A functional model for affordance-based agents

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Abstract. Today's mobile artificial agents, such as mobile robots, are based on an object-oriented paradigm. They partition their environment into various objects and act in relation to individual properties of these objects. Such perception and acting is insufficient for goal-directed behavior in dynamic environments, which requires action-relevant information in the form of affordances. Affordances describe action possibilities with respect to a specific agent. In this paper, we propose a functional model for affordance-based agents. This model integrates an adjusted version of the HIPE theory of function and an extended theory of affordances. We demonstrate the applicability of the functional model by relating it to two different cases of mobile robot interaction and outline an affordance-oriented robot architecture.

1. Introduction

Current mobile robot interaction with the environment is limited due to the wealth of dynamic and action-relevant information, which cannot be handled by today's architectures (Rome *et al.* 2006). Perception mechanisms are focused on the objects and their properties but do not directly concentrate on the available action possibilities. Detecting agent-specific action possibilities is a necessary process for the robot in order to evaluate whether certain tasks can be fulfilled or not. In this paper we propose a functional model for affordance-based agents. Affordances are action possibilities with regard to a specific user and allow for a distinction between such possibilities and the actual performance of actions. They are ideal candidates for focusing on the *agent-environment mutuality* (Gibson 1979).

The original affordance idea introduced by J. J. Gibson was grounded in the paradigm of direct perception. In order to compensate for the neglect of cognitive processes, we use an extended theory of affordances (Raubal 2001)—including cognition, situational aspects, and social constraints—for the affordance-based representation. This theory is integrated with the HIPE theory of function (Barsalou *et al.* 2005) and therefore makes a functional model for affordance-based agents possible. Such representation allows the robot to detect action-relevant properties of the environment tailored to its own spatio-temporal context, tasks, and capabilities. In addition, action possibilities for humans can be modeled in the same way, which supports the sharing of functionalities between human and robot, and facilitates communication. We apply this model to two different scenarios for mobile robots and discuss the advantages of this approach also with regard to architectural issues.

Section 2 introduces Gibson's affordance theory, discusses its downsides, and presents an extended theory of affordances. In Section 3 we describe the functional framework of representing affordances, which is based on the HIPE theory of function. Two mobile robot systems (*Rolland* and *PEIS*) are briefly illustrated in Section 4. We then develop possible scenarios for these systems and represent them within the new functional affordance model. Section 5 proposes an integration of the model within a robot architecture. Finally, we give conclusions and present directions for future research.

2. Affordances

This section introduces the notion of affordance, discusses deficiencies of the original theory, and presents an extended affordance theory.

2.1 Gibson's theory of affordances

The term *affordance* was originally introduced by James J. Gibson who investigated how people visually perceive their environment (Gibson 1977). His theory is based on *ecological psychology*, which advocates that knowing is a direct process: The perceptual system extracts invariants embodying the ecologically significant properties of the perceiver's world. Gibson's theory is based on the tenet that animal and environment form an inseparable pair. This complementarity is implied by Gibson's use of *ecological physics*. Such physics considers functions of the environment at an ecological size level contrary to a description in terms of space, time, matter, etc., within classical physics.

Affordances have to be described relative to the person. For example, a chair's affordance 'to sit' results from a bundle of attributes, such as 'flat and hard surface' and 'height', many of which are relative to the size of an individual. Later work with affordances builds on this so-called *agent-environment mutuality* (Gibson 1979; Zaff 1995). According to Zaff (1995), affordances are measurable aspects of the environment, but only to be measured in relation to the individual. It is particularly important to understand the *action relevant* properties of the environment in terms of values intrinsic to the agent. Warren (1995) demonstrates that the 'climbability' affordance of stairs is more effectively specified as a ratio of riser height to leg length. Experimentally, subjects of different heights perceived stairs as climbable depending on their own leg length, as opposed to some extrinsically quantified value. Additionally, dynamic or task specific conditions must be considered.

