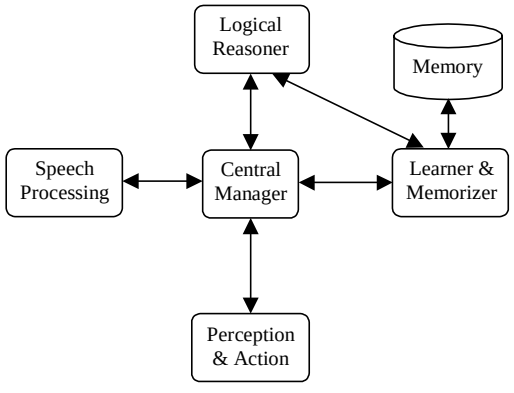


Figure 2*: Current software architecture of Carl*

3. Processes for Situated Activity

Carl is a prototype of a robot capable of performing actions in the real world according to spoken instructions from humans. Perception, navigation and spoken language processing are basic capabilities for such a robot.

3.1 Perception and navigation

For robustly navigating in complex unstructured environments, such as an office or home environment, robots will benefit from using multiple sensor modalities.

For instance, legs of chairs and tables are extremely hard to detect and locate by a robot only equipped with sonars.

The navigation strategy of Carl is based on the fusion of vision, sonar and infra-red sensing information.

Vision information is used to build a local map of the robot's neighborhood. Since the only camera of Carl is the EVI camera, Carl does not perform any sort of stereo vision processing. Nevertheless, a single camera can be used to detect free space on the floor in front of the robot, provided that the floor in the robot's environment is flat and its color is approximately constant.

The first time that these constraints, typical of many human environments, such as office environments, were used to simplify visual processing was in Polly [6]. This purely behavior-based robot navigated by following free space, as perceived through a single camera. Given it's reactive nature, Polly did not build any sort of map and, therefore, could not react to an obstacle, unless it actually was in the vision field.

We re-discovered the idea of recognizing free space with a single camera. In fact, only after developing Carl's navigation module we became aware of Polly's navigation strategy. Possibly other researchers have used variations of the idea. Nevertheless, our system takes full advantage of the it, by actually building local and global maps.

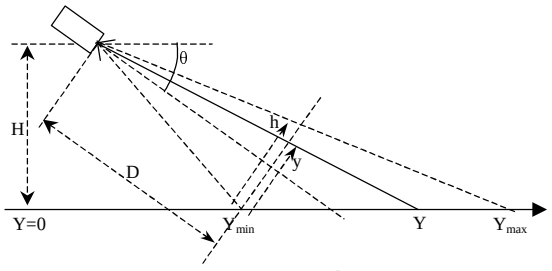
Fig. 3 illustrates the computation of the projection of an (X,Y) point on the floor to a plan parallel to the camera. Given the variables identified in the figure, the projection is computed by the following formulas:

$$x = \frac{D}{H} \cdot X \cdot \sin\left(\tan^{-1}\left(\frac{H}{Y}\right)\right)$$

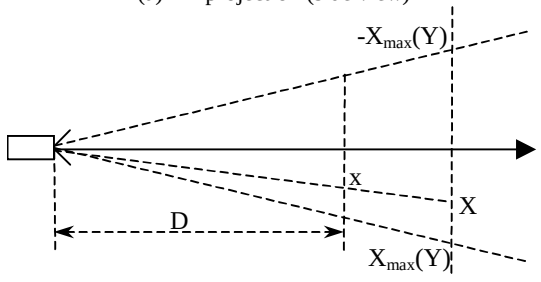
$$y = D \cdot \tan\left(\theta - \tan^{-1}\left(\frac{H}{Y}\right)\right) + \frac{h}{2}$$

Based on this, the local map is built and maintained. By local map it is meant simply a structure storing the coordinates of points that represent, with a certain resolution (e.g 30 mm), the boundary of the free space around the robot. The process is as follows:

