An Affordance-based Conceptual Framework for Spatial Behavior of Social Robots

Felix Lindner and Carola Eschenbach

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 knowledge about (socio-)spacial aspects of affordances can be used in various reasoning tasks relevant to human-robot interaction. Applying the notion of a practical reason, socially-aware robots are able to solve the social activity-placement problem.

Key words: social robots, spatial behavior, conceptual model, affordances

1 Introduction

Gibson (1977) 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.

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The concept of affordance has inspired several researchers in various disciplines such as psychology (Turvey, 1992; Chemero, 2003; Stoffregen, 2003), human-computer interaction (Norman, 1999), geographic information systems (Kuhn, 2007; Raubal, 2001), and robotics (Stoytchev, 2008; Şahin, Çakmak, Doar, Uur, & Üçoluk, 2007; Saffiotti & Broxvall, 2008; Raubal & Moratz, 2008; Krüger et al., 2011), just to name a few. In philosophy, the notion of affordances has been related to phenomenology of Merleau-Ponty (Dohn, 2009). From the perspective of Gibson (1977), 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 (Dohn, 2009).

Traditionally, in robotics, the notion of affordances is related to the action possibilities of a single agent (e.g. Stoytchev, 2008). However, if agents have to coordinate their actions, taking 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.

We have presented a taxonomy of socially meaningful spaces (Lindner & Eschenbach, 2011; Lindner, 2015) including *affordance spaces* and *activity spaces* produced by affordances and activities, respectively.[1] 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 requires taking care of the spatial requirements of the other's activities and coordinating 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

[1] 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.

through, it might be an obstacle for a father with a baby-stroller. Thus, to act in a socially aware manner regarding space requires knowledge about other inhabitants of one's 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 3 discusses activity spaces and affordance spaces in relation to each other and provides a coherent model of affordances and affordance spaces interrelating them with relevant concepts. Section 4 shows how knowledge about affordances and affordance spaces can be used for different spatial reasoning tasks and motivates the need for rating affordance spaces regarding social effects of their use within an environment. Section 5 introduces reasons related to affordance spaces and expected co-inhabitants of the environment as a means to identify socially relevant regions and address the problem of choosing a socially adequate place to carry out an activity. The conceptual framework is applied to two case studies presented in Sect. 6. Sect. 7 discusses the contributions of our framework and provides an outlook.

2 Affordances in Robotics

With a focus on affordance-based robot control, Şahin et al. (2007) 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 (2008). 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 also been done in robot manipulation planning (cf. Krüger et al., 2011).

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 (2008) present an ecology of robots with heterogeneous abilities that can co-jointly 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.

Some approaches concerned with spatial aspects of human-robot interaction address the question of how affordances structure space and yield spatial restrictions.

For example, Yamaoka, Kanda, Ishiguro, and Hagita (2008) 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 (1990). In Section 4, we will indicate how F-Formations can be derived from the combination of more simple affordance spaces.

Sisbot, Marin-Urias, Broquère, Sidobre, and Alami (2010) 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 object to a human, a robot should take the human's field of view into account as well as its own arm length.

The approaches of Yamoaka and colleagues, and of Sisbot and colleagues 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.

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.

3 Activity Spaces and Affordance Spaces

3.1 General Structure of Activity Spaces

Activities are located in space (Kendon, 1990). Any activity occurs somewhere and has a relationship to the spatial regions the participants of the activity are located in. Kendon (1990) 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 (see Fig. 1): The participating agents are located in the *agent region* (p-space). There is a common *transactional region* (o-

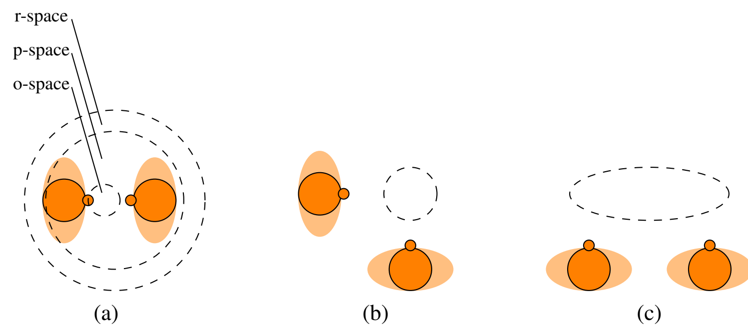

Fig. 1 Several types of F-Formations: (a) vis-a-vis, (b) L-shape (c) side-by-side.

space), 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) 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 (Ciolek & Kendon, 1980). 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. Depending on the relative orientation of the participants, Kendon (1990, p. 213) distinguishes three kinds of F-Formations called vis-a-vis, L-shape, and side-by-side (see Fig. 1).

