Affordances and Affordance Space: A Conceptual Framework for the Application in Social Robotics

Felix LINDNER [1] and Carola ESCHENBACH
Knowledge and Language Processing Group
Department for Informatics, University of Hamburg, Germany

Abstract. Socially aware robots have to coordinate their actions considering the spatial requirements of the humans with whom they interact. We propose a general framework based on the notion of affordances that generalizes geometrical accounts to the problem of human-aware placement of robot activities. The framework provides a conceptual instrument to take into account the heterogeneous abilities and affordances of humans, robots, and environmental entities. We discuss how affordance knowledge can be used in various reasoning tasks relevant to human-robot interaction.

Keywords. Affordances, Abilities, Socially Aware Robots, Social Spaces, Shared Space

Introduction

Gibson [1] introduced the notion of affordance as the central concept of ecological psychology. According to him, affordances are the possibilities for actions the environment offers to agents in cases where the abilities of agents and properties of the environment match. For example, chairs afford sitting to humans, stairs afford climbing to many humans, but form obstacles for many types of robots and for humans in wheelchairs, and some types of ramps afford climbing to both humans and robots. Both humans and robots also provide affordances to other humans and robots, thereby enabling interaction with other agents. The concept of affordance has inspired several researchers in various disciplines such as psychology [2,3,4], human-computer interaction [5], geographic information systems [6,7], and robotics [8,9,10,11,12], just to name a few. In philosophy, the notion of affordances has been related to phenomenology of Merleau-Ponty [13]. From the perspective of affordance theorists, there is meaning in the world (i.e., affordances) and therefore agents can act. This is complementary to the view taken by some phenomenologists, viz., agents can act and therefore the world is meaningful [13].

Traditionally, in robotics, the notion of affordances is related to the action possibilities of a single agent (e.g., [8]). However, if agents have to coordinate their actions, tak-

[1] lindner@informatik.uni-hamburg.de
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ing care of the action possibilities of someone else becomes essential. Thus, the world is not just meaningful to a particular agent insofar as the world offers possibilities for action to this agent, but also insofar as it offers possibilities for action to other agents. Reasoning about affordances in social robotics requires to take agents with different abilities and needs into account. In this article, we put the focus on the spatial structure of affordances. This, we argue, is pivotal for the design of socially acceptable autonomous robot behavior.

In [14] a taxonomy of socially meaningful spaces is proposed. Affordances and activities produce social spaces, which are called *affordance spaces* and *activity spaces*, respectively.[2] In a nutshell, activity spaces are spaces used by agents while performing an activity, and affordance spaces are spaces that enable the execution of the afforded activity to an agent. (In the following, the term *activity* refers to any kind of event or process involving an agent, independently of the temporal aspect or abstraction level.)

In comparison to affordances, activities are short-lived. Activities exist only as long as they take place. Affordances are possibilities of activities and can exist independently of activities actually taking place. A single affordance can be realized more than once by different activities. The approach to affordances we present here also allows that different agents can act upon a single affordance.

Activity spaces of activities taking place simultaneously can yield conflicts, e.g., when two agents try to move through one door at the same time. Social interaction means to take care of the spatial requirements of the other's activities and to coordinate such activities. Similarly, if an affordance space is blocked, e.g., by a robot parking in some region, an agent may be unable to perform some activity. Thus, independently of whether there is an agent present that plans to act upon an affordance, social action planning should take care of affordance spaces for which it is to be expected that some agent will use it.

Taking affordances to be (mere) possibilities of activities with different agents, the spatial requirements of different agents acting upon an affordance can vary. While a small robot parking in a doorway might not hinder many humans to walk through, it might be an obstacle for a father with a baby-stroller. Thus, to act socially aware regarding space requires knowledge about other inhabitants of ones environment regarding their spatial requirements in acting. As these inhabitants might differ regarding their abilities and spatial requirements, a general model must allow for different affordance spaces for different types of agents.

The next section gives a short overview on affordances in robotics. Section 2 discusses activity spaces and affordance spaces in relation to each other. Section 3 shows how knowledge about affordances can be used for different reasoning tasks. Section 4 provides a coherent model of affordances and affordance spaces interrelating them with relevant concepts. In Sect. 5, we discuss the contributions of our framework and provide an outlook.