1. An image of the scene in front of the robot is captured. (e.g. Fig. 4a.)
2. Free space in the image is detected - this is done by scanning the image from bottom to top until, in each column, a pixel is found out of the intensity interval of the floor; this is considered as the border of an obstacle. (In Fig. 4b, occupied space is marked black; note that the foot and the chair legs are easily detected.)
3. Based on the above equations, a top view of free space is generated (Fig. 4c). Note that only the base of each obstacle (laying on the floor) is correctly located; this is enough for obstacle avoidance, since the base of the obstacle appears to be closer to the robot Whatever appears to be further way can be ignored.
4. The top view image is segmented into a grid; scanning this grid from bottom to top, the first cells that are found occupied (the average pixel intensity is on average below or above the floor intensity range) can be marked as potential obstacles in the local map.



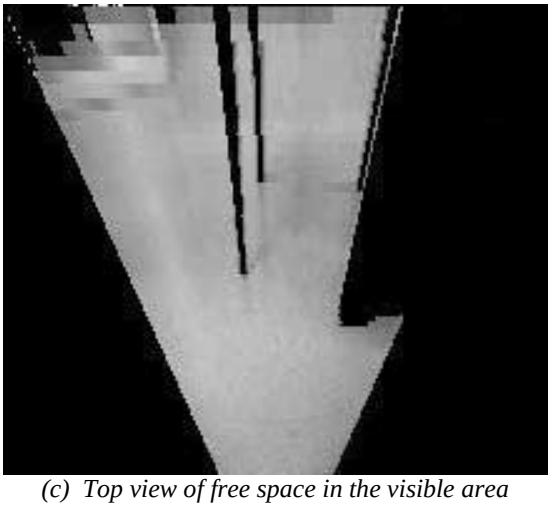
(a) - Y projection (side view)



(b) - X projection

***Figure 3**: Meaning of main geometric variables involved in the generation of a map of free space based on vision information*

(a) Acquired image *(b) Free space*



(c) Top view of free space in the visible area

Figure 4: Example of the process of generating a top view of free space on the floor in front of the robot

5. As the robot moves around, the positions of these points relative to the robot are updated and those that are too far (e.g. more than 1.2 m) are removed; previously recorded points that are again in the view

field of the robot are also removed, so that new points, corresponding to the current perception, can be recorded.

The top view image is also used to update a global map. The global map of Carl is currently a grid-based map. The grid resolution is 100 mm. Each time the robot sees that a given cell of the global map is free, according to the mentioned top view, an occupancy indicator for that cell is updated.

During navigation, each obstacle point in the local map exerts a certain virtual force in the speed and direction of movement of the robot. The approach is based on the Virtual Force Field (VFF) concept of Borenstein and Koren (1991).

Provided that contrast between floor intensity and obstacle intensity is sufficient, Carl can navigate based on vision only. However, sometimes an obstacle can really be confused with the floor. Therefore, complementary sources of information are taken into account, namely sonar and infra-red sensing information.

Obstacles "seen" by sonars and infra-red sensors are also handled through the same VFF-like approach. The speed and angle values obtained by applying VFF to vision, sonar and infra-red data are combined to produce values that are finally applied to adjust the robot's trajectory. This way, Carl is able to robustly navigate in complex human environments.

3.2. Spoken language processing

A spoken language interface enables humans to comfortably instruct their robots. The spoken language processing modules address the well known problems presented in Table I. The current interface of Carl builds on work described in previous papers of our group [14].

In this project, human-robot communication is modeled as the exchange of messages, much like is done in multi-agent systems. Se set of performatives or message types in our Human-Robot Communication Language (HRCL) is inspired in KQML, the outer language of ACL [7].