Norman (1988) investigated affordances of everyday things, such as doors, telephones, and radios, and argued that they provide strong clues to their operation. He recast affordances as the results from the mental interpretation of things, based on people's past knowledge and experiences, which are applied to the perception of these things. Gaver (1991) stated that a person's culture, social setting, experience, and intentions also determine her perception of affordances. Affordances, therefore, play a key role in an *experiential* view of space (Lakoff 1988; Kuhn 1996), because they offer a user centered perspective. Similarly, Rasmussen and Pejtersen (1995) pointed out that modeling the physical aspects of the environment provides only a part of the picture. “The framework must serve to represent both the physical work environment and the ‘situational’ interpretation of this environment by the actors involved, depending on their skills and values.” (Rasmussen and Pejtersen 1995, p. 122) This can be broken into three relevant parts, the mental strategies and capabilities of the agents, the tasks involved, and the material properties of the environment.

2.2 Extended theory of affordances

In this work we use an extended theory of affordances within a functional model for affordance-based agents. It supplements Gibson’s theory of perception with elements of cognition, situational aspects, and social constraints. This extended theory of affordances suggests that affordances belong to three different realms: physical, social-institutional, and mental (Raubal 2001).

Physical affordances require bundles of physical substance properties that match the agent’s capabilities and properties—and therefore its interaction possibilities. One can only place objects on stable and horizontal surfaces, one can only drink from objects that have a brim or orifice of an appropriate size, and can be manipulated, etc. Common interaction possibilities are grasping things of a certain size with one’s hands, walking on different surfaces, and moving one’s eyes to perceive things. Physical affordances such as the ‘sittability’ affordance of a chair depend on body-scaled ratios, doorways afford going through if the agent fits through the opening, and monitors afford viewing depending on lighting conditions, surface properties, and the agent’s viewpoint.

Many times it is not sufficient to derive affordances from physical properties alone because people act in environments and contexts with social and institutional rules (Searle 1995; Smith 1999). The utilization of perceived affordances, although physically possible, is often socially unacceptable or even illegal. The physical properties of an open entrance to a subway station afford for a person to move through. In the context of public transportation regulations it affords moving through only when the person has a valid ticket. The physical properties of a highway afford for a person to drive her car as fast as possible. In the context of a specific traffic code it affords driving only as fast as allowed by the speed limit. Situations such as these include both physical constraints and social forces. Furthermore, the whole realm of social interaction between people is based on social-institutional affordances: Other people afford talking to, asking, and behaving in a certain way. Many of these affordances are not tied to particular locations, e.g., people can also talk to other people over the phone.

Physical and social-institutional affordances are the sources of *mental affordances*. During the performance of a task a person finds herself in different situations, where she perceives various physical and social-institutional affordances. For example, a public transportation terminal affords for a person to enter different buses and trains. It also affords to buy tickets or make a phone call. A path affords remembering and selecting, a decision point affords orienting and deciding, etc. In general, such situations offer for the person the mental affordance of deciding which of the perceived affordances to utilize according to her goal.

3. A functional affordance model

The functional representation of affordance-based agents utilizes Barsalou's HIPE theory of function. We first describe this theory and then apply it to the construction of the functional affordance model.

3.1 HIPE theory of function

In an effort to analyze the detailed structure of *function* and how functional knowledge is represented and processed, Barsalou *et al.* (2005) developed the HIPE theory of function. This theory explains people's knowledge about function by integrating four types of conceptual knowledge: History, Intentional perspective, Physical environment, and Event sequences. Functional knowledge emerges during mental simulations of events based on these domains.

It is argued that agents believe that the *histories* of an artifact are central to its function. Furthermore, the physical structure of an object depends on its original design purpose. Barsalou et al. reason though that the physical structure alone is insufficient for knowing its function because context, such as knowledge of the setting, is necessary too[1]. This also leads to non-standard functions that obscure standard roles. For example, a hammer might also be used as a paper weight. When representing a function, the agent's *intentional perspective* determines the subset of functional knowledge, which gets retrieved. Such meta-cognitive perspective and point-of-view therefore determine the content of the functional simulation. The *physical environment* comprises not only the object whose function is to be determined and various aspects of the setting, but also external agents. Their physical structures are central to the function of an object[2]. Together, the object, the setting, and optional external agents constitute a physical system that is sufficient to produce a functional outcome, e.g., an affordance outcome. Finally, when this physical system is present, an *event sequence* is simulated. It includes the behaviors of all relevant objects and agents, and produces an outcome.

The HIPE theory explains function as a complex relational structure distributed across different modalities. It is a meta-framework that can distinguish different function theories at an abstract level, such as affordance theories and historical views. In addition, HIPE makes it possible to generate useful predictions depending on the represented theories.