[2] In this context, 'social space', refers to spatial structures that are significant for assessing the social appropriateness of agent behavior. Thus, the use of this notion is not limited to social spaces like the internet or public parks.

1. Affordances in Robotics

With a focus on affordance-based robot control, Şahin and colleagues [9] identify three different perspectives for describing affordances. The observer perspective relates agents, environmental entities, behaviors, and effects. The agent perspective fixes an agent and relates the other three components, while the environmental perspective fixes an environmental entity.

The agent perspective is the perspective taken in approaches to single-robot learning and planning. An example for affordances in the agent perspective is given by Stoytchev in [8]. He proposes a representation of affordances based on observations before and after a robot executes a behavior on an entity using a particular tool. That way, the robot learns the effects of behaviors and, thus, what the entity affords to it. As the derived representations are tightly coupled to the specific perceptual-motor-capabilities of the robot platform at hand, they cannot be used to reason about affordances the entity provides to other agents. Much work in this direction has been done in robot manipulation planning, cf. [12].

If agents with diverse abilities cooperate, they must be able to reason about the affordances provided by and provided for other agents just as about their own. Saffiotti and Broxvall [10] present an ecology of robots with heterogeneous abilities that can cojointly solve tasks. Therefore, each robot publishes its functionalities to a central unit, which allows to integrate the functionalities available in the different robots and use a subset of these functionalities to plan a configuration that fits to the current context or task. However, the integration of humans in this approach is still an unsolved problem.

The mentioned approaches dealing with affordances do not consider the question of how affordances structure space and yield spatial restrictions. However, some work concerned with spatial aspects of human-robot interaction address such aspects. For example, Yamoaka and colleagues [15] focus on how a robot with the task to present information about an object to a human should place itself relative to the listener and relativ to the presented object. To analyze this problem, the authors employ F-Formations, a spatial model of activities proposed by Kendon [16].

Marin-Urias and colleagues [17] consider several constraints for human-aware placement planning that take both human properties and robot properties into account. For example, to determine a good pose for handing an objects to a human, a robot should take the human's field of view into account as well as its own arm length.

The two approaches mentioned can be reframed in terms of socially adequate spatial behavior based on affordances of robots and their human interactants. However, a link to affordance theory has not been explicitly established by the authors.

A general approach to human-aware spatial behavior of robots requires to model the influence of affordances on the functional and social structure of space. The dominating agent perspective of affordances seems to result in neglecting the task of recognizing affordances the environment might provide for agents with diverging abilities and spatial constraints. For example, humans may be interested in viewing pictures or other kinds of displays. Even though these kinds of activity might not be relevant for robots, taking the perspective of humans in spatial planning also involves taking care of such human activities and their spatial requirements. Moreover, a more elaborated approach should consider the heterogeniety of robot platforms as well as the heterogeniety of human beings, which also differ regarding abilities and spatial requirements.

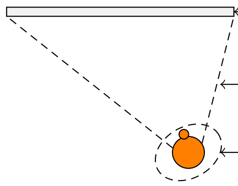

Figure 1. Scheme of the activity space of an activity of viewing a picture.

This short discussion of affordances shows that the spatial structure imprinted by affordances on the surrounding has only been considered for very specific interaction contexts. The social dimension deriving from the possibility that agents can deactivate affordances for other agents due to inappropriate behavior is largely ignored.

2. Activity Spaces and Affordance Spaces

2.1. General Structure of Activity Spaces

Activities are located in space [16]. Any activity occurs somewhere and has a relationship to the spatial regions the participants of the activity are located in. Kendon [16] discusses so-called F-Formations, which are spatial structures produced by activities of interacting agents. According to Kendon, three regions can be distinguished within such an F-Formation: The participating agents are located in the *agent region* (p-space in [16]). There is a common *transactional region* (o-space in [16]), in which most of the activity takes place, i.e., the region into which the agents look, speak, or where they handle objects. In addition, the *buffer region* (r-space in [16]) separates the activity from the rest of the environment. Each of those regions carries a social meaning to both the participants of the activities and to non-participants [18]. E.g., non-participants avoid crossing the transactional region or entering the buffer region. Agents that intend to participate in the ongoing activity signal their intention in the buffer region before they enter the agent region and become part of the activity.