While Kendon focuses on the spatial structure of interactions between humans, we are generally concerned with activities of humans or robots involving some environmental entity, which affords the activity. However, in Kendon's analysis, environmental entities affording an activity are not considered.

Therefore 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, on the other hand, we allow to distinguish environmental objects as passive participants from agents as active participants of an activity. 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. 2 and Fig. 3). 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 space as they carry different social meanings for participants and non-participants of the activity.

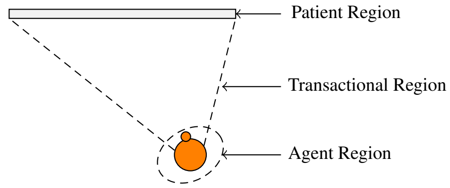

Fig. 2 Scheme of the activity space of an activity of viewing a picture.

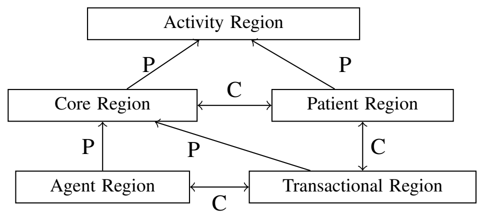

Fig. 3 The social regions of an activity space. The specification makes use of the relations parthood (P) and connection (C). If a region is part of another region, then these regions are also connected.

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).

The agent region of an ongoing activity is occupied by the agent. Therefore other agents should avoid to use it at the same time as the agent region of their activities or pass through it. Also placing oneself in the transactional region or even passing through a transactional region yields a disturbance of the other's activity and should be avoided. However, passing through a transactional region is less critical than passing through an agent region or standing in the transactional region for a longer time. To avoid disturbing ongoing activities activity spaces of ongoing and planned (potential) activities have to be tested for conflicts. Affordance spaces provide a means to model the spatial structure of potential activities.

3.2 General Structure of Affordance Spaces

In analogy to the notion of affordances as potential activities, affordance spaces are potential activity spaces (Lindner & Eschenbach, 2013; Lindner, 2015). 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

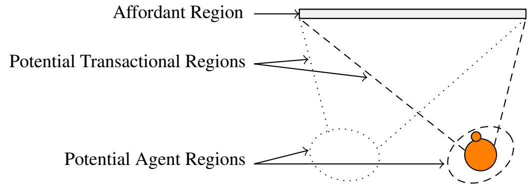

Fig. 4 Two affordance spaces produced by the picture's affordance of being viewable. An unused affordance space (dotted lines) and an affordance space used by an activity (dashed lines), i.e. an activity space.

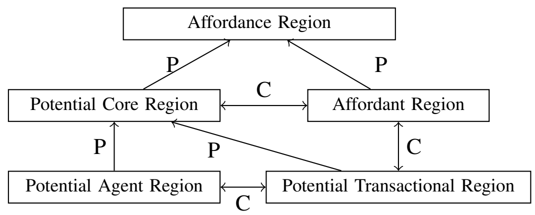

Fig. 5 The (social) regions of an affordance space.

produces an activity space. The spatial structure produced by an affordance corresponds to the structure of the activity (see Fig. 5): 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 (see Fig. 4). We define an activity space as follows: An affordance space *sp* related via an affordance to an activity type Φ is an activity space at some time point t if and only if at t there is an activity of type Φ taking place at *sp*, whereby 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.

Some activities such as viewing a painting do not use the transactional region physically, that is, while the activity takes place, the transactional region is kept free. This is not true for activities such as watering a flower, where the transactional region is filled by the watering can and water. We say that a potential transactional region is *physically used* if and only if the instances of the activity type the affordance space is related to use the transactional region physically.