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[1] S. Chaigneau and L. Barsalou (forthcoming) elaborate the fact that physical affordances in the sense of Gibson seem to be more important to understand functions, but history can become important under certain conditions.

[2] This is essentially a functional affordance, which emerges through the agent-environment mutuality.

3.2 Functional representation of affordances

The HIPE theory is well suited for the formalization of affordances because of their functional character. Similar to functions, affordances are complex relational constructs, which depend on the agent, its goal and personal history, and the setting. The HIPE theory allows for representing what causes an affordance and therefore supports reasoning about affordances. More specifically, it is possible to specify which components are necessary and sufficient to produce a specific affordance for a specific agent.

Figure 1 demonstrates the abstract functional representation of the relation between the three affordance categories presented in section 2.2 during the process of an agent performing a *task*. The agent is represented through its physical structure (*PS*), spatial and cognitive capabilities (*Cap*), and a goal (*G*). Physical affordances (*Paff*) for the agent result from invariant compounds (*Comp*)—unique combinations of physical, chemical, and geometrical properties, which together form a physical structure—and the physical structure of the agent. This corresponds to Gibson's original concept of affordance: a specific combination of (physical) properties of an environment taken with reference to an observer.

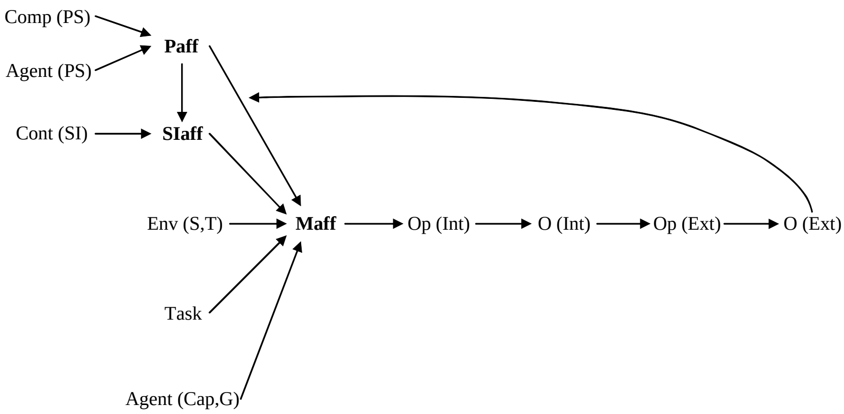

Figure 1: Functional representation of affordances for an agent—from (Raubal *et al.* 2004).

Social-institutional affordances (*SIaff*) are created through the imposition of social and institutional constraints on physical affordances—when physical affordances are perceived in a social-institutional context *Cont (SI)*. While performing a task the agent perceives various physical and social-institutional affordances within a spatio-temporal environment represented through *Env (S,T)*. This corresponds to HIPE's notion of a physical system and allows for localizing the perception of affordances in space and time.

Mental affordances (*Maff*) arise for the agent when perceiving a set of physical and social-institutional affordances in an environment at a specific location and time. Affordances offer possibilities for action as well as possibilities for the agent to reason about them and decide whether to utilize them or not, i.e., mental affordances. The agent needs to perform an internal operation *Op (Int)* to utilize a mental affordance. Internal operations are carried out on the agent's beliefs (including its history and experiences) and lead to an internal outcome *O (Int)*. In order to transfer such outcome to the world, the agent has to perform an external operation *Op (Ext)*, which then leads to an external outcome *O (Ext)*, i.e., some change of the external world. This external change, in turn, leads to new physical affordances, situated in social-institutional and spatio-temporal contexts.

4. Application scenarios for linguistically enabled robots

In the following, we describe two real robotic systems, give scenarios for each of them, and present their semiformal representations within the new functional affordance framework.

4.1 Robotic system descriptions

This section briefly introduces the two robotic systems considered for the proposed functional affordance model, namely the Bremen Autonomous Wheelchair *Rolland* and the *PEIS* (Physically Embedded Intelligent Systems) ecology.

Figure 2: Bremen Autonomous Wheelchair *Rolland*.

4.1.1 Rolland

The Bremen Autonomous Wheelchair *Rolland* (figure 2) has a specific reactive layer, the so-called *safety layer* (Röfer and Lankenau 2000). Its purpose is to guarantee obstacle avoidance by a formally verified low-level module. More complex behaviors such as *wall following* send their commands to the safety layer, which checks their effects with regard to whether they would lead to collisions.