We take Kendon's analysis as the basis for our spatial model of activities and affordances but have to generalize it in two respects. On the one hand, we include in the model activities of individual agents in addition to activities of interacting agents focused by Kendon, on the other hand, we focus on activities involving environmental objects as passive participants in addition to agents as active participants. In Kendon's analysis, environmental entities affording an activity are not considered. Furthermore, we assume that buffer regions are relevant for cases of complex activities such as interactions of agents only. Activities involving only one agent and an environmental entity do not necessarily induce buffer regions.

Our model of activity spaces provides three basic regions: agent region, transactional region, and the *patient region*, which is the region occupied by environmental entities that are passive participants in the activity (cf. Fig. 1 and Fig. 2). Furthermore, the union of the agent region and the transactional region is called *core region* and the union of the core region and the patient region is called *activity region*.

The term *activity space* is used to refer to a structure that identifies the five named regions. The regions are also called *activity space regions* or *social regions* of the acitivity

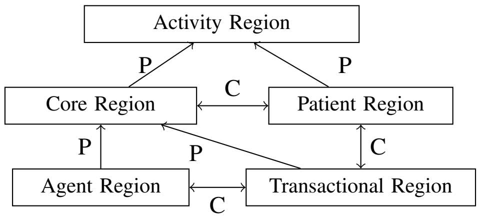

Figure 2. The social regions of an activity space. The specification makes use of the relations parthood (P) and connection (C). If a region is part of another region, then these regions are also connected.

space as they carry different social meanings for participants and non-participants of the activity.

The extension and geometry of the social regions within an activity space depends on the type of activity and spatial properties of the participants. However, the transactional region of an activity space is connected to both the agent region and the patient region. But depending on the activity and the granularity of modelling, the transactional region might also be part of the agent region (e.g., in modelling reading a book by a human, it might not be worth distinguishing a transactional region from the agent region).

2.2. General Structure of Affordance Spaces

In analogy to the notion of affordances as potential activities, affordance spaces are potential activity spaces [14]. Environmental entities function as source or host of an affordance. Such an entity providing an affordance is called *affordant* in the following. If an activity realizes an affordance, then the affordant is a (passive) participant in the activity and the activity produces an activity space. The spatial structure produced by an affordance corresponds to the structure of the activity (s. Fig. 4): An affordance space provides a *potential agent region*, a *potential transactional region*, and an *affordant region*. We call the union of the potential agent region and the potential transactional region the *potential core region*. The union of the potential core region and the affordant region is called the *affordance region*. The five regions provided by an affordance are also called *affordance space regions* or *(social) regions* of the affordance space.

While an activity is taking place, the affordance space used by the activity turns into an activity space (s. Fig. 3). The affordant region of the affordance space turns into a patient region, the potential agent region turns into an agent region, and the potential transactional region turns into a transactional region. Hence, the potential core region of the used affordance space turns into the core region of the activity space and the affordance region turns into the activity region. For instance, while viewing a painting, the affordance space produced by the viewing affordance turns into an activity space produced by the actual viewing.

We consider affordance space regions to be vulnerable to spatial behavior similar to activity space regions. In particular, potential agent regions or potential transactional regions can be blocked, and thus, action possibilities for agents become deactivated. However, the number of affordance spaces included in an environment might become rather large, as, for example, every object and every piece of wall affords viewing. Thus, among the existing affordance spaces the *social affordance spaces* are the ones that are distinguished as being socially relevant. In [19] it is discussed how different facts about

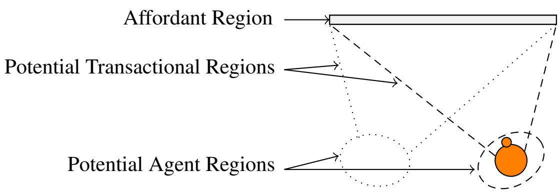

Figure 3. Two affordance spaces produced by the picture's affordance of being viewed. An unused affordance space (dotted lines) and an affordance space used by an activity (dashed lines), i.e. an activity space.