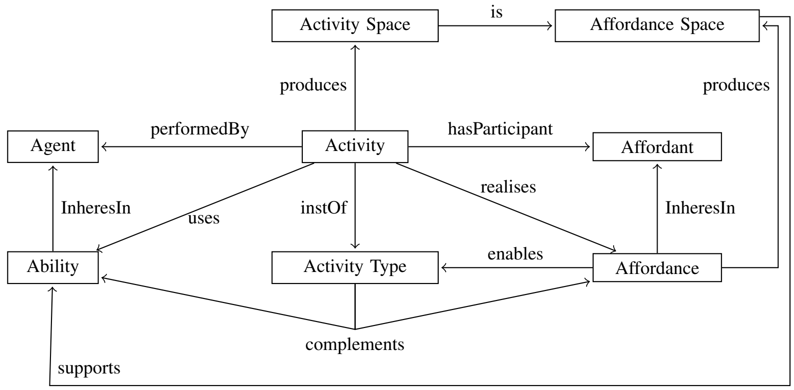

Fig. 6 The interrelations between concepts in the theory of affordances and affordance spaces.

3.3 Affordances and Affordance Spaces

Affordance spaces are *produced by* affordances and represent generic spatial constraints for the afforded activities. Fig. 6 summarizes the interrelations between the concepts we use to describe affordances and affordance spaces. A formal axiomatization of the conceptual model can be found in (Lindner, 2015).

Affordances are properties (dispositions) that *inhere in* affordants. Thus, we adopt the view of Turvey (1992) according to which affordances are properties of environmental entities such as objects and living beings. 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. Again, the idea of abilities and affordances being complementary is in line with Turvey's affordance ontology (Turvey, 1992).

The structure of affordance spaces derives from the spatial needs of activities as discussed in Sect. 3.2. 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. We also say in such cases that the affordance space is *attached to* the affordant.

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.

We consider affordance-space regions to be vulnerable to spatial behavior comparable to activity-space regions. In particular, by selecting a certain position for carrying out an activity (e.g., for recharging) potential agent regions or potential transactional regions related to some other kind of activity can be blocked, and thus, action possibilities for agents become deactivated. However, the number of affordance spaces included in an environment might be rather large, as, for example, every object and every piece of wall affords viewing. Therefore, we need the possibility to distinguish affordances spaces that are socially relevant (we call them *social affordance spaces*) and evaluate potential conflicts derived from blocking them. In Sect. 5 we argue that social affordance spaces are affordance spaces to which socio-spatial reasons against blockages apply. Socio-spatial reasons derive from rules that take expected activities of other agents in the environment into account. But before going into the details of this model, we give some examples to show that afforcance-space knowledge can be used in the context of different types of positioning tasks.

4 Affordance-Space Awareness

Knowledge about affordances and affordance spaces can be exploited 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. 2, 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

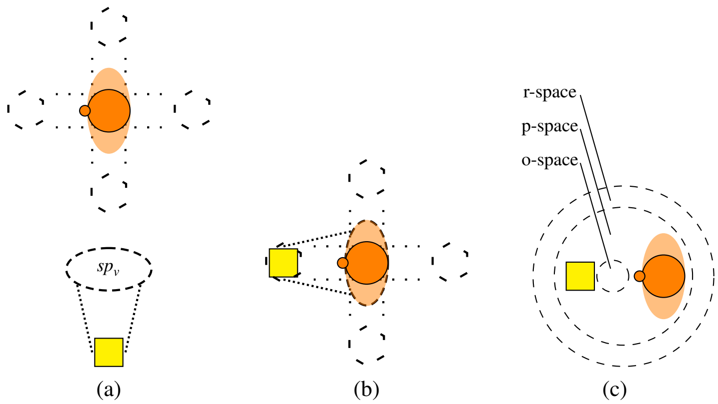

Fig. 7 Simplified illustration of four affordance spaces produced by the talking affordance inherent in a human and one affordance space produced by the viewing affordance inherent in a robot (square) with potential agent regions (dashed) and potential transactional regions (dotted). In (a) interaction 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.

affordance spaces to affordances provided by humans regarding interaction. Thus, 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. 7. The robot provides an information screen that can be viewed by humans with intact vision producing an affordance space sp_v. The human affords being talked to by the robot, and therefore, corresponding affordance spaces are available.