Rolland's linguistic module interprets route descriptions by a human instructor (driver) (Mandel *et al.* 2006). The mappings between linguistic constituents and internal qualitative spatial maps (route graphs) are based on ontological representations (Ross *et al.* 2005).

4.1.2 PEIS ecology

The *PEIS* (Physically Embedded Intelligent Systems) ecology is a network of heterogeneous smart devices that ranges from simple gadgets, such as refrigerators with sensors, to sophisticated mobile robots. These intelligent devices communicate on a high, abstract level to combine physical and virtual functionalities to perform complex tasks (Broxvall *et al.* 2006). In a typical application of the PEIS ecology a human inhabitant is supported in his flat (e.g., elderly care). Food supply checking, cleaning services, load carrying, and other support are provided by the PEIS network in this scenario. A detailed account of the PEIS ecology can be found in the present volume (Saffiotti this volume).

4.2 Affordance-based scenarios

This section shows exemplar interaction sequences for the robotic systems described in the previous section. These sequences focus on the involved affordances. Even if the examples are inspired by the capabilities of the real robotic systems we here refer to potential future versions of the systems with slightly enhanced features.

4.2.1 Scenario 1: Rolland

In this scenario a handicapped user of the Rolland system wants to make a tour starting at the rehabilitation centre with the goal of performing a transaction at the municipal authority. The first important affordance in this context is the social-institutional affordance created by the opening hours of the municipal authority. This affordance is represented as part of the background knowledge of the Rolland system, which shall also support users with cognitive deficits such as memory disorders. Taking into account this social-institutional affordance an adequate starting time for the journey is selected by the route planner of the Rolland system. Rolland's internal map of the city contains drivable sidewalks, possibilities for street crossing (lowered curbstones), suitable elevators in buildings, etc[3].

Based on the mental affordance of evaluating the possibility of performing the given task, the route planner of the Rolland system generates a route from the rehabilitation centre to the municipal authority. When the Rolland system follows the route, the physical affordances of the environment are perceived. In case of deviations, for example, due to road construction work, the system must replan based on the updated map. Additional mental affordances for the robotic system lead to

[3] Since these internal representations are not necessarily correct with respect to the corresponding true state of the physical world, they should not be confused with these real physical properties of the environment (physical affordances).

high-level decisions (state/subgoal changes in the deliberative layer, see section 5) about the present location of the robot (self localization).

4.2.2 Scenario 2: PEIS ecology

As reported above the PEIS ecology consists of multiple robots and smart devices that interact with a human user. In the presented scenario a small PEIS robot is blocked by an obstacle. The obstacle itself can be a simple PEIS entity. Then the necessary information about potential pushability would be communicated by this blocking physical object itself. If the small robot were not able to push the obstacle, the PEIS network could offer a solution by shared functionalities. For example, the obstacle might offer different *physical affordances* to a bigger and stronger PEIS robot in the current network. This second robot could be capable of pushing the obstacle away. Then the smaller robot could send a message (i.e., communicate, which is a *social-institutional affordance*) to the bigger robot, asking it to move the obstacle away. In this scenario the *mental affordances* result from the offered functionalities of the different PEIS entities in the distributed PEIS network configuration memory (Broxvall *et al*. 2006). A planner on a local PEIS entity can then access these functionalities offered by other PEIS entities. Another example of *social-institutional affordances* in this scenario is the constraint for the mobile robots not to drive around too fast making noise at night and therefore wake up the human inhabitants of the flat.

4.3 Representation within functional affordance model

In the following we represent both scenarios within the functional affordance model and discuss the proposed representations.

4.3.1 Representation of scenario 1

It is important to notice that there are different hierarchical levels for the task of performing a transaction at the municipal authority. The most generic representation is at the top level and the further one goes down in the hierarchy the more specific the affordances become. For our scenario, one top-level action (resulting from a physical affordance) is navigating from the rehabilitation centre to the municipal authority office. Examples for actions on lower levels are street crossing, turning left/right, or halting in front of a red light. Figure 3 shows the representation at the top level. The compound affording something is marked through outgoing dotted arrows.