Table I – Spoken language processing sub-problems

	Speech	*Language*	*Semantics*
Input	*Speech recognition*	*Language parsing*	*Semantics extraction*
Output	*Speech synthesis*	*Language generation*	*Semantics construction*

Table II – Currently supported performatives (S=sender, R=receiver)

Performative	*Description*
Register(S,R)	*S announces its presence to R*
Achieve(S,R,C)	*S asks R to perform action C in its physical environment*
Tell(S,R,C)	*S tells R that sentence C is true*
Ask(S,R,C)	*S asks R to provide one instantiation of sentence C*
Ask_if(S,R,C)	*S wants to know if R thinks sentence C is true*
Thanks(S,R)	*S expresses gratitude to R*
Bye(S,R)	*S says good-bye to R*
Dye(S,R)	*S (human master) asks R (robot) to close all execution processes*

Table II lists the currently supported performatives.

For spoken language input, a grammar for a subset of the English language has been specified using the APSG (Augmented Phrase Structure Grammar) formalism. For each performative, a certain number of grammar rules has been written. In total, approximately 50 phrase structure rules are being used together with a vocabulary of approximately 100 words. This allows the grammar to accept over 12000 different sentences.

A set of public domain tools is being used by the project for spoken language processing. Speech recognition and speech synthesis are handled by Linux processes based on IBM ViaVoice. Natural language parsing and phrase structure construction are handled by another Linux process based on the CPK NLP suite [3].

One of the problems of current spoken language systems is the lack of robustness of the speech recognition process. Variations in environment noise, speaker language accent or speaker tone of voice, have dramatic consequences on the recognition performance. For our experiments, HMM speech models (of ViaVoice) have been trained for a set of four speakers. With this training and in a reasonably silent environment, Carl is able to recognize utterances well enough to enable dialogue.

Of course, the utterance must be acceptable by the grammar. The large grammar that is being used stretches the limits of current technology. However, large as it appears to be, it still covers only a small part of the English language. For instance, in the tell, ask and ask_if performatives, only sentences based on the verb *to be* are accepted, for example: "*The professor is in Portugal*"; "*The car of Peter is at the University*"; or "*The chairman of the conference is a professor*".

The final step in processing an utterance is the extraction of the semantics from the phrase structure description produced by the CPK parser. This is done by a Prolog program designed and implemented by our group. The semantics of a sentence is a relational description. For instance, the Prolog clause given in Fig. 5 extracts the semantics of sentences that are based on the verb *to be* and include a prepositional phrase. A recursive call extracts the semantics of the noun phrase, producing NP1sem and additional relations in list L1. A similar call handles the other noun phrase. Finally, the semantics is given by the relation is_(NP1sem,What), with other complementary relations given in list L3. Many other clauses of this type handle the different cases allowed by the grammar. As an example, the semantics of "*Professor Carlos is at the university of Aveiro*", would be represented by the following list of relations, as computed

```
semantics(
  tell(phrase(NP1,verb(be),prep(P),NP2)),
  is_(NP1sem,What),
  L3
):- semantics(NP1,NP1sem,L1),
    semantics(NP2,NP2sem,L2),
    What =.. [P,NP2sem],
    append(L1,L2,L3).
```

Figure 5*: A semantics extraction rule*

by the program: [is_(X, at(Y)), is_(X, professor), obj_name_(X, carlos), of_(Y, Z), is_(Y, university), obj_name_(Z, aveiro)].

4. Execution management

The central manager is an event-driven system. Events originating in the speech interface, in sensors or in the navigation activity as well as timeout events lead to state transitions. Such apparently different activities as dialog management and navigation management are integrated in a common unified framework.

It is mostly implemented in Prolog, in order to have easy access to the Prolog inference engine. Some parts of the manager are written in C language, either for reasons of efficiency or for access to the Linux inter-process communication facilities.

The central manager is essentially a state transition function (Fig. 6) specified as a set of Prolog clauses. Each clause, specifying a transition, has a head of the following form:

```
state_transition(State,Events,Restrictions,
                                    SpeechAct,Actions,NewState)
```

State is the current state; Events is a list of events that will cause a transition to NewState, provided that the Restrictions are satisfied. These events can be speech input events, navigation events, timing events, robot body events. SpeechAct, if not void, is some verbal message that the robot should emit in this transition. Actions are a list of other actions that robot should perform. These can be actions related to navigation, but also internal state update and dynamic grammar adaptation.