In situations as in Fig. 7a interaction is not possible. To interact with the robot, the human has to be located in the agent region of sp_v, i.e., to be sufficiently close to see the display. Moreover, the human has to be oriented towards the display, i.e., according to the potential transactional region of sp_v. Similarly, to talk to the human the robot has to be in the agent region of a fitting affordance space.

When both agents are located in respective agent regions as in Fig. 7b, bilateral interaction can take place. During interaction, the human viewing the screen occupies the agent region of sp_v, and the robot talking to the human occupies the agent region of an affordance space of the human.

Initially, we have started out by adopting Kendon's analysis of F-Formation and fit it to the case of single agents acting upon affordances. Now we see that Kendon's original F-Formations emerge from several activity spaces, viz., they are constituted by those activity spaces used by agents that interact with one other (Fig. 7c).

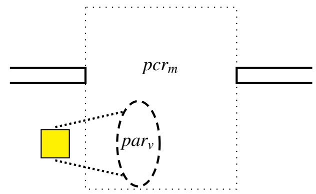

Fig. 8 A potential conflict due to the spatial relation between two affordance spaces. The potential core region (pcr_m) of the movement affordance provided by the doorway intersects the potential agent region (par_v) of the viewing affordance provided by the robot (hexagon).

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

In Fig. 8, 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. 8 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.

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.[2] 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

[2] 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.

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 affordance 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. Yamaoka et al., 2008; Sisbot et al., 2010). 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.

5 Reason-driven Activity-Placement Planning

In the following, we focus on solving the *social activity-placement problem*, which is defined as follows: *Given an activity type ϕ and a potential agent α, a placement π should be determined, such that α can successfully ϕ at π, and π is among the most socially adequate placements for α to ϕ* (Lindner & Eschenbach, 2013). The activity-placement problem is a generalization of the robot placement problem (e.g. Stulp, Fedrizzi, Mösenlechner, & Beetz, 2012; Zacharias, Borst, Beetz, & Hirzinger, 2008). The potential agent can be the robot itself, but it can also be some other agent for whom the robot has to find a placement.

To determine a most socially adequate placement for an activity, a social robot needs to identify locations where its own and others' activities can be placed (functional level), identify potential conflicts related to these placements (functional level), find the socio-spatial reasons that speak for or against the derived candidate placements relative to the identified potential conflicts, and determine the preference order of the placement candidates resulting from the related reasons (social level). In the first subsection, we will address the functional level, in the second subsection, we will address the social level on this basis.

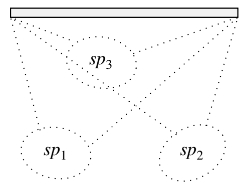

Fig. 9 Affordance spaces of the painting in conflict to each other.

5.1 Candidate Affordance Spaces and Conflicts

To establish the foundation for an affordance-based solution to the social activity-placement problem, we define candidate affordance spaces and conflicts between affordance spaces. An affordance space *sp* is a *candidate affordance space* for activities of the type ϕ as performed by an agent α if and only if the affordance that produces *sp* is complementary to an ability of α with respect to ϕ and *sp* supports the spatial ability of α. The available candidate affordance spaces in a given situation thus constitute the space of functionally possible placements for an activity of type ϕ performed by agent α.

With respect to the social level, we aim to implement a principle of social activity placement which says "You should not block others' possiblities for action." Therefore, we have to settle what it means to block a possiblity for action. To this end, we introduce definitions of types of conflicts between affordance spaces (cf. Lindner, 2015).

First, we observe that affordance spaces cannot be used by different activities in parallel if their potential agent regions overlap, because otherwise the agents of the two activities would physically collide. Thus, affordance spaces are in *conflict of type AA* if and only if their potential agent regions overlap. We observe that every affordance space is in *AA*-conflict with itself. This fits the demand that the conflict relation models which affordance spaces cannot be used by different activities (with different agents) at the same time.