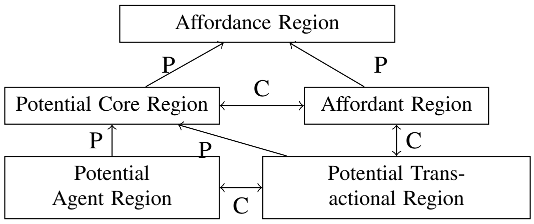

Figure 4. The (social) regions of an affordance space.

affordance spaces can provide reasons for action, viz., as reasons in favor of placing an activity in a particular affordance space or as reasons against doing so.

3. Affordance-Space Awareness

Knowledge about affordances and their spatial aspects is needed on different levels of planning and acting. First, if an agent acts on an object, knowledge about the affordances provided by the object helps to act successfully. For example, to successfully grasp a bottle, a robot needs to move into an appropriate area and approach the bottle with its manipulator from a specific direction. Thus, affordance knowledge can be employed on the functional level. This use of affordances might not require the ability to take the perspective of other agents on the affordances into account. As mentioned in Sect. 1, different approaches in robotics address the acquisition of functional affordance knowledge and its spatial aspects.

Robots are artifacts themselves that provide affordances to humans. When a robot moves, the affordance spaces it provides move as well. Similarly, we can also ascribe affordance spaces to affordances provided by humans regarding interaction. The second use of knowledge about affordances concerns the interaction of two or more agents based on interaction affordance spaces. Successful interaction often requires spatial coordination, such that the agents have to move to affordance spaces provided by other participants.

An example concerning affordances of interaction between a human and a robot is depicted in Fig. 5. The robot provides an information screen that can be viewed by humans with intact vision producing an affordance space as_v. The human affords being talked to by the robot, and therefore, corresponding affordance spaces are available.

In situations as in Fig. 5(a) interaction is not possible. To interact with the robot, the human has to be located in the agent region of as_v, i.e., to be sufficiently close to see

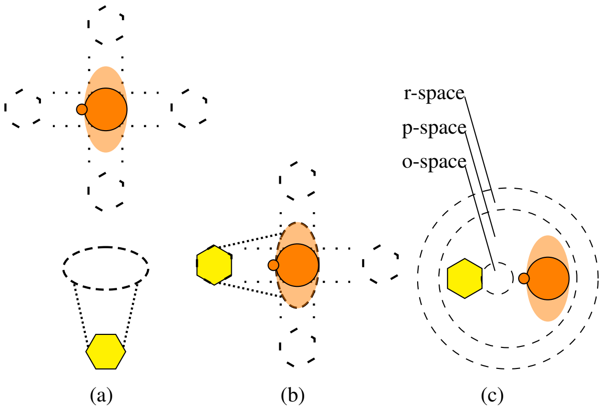

Figure 5. Simplified illustration of four affordance spaces produced by the talking affordance inherent in a human (orange) and one affordances space produced by the viewing affordance inherent in a robot (yellow hexagon) with potential agent regions (dashed) and potential transactional regions (dotted). In (a) interaction is hindered by the separation of the affordance spaces. In (b), the robot occupies the potential agent region of a fitting affordance space of the talking affordance of the human, and the human occupies the potential agent region of a fitting affordance space of the viewing affordance of the robot, the viewing area aligned with the potential transactional region as necessary for interaction. (c) shows the F-Formation constituted by the interaction of the human with the robot.

the display. Moreover, the human has to be oriented towards the display, i.e., according to the potential transactional region of as_v. Similarly, if the robot intends to talk to the human, it has to move into the agent region of a fitting affordance space.

When both agents are located in respective agent regions as in Fig. 5(b), bilateral interaction can take place. During interaction, the human viewing the screen occupies the agent region of as_v, and the robot talking to the human occupies the agent region of an affordance space of the human.

Third, affordance knowledge can be employed on a social level to avoid disturbing other agents in their activities. In this case, activities of other agents and their spatial requirements have to be taken into account.

In Fig. 6, there is a doorway and a robot. Among others, the doorway affords moving through to humans. The robot's task is to provide information to humans and therefore it has a monitor mounted on its body that affords viewing to humans. Consequently, there are two affordances constituting two affordance spaces.