On the top level, the municipal authority building affords Rolland to enter the building. Entering is constrained by the opening hours of the municipal authority, which create a *SIaff* on top of the *Paff*. The environment for perceiving affordances consists here of two parts: first, the *physical environment*, where Rolland is spatio-temporally located, i.e., the rehabilitation centre at 9am; and second, Rolland's *internal map* of the city, which offers synthetic affordances in the sense that they might be different from the real-world affordances. Rolland's task is to perform a transaction at the municipal authority. Its capabilities comprise the safety layer and also various complex behaviors. The goal is imposed (through communication) by its handicapped user. All of these functions result in the top-level *Maff* for Rolland, namely to evaluate whether this task can be fulfilled with the given constraints represented through the functions. More formally, the (interconnected) sets of physical and social-institutional affordances at a given point in space and time result in a set of mental affordances for the agent: $\{Paff, SIaff\}_{Env(S,T)} \Rightarrow \{Maff\}$. *Maffs* are therefore higher-order functions because *Paffs* and *SIaffs* are functions themselves.

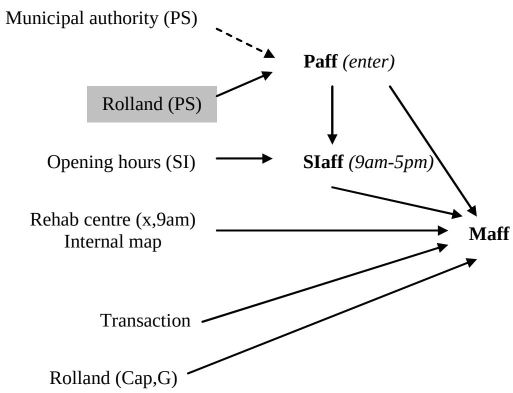

Figure 3: Top level for Rolland's task.

The second part of the top-level process is represented in Figure 4. Rolland performs internal operations (within a planning process), deciding whether the task can be performed based on the given functions. The outcome of this operation is a specific route (under temporal constraints) to the municipal authority building. Navigating to this building is an external operation and after some time Rolland can reach the building. The external outcome is then reaching and finally entering the building (and subsequently performing the transaction). Again, during the actual process of navigating, Rolland perceives physical affordances in the actual environment and must react and replan if needed.

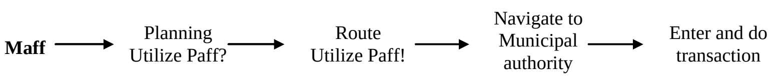

Figure 4: Functional activity process for Rolland.

4.3.2 Representation of scenario 2

This representation is more complex because it involves two robots, which are also able to communicate with each other (figure 5). The obstacle is too heavy and therefore affords the small robot (Robot1) *not* to push it away, which is a *negative* affordance (Gibson 1977). On the other hand it affords a bigger robot (Robot2) to push it away due to the different physical structure and capabilities of this robot. An important point demonstrated in the PEIS scenario is the possibility of *affordance* *transfer*, i.e., affordances can be utilized indirectly via other agents[4]. Here, this is made possible by the physical network infrastructure, which affords communication (in the technical sense), and the *SIaff* for Robot1, i.e., that Robot2 affords asking to push the obstacle away. Robot1 is located in the flat at position x and time 10pm. The floor of the flat affords driving around (*Paff*) and the time of the day imposes a *SIaff*—drive slowly without making noise (not represented in the figure to keep it simple). The task of Robot1 is to move the obstacle, which is blocking the robot's way. Its capabilities comprise various behaviors and the overall goal might be driving into the kitchen. Again, all of these functions result in the *Maff* for Robot1, namely to determine the best way for moving the obstacle.

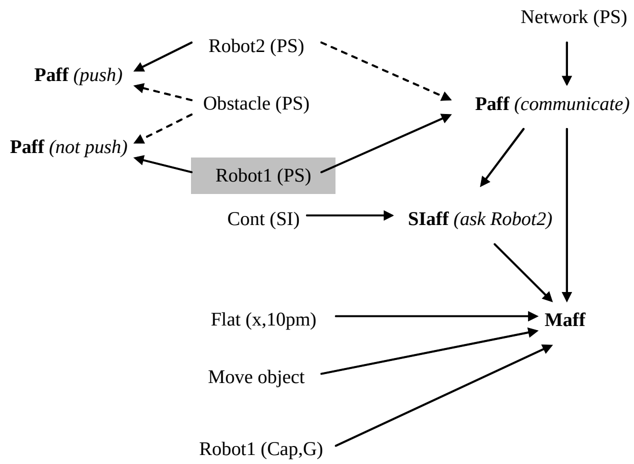

Figure 5: Top level for PEIS scenario.