It is not necessarily the case that two affordance spaces are in conflict if their potential transactional regions overlap. For instance, the affordance spaces sp_1 and sp_2 in Fig. 9 can be used in parallel by two different visitors viewing the painting. However, if activities using the affordance spaced make conflicting physical use of the transactional regions (for instance, activities of painting), then the affordance spaces should be classified as being in conflict. Affordance space *sp conflicts with type TT* with affordance space sp' if and only if the potential transactional regions of *sp* and sp' overlap and the physical use associated with the potential transactional region of *sp* conflicts with the physical use associated with the potential transactional region of sp'. Note that while *AA*-conflict is a symmetric relation, this is not true for *TT*-type conflicts.

Furthermore, in Fig. 9 the affordance space sp_3 cannot be used in parallel without the agent of the activity placed in sp_3 standing in the field of view of the agent placed in sp_1 or sp_2. This is because the potential agent region of sp_3 overlaps the potential transactional regions of sp_1 and sp_2. This type of conflict is of the *AT*-type. Affordance space *sp conflicts with type AT* with affordance space sp' if and only if the potential agent region of *sp* overlaps the potential transactional region of sp' and the presence of an agent in the potential agent region of *sp* conflicts with the physical use associated with the potential transactional region of sp'. Correspondingly, affordance space *sp conflicts with type TA* with affordance space sp' if and only if the potential transactional region of *sp* overlaps the potential agent region of sp' and the physical use associated with the potential transactional region of *sp* conflicts with the presence of an agent in the potential agent region of sp'.

We say that two (not necessarily distinct) affordance spaces are in *conflict* if and only if they stand in one of the discussed conflict relations. Sometimes, it turns out to be more convenient to subsume *AA*-conflicts and *AT*-conflicts under the concept of an *AC*-conflict, which is a conflict due to the overlap of a potential agent region with a potential core region: If and only if two affordance spaces stand in conflict of type *AA* or of type *AT*, they stand in conflict of type *AC*.

5.2 Socio-Spatial Reasons

So far, the model contains candidate affordance spaces in which activities can be placed as well as conflict relations between affordance spaces. However, this information is not yet sufficient to solve the social activity-placement problem for at least two reasons: First, not every conflict yields a real problem. Think of all the affordance spaces around us no one might ever (or rarely) use, e.g., the affordance spaces attached to the wall which can be used to hang up a picture. Usually, it is not expectable that someone uses such affordance spaces and therefore we block such affordance spaces all the time without being accused of inconsiderate behavior. Second, often there is no way to avoid conflicts. In such dilemma situations, to pick the socially most adequate candidate affordance space for an activity, one needs a means to rank the available candidates based on the identified conflicts.

To provide normative meaning to the relevant affordance spaces and to be able to rank candidate affordance spaces, the concept of a socio-spatial reason is introduced and put into action using a decision rule.

Our reason-driven view (cf., Lindner, 2015) is inspired by contemporary work in practical philosophy. Particularly, the moral philosopher Joseph Raz characterizes reasons as “facts that have normative bearing or force” (Raz, 2011, p. 23). Furthermore he claims that “[Reasons] are called ‘reasons’ because they can serve as stepping-stones in reasoning about what to believe or what to do. Deliberating from the reasons that apply to us we become aware of the attractions and drawbacks of options” (ibid).

According to this characterization, we introduce *socio-spatial reasons* as a special sort of reasons. They are normative facts like “one should not block this affordance”. As such they are connected to particular affordances via a relation called

	sp_1		sp_2		sp_3	
	Pro	Con	Pro	Con	Pro	Con
Strong					ρ_6	
Medium	ρ_1		ρ_3			
Weak		ρ_2		ρ_4, ρ_5	ρ_7	ρ_8

Table 1 Example bipolar decision case: Candidate affordance spaces sp_1, sp_2, sp_3 and reasons $\rho_{1\text{-}8}$ having polarity (pro/con) and strength (strong, medium, weak).

source-of. For instance, in Fig. 8 (p. 11), the affordance inherent to the doorway is source of a reason "one should not block the affordance to walk through this door". Socio-spatial reasons *apply to* agents placing activities at affordance spaces. In the case depicted by Fig. 8, the reason applies to placing viewing activities in the affordance space attached to the robot.