In total, Carl's state space includes around 15 states and 40 state transitions. Fig. 7 shows two examples of state transitions. The first one is a transition from a normal motion state (explore or wander) or stay state to a state in which the main activity of the robot is to go to the refill area. The triggering event is the absence of biscuits in the food tray of the robot. This activity, event and state transition were introduced for the AAAI competition (section 6.). The second state transition in Fig. 7 is a transition to the same state, in this case the interacting state. The triggering event is the reception of an instance of the tell performative. The robot immediately stops and acknowledges, then memorizes the told information. The time of this event is recorded, so that the robot may later recognize that the interaction is over, if it didn't finish with an explicit "good bye" from the human interactant.

```
state_transition(
  State,
  [no_biscuits],
  ( member(State,[explore,wander,stay]) ),
  nothing,
  [ retract_all_times,assert_go_to_refill_time,
    execute_task(go_to_refill_area) ],
  going_to_refill
).

state_transition(
  interacting,
  [ heard(tell(Phrase)) ],
  true,  % no restrictions
  acknowledge_told_fact(Phrase),
  [ execute_motion(stop),retract_all_times,
    memorize_told_fact(Phrase),assert_last_heard_time],
  interacting
).
```

***Figure 7**: Examples of state transitions*

5. Learning

Learning and grounding are key concerns in our project, as already pointed out. Now that all the basic capabilities have been included in the software system, learning and grounding will become main the focus of the research.

For a given robot, the general idea is to integrate, in a so-called "construction phase", a variety of processing and inference capabilities. In contrast, the initial body of knowledge should be minimal. After this phase is concluded (after the robot is born!), a life-long learning process can start [14]. The robot learns new skills, explores its environment, builds a map of it, all this with frequent guidance from human interactants.

Part of these capabilities have already been integrated in the current Carl prototype. Others, related to explanation-based/case-based learning, will be supported in the near future, through the integration of modules previously developed by the research team [11,12].

It should also be noted that on-line lifelong learning in robotics has seldom been described. Moreover, the few known systems demonstrating on-line learning, still are mostly limited to sub-symbolic learning.

In the case of Carl, recent efforts in this field are mainly aimed at building something that demonstrates on-line symbolic learning. The perfection of the architecture is not a priority yet, as this is still groundbreaking work.

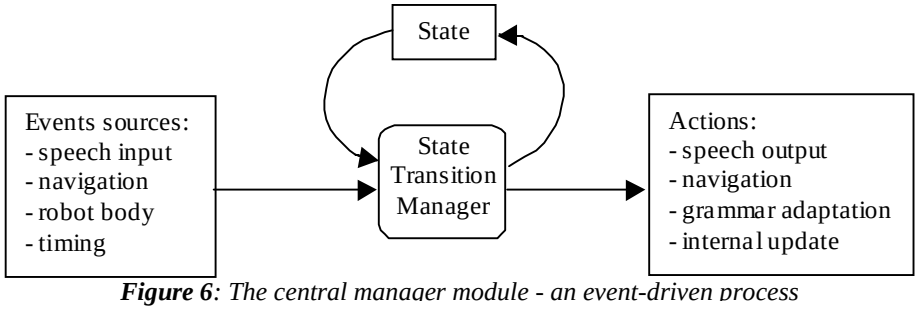


***Figure 6**: The central manager module - an event-driven process*

Two main learning tasks are being addressed.