Figure 6 represents the second part of the decision process for Robot1. The robot performs an internal planning operation with regard to its task of moving the obstacle. Based on the available functions and information from the distributed PEIS network configuration memory, the robot makes a decision to ask Robot2 for help, i.e., to utilize the *SIaff*. It then performs the corresponding external operation (sending a request over the network) and the resulting outcome of this process is a *Maff* for Robot2, namely to decide whether to help Robot1 or not. This also demonstrates the connectivity between various decision processes in the functional affordance model: The external outcome of one process offers another affordance for the same or other agents in the system. In this sense, all processes within spatio-temporal multi-agent environments can be represented as higher-order functions.

[4] This is crucial when considering computational complexity because often a large number of possibilities for affordance transfer exists in reality.

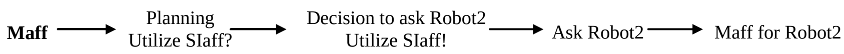

Figure 6: Functional activity process for Robot1.

5. Affordance-based architectures for human-robot interaction

This section outlines an integration of the new functional affordance-based representation within a robot architecture. We also discuss the advantages of such an architecture compared to traditional approaches.

The proposed robot architecture is a modification of the standard three layer architecture (Gat 1998; Wasson *et al.* 1999). Three layer robot architectures typically consist of a *deliberative* layer, a *skill* layer, and a *reactive* layer. The deliberative layer takes a high-level goal (in our case typically an instructor command) and synthesizes it into a partially ordered list of operators. These operators correspond to skills/behaviors in the skill layer. The skill layer activates basic action and perception patterns in the reactive layer.

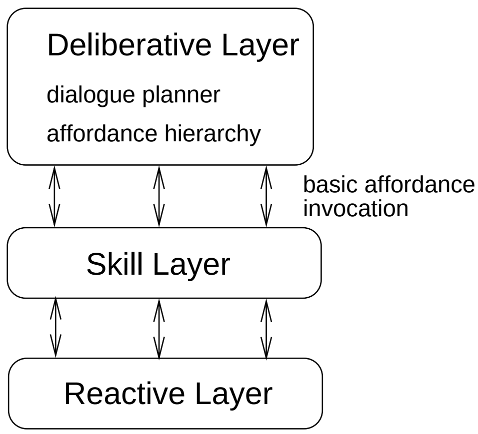

Figure 7: Basic affordances as interface between deliberative and skill layer.

Our proposed modification of this architecture (figure 7) aims at the nature of the skills/operators, and the interface between deliberative layer and skill layer. Similar to the architecture proposed by Arkin *et al.* (2003) we focus on a cognitive basis for defining the set of operators. Whereas Arkin et al. use motivation-oriented animal activities as blueprint for their design we pose the design constraint on our architecture that the operators have to represent relevant affordances of the shared interaction domain of human and robot (or robot and robot as in the PEIS scenario). Affordances are therefore ‘first-class citizens’. Within this architecture, the robot’s central focus is on functional compounds rather than properties in isolation.

The affordances in a scenario represent the relevant action possibilities for both robots and humans. Relevance of the robot action possibilities in this view does not only refer to the robot's planner but mainly to the user's mental model (Gentner and Stevens 1983) of the robot. In practice this results in the design principle to investigate the mental models of human users and to take them into account for the design of the interface between the deliberative layer of the robot and its lower levels.

Due to this design principle the robot can verbalize its currently planned sequence of high-level actions. The motivation for performing an action is to reach a subgoal. In our architecture the robot is then able to verbalize its subgoals. As humans expect their communication partners to be able to verbalize their subgoals our proposed architecture supports clarification dialogues. These clarification dialogues are crucial in situations where the human must support the robot with hints or even physical assistance. In general, the utility of dialogues in human-robot teams increases the trust of the human operator in the robots under command (Jones and Rock 2002).