In addition to being sourced by entities such as affordances, socio-spatial reasons are modeled as having normative force. Normative force is assumed to take values in a two-dimensional space spanned by polarity (pro or con) and strength (e.g., strong, medium, and weak). For instance, the fact "you should not block the affordance to walk through this door" is a con-reason. The strength might depend on different factors like how many other doorways there are to enter this area and how many humans are expected to move into and out of this area. On the other hand, affordances are sources of pro-reasons like "one should behave as expected". For instance, if a particular robot usually recharges its batteries at a particular outlet such that the others expect the robot to use it if needed, the robot should keep using this particular outlet, that is, the affordance space attached to it.

Having said that, the activity-placement problem, viz. the problem to place an activity of type ϕ as performed by agent α, can be solved by a three-step procedure: First, the available candidate affordance spaces that can be used for ϕ-activities as performed by α are determined. Second, for each of these affordance spaces the socio-spatial reasons that apply to them are identified. Third, a decision rule ranks the candidate affordance spaces based on aggregating the reasons and proposes a best candidate based on this ranking.

Among the decision rules available, we choose the Levelwise Tallying rule (Dubois, Fargier, & Bonnefon, 2008). Bonnefon, Dubois, Fargier, and Leblois (2008) show Levelwise Tallying to predict many human choices in a psychological experiment.

Our adaption of Levelwise Tallying determines for each pair of candidate goal affordance spaces sp_1 and sp_2 whether the usage of sp_1 is to be preferred over the usage of sp_2. For both candidates, the number of con-reasons of the highest strength are subtracted from the number of the pro-reasons of highest strength. The candidate with the highest score wins. If the scores are equal, then the procedure is repeated on the next lower level of strength. If neither of the candidates is preferred to the other, they are ranked equivalent regarding preference.

An example is given in Table 1: A decision has to be made between using affordance space sp_1, sp_2, or sp_3. Since sp_3 is the only one with a pro-reason at the highest level and there is no con-reason at the same level, it wins the comparison with sp_1 and sp_2. Affordance space sp_1 is preferred to sp_2 as the reasons at the two highest levels are in balance and sp_2 has more con-reasons than sp_1 on the lowest level. Thus, the candidates are ordered as $sp_3 > sp_1 > sp_2$. After ranking the candidate goal affordance spaces, one of the best candidates can be selected (in this example, sp_3 will be selected).

6 Case Studies

This section demonstrates by two case studies how the social activity-placement problem can be solved by employing the concepts and relations so far defined. The case study in Subsect. 6.1 is about a human employing socio-spatial reasons to make a choice between two available candidate affordance spaces. Subsection 6.2 exemplifies how an affordant can use knowledge about affordance spaces and socio-spatial reasons to place itself attentively.

6.1 An Activity-Placement Scenario

In Fig. 10, there are a doorway, two terminals A and B, and a human H. The doorway inheres an affordance complementary to abilities of mobile actants with respect to the activity type of walking through the door. This doorway's affordance produces an affordance space depicted as a dotted rectangular in Fig. 10. Besides the doorway, there are two more affordants A and B. For the sake of this example, we assume A and B to be ATMs. Each of them inheres an affordance which is complementary to the ability of the human H to draw money at an ATM. Each of these affordances produces an affordance space at which the human can place its activities of type *drawing money*. The affordance space attached to ATM A is represented by sp_A and the one attached to ATM B is represented by sp_B.

Let us now assume that the human H wants to place an activity of the type *drawing money* socially, assuming that there are other humans around that want to pass through the doorway. That is, the human has to solve an instance of the social activity-placement problem: Given the activity type *drawing money* and the potential agent H, a placement π should be determined, such that H can successfully do *drawing money* at π, and π is among the most socially adequate placements for H to do *drawing money* (compare to the definition of the general social activity-placement problem on page 12).