In the spatial setting sketched in Fig. 6 the robot is positioned next to the door to provide information to people entering the room. It does not block the doorway and therefore people who do not need the information can just pass by. However, this arrangement might easily provoke conflicts, as the potential core regions of the two affordance spaces partially coincide. If a human would start to interact with the robot, the human would be located in the potential agent region (par_v) of the viewing affordance. Thus, the human would also be located within the potential core region (pcr_m) of the movement affordance, i.e., partially blocking the region that is needed for other humans to move through the doorway. Thus, a socially aware robot needs to be aware of affordance spaces produced by itself and by other entities in its vicinity to be able to evaluate spatial configurations with respect to their social acceptability.

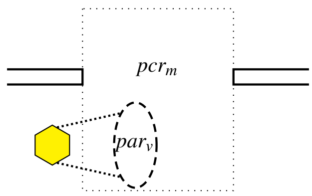

Figure 6. A potential conflict due to the spatial relation between two affordance spaces. The potential core region (pcr_m) of the movement affordance provided by the doorway intersects the potential agent region (par_v) of the viewing affordance provided by the robot (hexagon).

The final example in this section shall demonstrate that the spatial requirements associated to an affordance also depends on the abilities of agents that act upon the affordances. Service robots that deliver fresh supplies (e.g., food trays, sheets) need to be able to decide about where to leave the supplies in case there is no human agent available to directly take care of them. For humans, it is obvious that the center of a corridor, a door, or the area in front of a light switch are not the regions to choose to deposit such supplies, even though there might not be anyone present who acts in those spaces.[3] Both corridors and doorways are environmental entities that afford movement. The area to be kept free depends on the expected traffic, the size of the agents, the objects they transport, and on abilities of the potential agents. Correspondingly, people prefer to deposit goods along walls and keep the center of a corridor free for traveling. However, if hand railings are mounted on a corridor wall, the corridor produces an affordance space for people who prefer to move supported or guided by such railings. In this case, placing objects along the wall blocks this affordance space and thereby deactivates the affordance for people using railings. When different types of agents with different abilities populate an environment, different affordance spaces might be associated with one affordance. Thus, the presence of a railing on one wall of the corridor does not justify the assumption that supplies can be deposited in the center of the corridor, as other agents might want to move there. To be able to identify the affordances spaces that are relevant on the social level within an environment shared by different types of agents, a socially aware robot needs knowledge about which activities are to be expected by its co-inhabitants of the environment.

The examples in this section show that knowledge about affordances and affordance spaces can be employed in a variety of action and planning tasks. Correspondingly, several approaches in robotics are concerned with modelling the spatial constraints of (inter-)actions (e.g., [15], [17]). Although the focus of such work might be directed to a specific task such as the robot's task to position itself to provide information or to hand objects to some person, the same knowledge can be employed to avoid to park in such regions when interaction with a human is not intended. However, the multiple use of knowledge about activities and affordances requires linking the specific action models to a general framework for modelling activities, affordances and the social spaces they produce.

[3]Regions that need to be free of obstacles for safety reasons can be marked in maps. However, more general mechanisms that model potential activities and their spatial requirements might be called for when service robots are brought into environments that are not completely mapped beforehand and that contain mobile artifacts providing affordances.

4. Affordances and Affordance Spaces

Affordance spaces are *produced by* affordances and represent generic spatial constraints for the afforded activities. The structure of affordance spaces derives from the spatial needs of activities as discussed in Sect. 2. Fig. 7 summarizes the interrelations between the concepts we use to describe affordances and affordance spaces.

Affordances are properties that *inhere in* affordants. Activities *realize* affordances but affordances exist independently of the activity taking place. Therefore, we model affordances as primarily related to *activity types enabled* by affordances. Activities are *performed by* agents and can have an affordant as *participant*. If a robot grasps a bottle, then the robot is agent of and the bottle is participant in the grasping activity. An agent of an activity requires certain *abilities used* in the activity fitting to the affordances of the affordant for success. These abilities include spatial requirements of the agent. Thus, if a robot (agent) grasps a bottle, the grasping (activity) uses the robot's manipulation abilities. If the agent's abilities fit to the affordant's dispositions for carrying out the enabled activity type, then we say that the abilities *complement* the affordances relative to the activity type. Hence, if the robot's abilities complement the bottle's affordance with respect to grasping, then we can say that the bottle affords grasping to the robot. When the robot grasps the bottle, then the activity of grasping uses the robot's ability and realizes the object's affordance.