This trust is crucial in situations were the robot (-team) supports a handicapped user. For example, the Rolland system could recognize that a lowered curbstone as part of its path is blocked by a halting car. Then Rolland could either autonomously replan the path or first communicate this blocked *physical affordance* to the user. If the driver of the car is present the user of Rolland could then ask the driver to remove the car. Figure 8 demonstrates the affordance-based representation of this situation. If we compare both alternatives it is obvious that the setting where Rolland would silently make a big detour to reach the goal would confuse the user and may destroy her trust in the system[5].

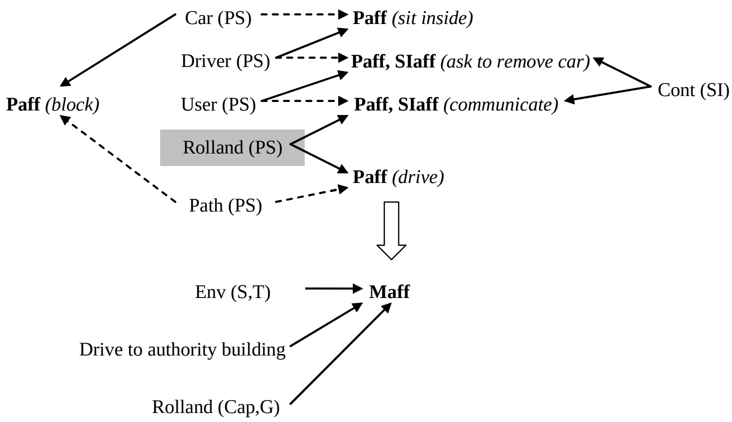

Figure 8: Affordance-based representation of 'blocking situation'.

To sum up, the difference between our proposed architecture and more traditional ones is to represent the corresponding action possibilities for both humans and robots in a given scenario in a uniform manner. The presented functional theory offers such unifying framework, representing the whole process from sensing to acting in terms of physical, social-institutional, and mental affordances. This design principle makes it easier in joint efforts of humans and robots to flexibly share functions/operations

[5] Generally, a handicapped person wants to be supported only in functionalities that she cannot perform on her own. Nobody would like to be carried by a robot like a passive payload.

within the heterogeneous human robot team. Especially important in our view is to assess the capabilities of the intended users and their mental models of the robots before designing the interface between high-level and lower-level layers of the robots involved.

The planning process itself would be performed by a planner capable of coordinating actions of several agents, e.g., human and robot in a typical scenario (Alami *et al.* 1998). A specific option relevant for our design methodology is using an interactive planner (Ambite *et al.* 2002). Another technology that fits well to the approach presented here, consists of a perception module for the robot, which is designed according to affordance-based criteria (Moratz and Tenbrink this volume).

6. Conclusions and future work

In this paper we presented first steps towards a framework for knowledge representation for human-robot interaction. The key elements of this knowledge representation are three classes of affordances: physical, social-institutional, and mental affordances. In such representation action-relevant properties of the environment, spatio-temporal context, tasks, and capabilities of the spatial agents are modeled. Affordances become 'first-class citizens'—to be seen as functional compounds—and allow for separating the perception and cognition of action possibilities from action performance.

We propose a robot architecture that uses a hierarchical affordance-based representation in the deliberative layer of the robot control system. The interface of this deliberative layer to lower layers consists of invocation of action possibilities, which correspond to basic physical affordances. The benefit of this new architecture variant compared to more traditional ones that focus on physical constraints of the robots is that also action possibilities of human users can be modeled in the same way. Then a uniform affordance-oriented representation supports flexible sharing of functionalities between robots and humans.

The next step regarding our approach will be building a simple dialogue system and simulated robots as in the system of Jones and Rock (2002). With this system we will focus on the extraction of affordances from the environment to be simulated and from human subjects who serve as test users. Another important direction for future work is the theoretical foundation of affordance hierarchies. These hierarchies span several levels, which are scale-dependent. For example, agents perceive and consider different affordances when planning a trip than when actually moving along crosswalks. In order to make it possible for agents to evaluate the utility of different affordances it will also be necessary to establish a theory of similarity measurement for affordances. Often, agents cannot utilize the best affordance for a given task due to various constraints but have to search for the second-best. Similarity measures will support this search because their outcomes are based on a continuous matching scale (Hahn and Chater 1998). Finally, it will be important to investigate how agents can learn different types of affordances based on previous interactions in spatio-temporal environments, and how these learned affordances influence future behavior.

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