The first step of the procedure is to determine the candidate affordance spaces for *drawing money* activities performed by H. These are the affordance spaces of A (sp_A) and of B (sp_B). Subsequently, the socio-spatial reasons are identified that

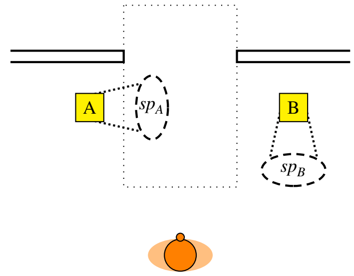

Fig. 10 Activity Placement: The human has the choice to either place its activity at the affordance space sp_A of affordant A or at the affordance space sp_B of affordant B.

apply to using either of these candidate affordance spaces. Based on the assumption that someone else will likely use the affordance space of the doorway, the socio-spatial reason of negative polarity provided by the affordance of the doorway applies to H using sp_A for drawing money as the sufficient conditions are fulfilled in this situation: The candidate affordance space sp_A is in conflict (of type AC) with an affordance space that someone else might want to use.

Hence, in this situation, the socio-spatial reason "you should not block the affordance of walking through the door" is a reason against H using sp_A for drawing money, but not against H using sp_B for drawing money. Consequently, the Levelwise Tallying rule outputs the order $sp_B > sp_A$.

Acting in a socially aware manner, the human H will now place its activity at sp_B.

6.2 An Affordant-Placement Scenario

The task of affordant-placement shows that a social robot that knows about the affordance spaces attached to one's own body can attentively position itself such that someone who wants to act upon one of the robot's affordances can do so without blocking the affordance spaces of others.

A corresponding situation is depicted in Fig. 11. Unlike the first example, A is the only ATM available and A can move.[3] As in the previous example there is a doorway affording walking through the door. The ATM A provides the affordance to withdraw money. This affordance produces the affordance space sp_1. In addition, A affords to be reloaded. Thus, if the fill status of A drops below a certain level, A can alert people who have the permission to open and refill A. This affordance produces affordance space sp_2.

[3] There already exists a robotic ATM prototype. Such machines might be deployed in casinos as pointed out in an online article that can be found on the internet: http://www.atmmarketplace.com/blogs/cash-at-your-service/

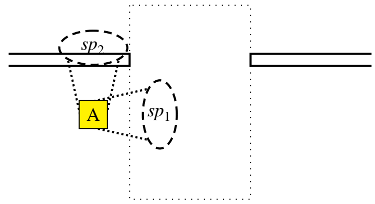

Fig. 11 Affordant placement: In the current situation, the affordance space sp_{A_1} attached to the robot cannot be used by a human without blocking the door. The affordance space sp_{A_2} cannot be used because it overlaps with the wall.

In the situation depicted in Fig. 11, the affordance space sp_1 is in conflict with the affordance space of the doorway, and affordance space sp_2 cannot be used because it overlaps with the wall. We assume that the robot can perform 90 degrees clockwise rotations and forward translations in half-meter steps. At each pose so reachable from the initial pose, the robotic ATM can identify the conflicts between affordance spaces using its knowledge about affordance spaces and conflicts. For instance, just using the knowledge about conflicts of affordance spaces, the ATM might decide to move to the bottom left corner, where none of the affordance spaces attached to A conflicts with the affordance space of the doorway. If none of the affordance spaces conflicts with the affordance space of the doorway, the socio-spatial reason not to block the doorway does not apply to any of them.

Figure 12 illustrates how the robot can systematically find a pose where none of its affordance spaces are in conflict with the affordance space of the doorway. Starting from the initial situation (S1) the robot successively simulates rotations and forward translations. After two virtual rotations, a state (S4) is found which fits the demand that both affordance spaces sp_1 and sp_2 can be used without conflicts.

However, one might also be interested in minimal sequences of actions that get the robotic ATM from the initial pose to a pose which is optimal with respect to the current expectations about the use of the affordance spaces sp_1 and sp_2. Assume that it is expectable that the human H uses sp_1 for withdrawing money. In this case, the search for a better pose can already be terminated after one rotation, because the resulting state (S2) has the property that there is no socio-spatial reason speaking against H using sp_1 for withdrawing money. Note that this state is suboptimal with respect to using affordance space sp_2.