The shape and size of the regions provided by an affordance space depend on the type of the afforded activity, the spatial structure of the affordant, the (spatial) abilities of the participants, and the surrounding. Affordants determine the reference frame for affordance space regions and activity space regions. Thus, if an affordant moves, the corresponding regions move as well.

Affordance spaces reflect the spatial constraints deriving from complementing affordances and abilities. The affordances of the affordant and abilities of (potential) agents determine the shape and size of the regions of activity spaces and of affordance spaces produced by the activities and affordances, respectively. For instance, a robot with a short manipulator needs to move closer to the bottle to grasp it than a robot with a long manipulator (these properties belong to the realm of abilities). On the other hand, the robot with the long manipulator might need to keep a certain distance to the bottle to be able to move the manipulator as needed. Thus, the potential agent region produced by the grasping affordance varies in size and distance to the affordant with the abilities of the agent (e.g., it might be more distant and bigger for the long-armed robot). To be able to clearly map between different abilities of agents and fitting geometries of affordance space regions, an affordance can produce different affordance spaces that *support* different abilities.

5. Discussion and Outlook

Affordances are the possibilities for activities provided by environments to agents. It is well-established that activities are spatially extended. Hence, activities have spatial requirements that depend on the type of the activity as well as on the participants' spatial properties (dispositions and abilities). Consequently, we observe that affordances structure space according to the spatial requirements of the afforded activities taking the abilities of potential agents into account.

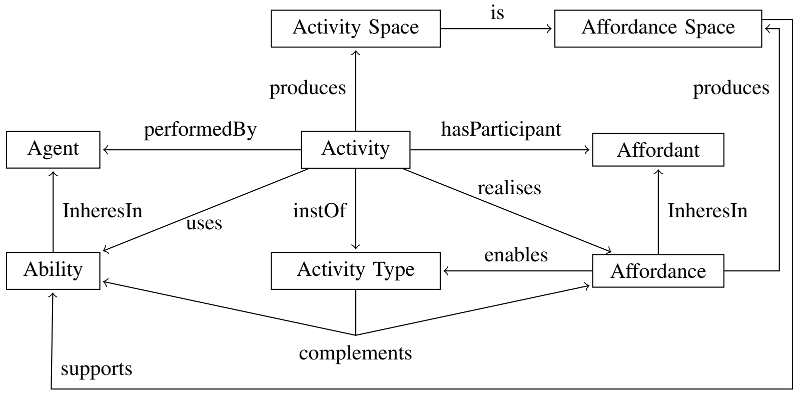

Figure 7. The interrelations between concepts in the theory of affordances and affordance spaces.

Defining affordance spaces as depending on affordances and on abilities of potential agents, our proposal allows to model spatial aspects of affordances in a flexible manner. Taking affordances and their affordance spaces into account, different perspectives on the structure and use of space can be derived.

The general framework for modelling affordances, activities, and their spatial requirement proposed in this article provides a basis for using knowledge about affordances and activities in a diversity of reasoning scenarios. The knowledge about the potential agent region of a viewing affordance provided by a screen mounted at one side of a robot can be used by the robot to reason both about where to move and how to orient to show certain information to a human, or to reason about where to wait for humans to come up when they seek information. Such reasoning would combine specific models regarding the size and shape of agent region and transactional region for specific activities with general rules regarding possible configurations of affordance spaces and activity spaces.

The acquisition of data for building models for optimal positioning of robots in specific activities is a complex and time-consuming task (s., e.g., [15], [17]). However, when such a model is related to the general framework for modelling affordances and affordance spaces presented in this paper, it can be employed in a variety of situations.

One general rule can be derived from the observation that potential agent regions of affordance spaces are occupied by agents when they act upon the affordance. Therefore, blocking (access to) potential agent regions and overlap between potential agent regions of different affordance spaces are conflict prone and should be avoided when one expects the usage of the affordance spaces by co-inhabitants of the environment. On the other hand, as a general difference between activity spaces and affordance spaces we find that motion through (unused) affordance spaces is much less problematic than motion through activity spaces. However, also there will be several more uses of knowledge of affordance space than just the ones mentioned up to now, as we could also think of recognizing actions or intentions of other agents by observing their location relative to affordance spaces.

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