- learning facts about the world through interaction with humans
- on-line human-supervised learning for object recognition and symbol grounding

The architecture of the learning module is illustrated in Fig. 8. Semantic information extracted from tell messages received from the human interactant are stored in a database of logical assertions (actually, the Prolog database). Here is an example of a dialog that leads to learning:

[Learning a new fact:]
H – *Hello, Carl!*
C – *Hi, would you like some food?*
H – *Thank you!*
C – *You are welcome.*
H – *Professor Doty is in Portugal.*
C – *Ok.*
[Later, provide the learned information:]
H – *Where is the professor?*
C – *Portugal.*
[Or:]
H – *Is the professor in France?*
C – *No.*

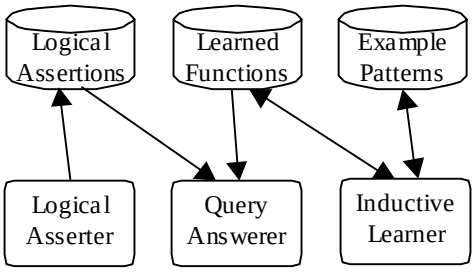


Figure 8*: The learning and memorization module*

Of course, this is learning of mostly non ground information. Nevertheless, this sort of functionality, if robust, may be useful for real-world applications.

The learning module of Carl also includes an inductive learner that we want to use for learning ground concepts. The particular task is the lifelong learning of object recognition knowledge. For instance, when Carl meets an obstacle, he may decide to ask:

"*Is this a person?*"

Based on the obtained answer ("yes" or "no") and the visual feedback, Carl may store a labeled example. A collection of labeled examples like this, will enable a supervised learning algorithm to induce the concept of "person".

The inductive learner that was developed, based on plain backpropagation neural networks, allows for the concurrent learning of multiple concepts. It works as a learning server for the robot. Although our focus is now on object recognition, it can also be used for synthesizing behaviors based on data collected in training sessions conducted by human teachers [14].

The complete cycle of lifelong learning from examples has not been demonstrated yet. Current efforts are concerned with automated feature extraction for improving the learning performance.

6. Demonstration

The *AAAI Mobile Robot Competition and Exhibition* event traditionally includes a competition under the title "Hors d'Ouevres anyone?". Participating robots are supposed to distribute food in a reception. This is a human-robot interaction competition. We, therefore, decided to let Carl participate in the 11th edition of the event (Seattle, Washington, USA, 2001) [13]. In a list of 6 registered robots, Carl was the only one with spoken language dialog capabilities.

This interesting evaluation opportunity has shown, in the first place, that it is extremely hard to have successful speech recognition in a crowdy and, therefore, noisy reception. During the reception, Carl almost didn't enter in dialog with humans due to the environment noise. It did say "*Hello, would you like some food?*", but almost never heard the reply, as it would, if the environment was quiet. This seems to show that it is still difficult to have talking robots being used in real-world applications.

Of course, this does not mean that the technology won't improve. Therefore, we will continue with our line of research on human-assisted learning, that we consider a basic ingredient for future intelligent robots.

From the point of view of navigation and collision avoidance, the AAAI reception was not particularly tuff. Although it was crowdy, humans are sufficiently large to be easily detected and avoided by robots. Carl would be able deal with much more complex environments.

Carl got the Third Place Award in the competition.

7. Conclusion and future work

Carl is a prototype robot that demonstrates the integration of communication, perception/action, reasoning and learning. It is an on-going project. Nevertheless, Carl is already able to: navigate in complex unstructured environments; enter in dialogue with a human being; and to learn some information from the human being.

Current work is particularly concerned with the grounding problem. A supervised learning system, designed to act as a life-long learning server and already implemented, is now being integrated in the software system of Carl. Concurrently, a feature transformation / dimensionality reduction module, has been developed and is now being integrated. This integration will, hopefully be completed soon. The next step is, then, to use all this infrastructure for on-line incremental concept learning.

Other efforts, perhaps less scientific, but nevertheless important, are concerned with improving the computational infrastructure of Carl in order to support the increasing demand for computational power. This will also enable better speech recognition.

Acknowledgements

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