A different situation occurs when the fill status of the ATM A drops and A sends an alert to someone who is authorized to refill the ATM (let us call this person $H2$). In this case, the ATM being in the initial situation realizes that there is no candidate affordance space usable that could be used by $H2$ refilling it. Thus, the robot invokes the search process and successively evaluates the resulting states with respect to the socio-spatial reasons that apply to $H2$ using sp_2 for refilling the ATM. Consequently, the search process in Fig. 12 finds a socially adequate pose after two rotations (S4). This is the same state found in the search for a state with no conflicts between the affordance spaces of the ATM and the affordance space of the robot. If we allow the robot to also perform counterclockwise rotations or sideway translations, the search

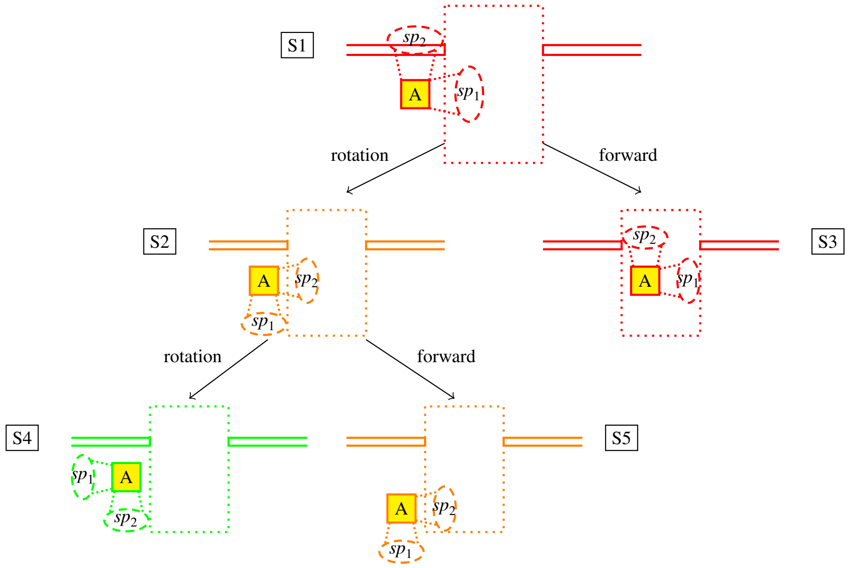

Fig. 12 Departing from the initial situation (S1) the space of possible poses is explored by virtally applying rotation and forward translation to the robot's position. Each resulting state is evaluated. S1 and S3: Both of the robot's affordance spaces sp_1 and sp_2 cannot be used without conflict. S2 and S5: At least one of the affordance spaces can be used without blocking the door. S4: Both of the robot's affordance spaces can be used without any reasons speaking against it.

process will find a pose which guarantees $H2$ to use sp_2 in a socially adequate manner after either one of these two actions.

As is once more shown by this example case for the affordant-placement task, the mere location of an affordant does not suffice to evaluate the social acceptability. Particularly, it is not sufficient to only check if A is in the doorway, because there are poses of A that lead to conflicts although A itself is not blocking the doorway at all. Only when the knowledge about the affordance spaces is represented, and thus the whole space that will be needed by activities, activities can be placed such that a potential user will not be accused of socially inadequate behavior.

7 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.

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 (see, e.g. Stulp et al., 2012; Zacharias et al., 2008; Yamaoka et al., 2008). 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, motion through (unused) affordance spaces is much less problematic than motion through activity spaces. Further principles of socially appropriate spatial behavior are formalized in (Lindner, 2015).

The reason-driven approach to modelling social affordance spaces gives a basis for communicating why a certain choice has been taken ("I recharge here as my battery is very low and recharging at the other recharging stations close by would disturb John watching TV or block the entry to the kitchen"), generating an apology ("I am sorry to block the entry to the library"), or doing both ("I am sorry to block the entry to the library but I have to recharge and all other stations are occupied by other robots").

Finally, from the perspective of robot behavior programming, it is noticable that the socially-aware robots presented here have the capability to adapt their spatial behavior autonomously. There is no need to program the robots, for instance, to move to one pose at eight p.m. and stay there until ten p.m. and then to move to another pose etc. Under the affordance-based and reason-driven perspective, all decisions rest upon the knowledge declared in the robot's knowledge base.

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