Towards a Formalization of Social Spaces for Socially Aware Robots

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Abstract. This article presents a taxonomy of social spaces distinguishing five basic types: personal space, activity space, affordance space, territory, and penetrated space. The respective space-constituting situations and the mereotopological structure for each social space type are specified. We show how permissions for actions of agents in social spaces can be modeled using the situations calculus. Specifications of social spaces and permissions build the fundament for socially aware action planning.

1 Introduction

Human-robot interaction (HRI) is concerned with the design of interaction between robots and humans and, thereby, to foster the acceptability of robots in every day situations, e.g., at home, at work, in museums, or in hospitals. In this respect, *social robots* are defined as "autonomous or semi-autonomous robots that interact and communicate with humans by following the behavioral norms expected by the people with whom the robot is intended to interact" [1].

A recent long-term study shows that the behavior of state-of-the-art service robots used in hospitals do not always meet people's expectations [15]. One insight gained from this study is that humans are sensitive to the spatial behavior of robots: Humans feel offended by robots cutting in on their paths, standing in the way, or approaching inappropriately close. Particularly, as robots are situated in physical space, socially adequate behavior inevitably involves socially adequate *spatial behavior*, which demands for the capability to reason about social restrictions regarding the performance of actions in spatial regions carrying social meaning.

To design spatial behaviors for robots that match people's expectations, we model human social spatial behavior that is phenomenologically described in literature on human social interaction. Drawing from ethnological studies [6, 7] and from existing approaches to conceptualize spacing in social sciences [13], we propose qualitative formalizations of social spaces. These formal specifications can be directly exploited for socially aware symbolic action planning in robotics. Our approach complements empirical findings and quantitative data raised during numerous HRI experiments, e.g., distances and orientations kept in human-robot encounters [8, 22].

This article is structured as follows: Section 2 outlines existing types of social spaces described in social sciences literature on human-human interaction and discusses their relevance for HRI. In Sect. 3, a taxonomy of social spaces is formally specified. Based on these formalizations, an axiomatization of permissions with regard to the social adequacy of actions in social spaces using the situation calculus [20] is proposed in Sect. 4. We introduce a simple action planner making use of the knowledge about social spaces and their respective social restrictions.

2 Social Spaces

Löw [13] defines social spaces as relational arrangements of living beings and social objects at places. In the constitution of social spaces, two sub-processes are involved: *Spacing* is the process of acting that leads to a specific arrangement of objects and living beings, and *synthesis* is the process of integrating, perceiving, and interpreting spatial constellations as social entities.

From a HRI point of view, the relevance of social spaces is twofold: On the one hand, robots are physically situated and, as they act in the environment, they produce social spaces. This social space production should take place in a socially adequate manner. On the other hand, a service robot will be faced with social spaces constituted by humans. The robot then should know about the social meaning of social regions to adapt its behavior accordingly in order to match people's expectations.

In this article, both of the roles of social spaces are described. However, our specification of socially aware spatial behavior focuses on socially adequate action sequences in the face of social spaces constituted by other agents, thereby neglecting the spaces produced by the robot while acting. In particular, we consider entering and parking in social regions: Our robot ought not to enter regions it is not allowed to enter, it ought to avoid blocking certain social regions by parking there or by putting objects in such regions.

Social spaces constitute a spatial layer that can be described by topological terms using regions as the basic spatial entities. Although the depictions in this section inevitably contain geometric representations, we do not discuss the geometry of social spaces, as a high diversity of factors determine the shape and size of social space geometries. The geometric grounding of social spaces varies with time, such that at certain times different social spaces can overlap or influence each other's geometric extension. Nevertheless, the internal topological structure of social spaces is temporally invariant. Therefore, topological notions are useful for describing the time-invariant spatial properties of the structure of social spaces. Specifically, topological specifications support reasoning about action permissions.

In the following, we distinguish five types of social spaces: personal space, activity space, affordance space, territory, and penetrated space.

2.1 Personal Space

In his seminal work [7], Hall describes personal space as an invisible ellipsoid-shaped space surrounding each human. The personal space consists of four basic regions: intimate region, personal region, social region, and public region. Each of these four regions is subdivided into a corresponding near region and a far region (see Fig. 1, which depicts eight regions in total).

Every such region carries a specific social meaning depending on the type of interaction and on certain properties like gender, age, cultural background, and social status of the interactants.

According to Hall, the intimate region is reserved for lovers and close friends. In this region, people touch and hug each other, whereas communication via other modalities (especially speech) is unusual. The far intimate region affords verbal communication in whispering mode. Visual perception in the intimate regions is distorted and people normally feel uncomfortable if someone intrudes their intimate region without permission.

People in public who stand in near personal region are perceived as a social unit and thus signal their intimate relationship, or their *withness* as Goffman [6] puts it. In some cultures, people tend to interpret intrusion of strangers into the near personal region as severe violation. The far personal region keeps people at arm length. In this region, dialogs with friends take place.

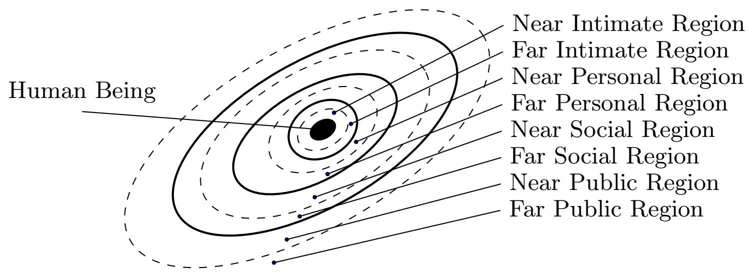

Fig. 1. The eight regions of Hall's Personal Space

The near social region is used for conversation in public and to nonfriends. People jointly working together position themselves in near social region. The far social region usually is free for intrusion by other people without annoying the claimant of the personal space. People positioned in the far social region are perceived as not belonging together.

People in the public region are normally ignored, but there are numerous formal settings, in which interaction in the public region takes place [11]: lectures to students, a speech, a concert, or a performance in a theater. The voice then must be raised, and the tempo and phrasing must be adapted. In Hall's conception, the public region is not limited in its extent. For our purpose, we think of the public region to be a limited region just like the other personal space regions. Thus, a personal space can be contained in a room or a building.

Personal space is relevant to social robots, because robots should place itselves appropriately with regard to the current task [22] and the social relationship between the robot and the human (i.e., the roles played in a given interactional context). A talking robot should place itself in a region appropriate for talking, a robot passing by should not enter regions that are too intimate.

2.2 Activity Space

A notion of social spaces that are constituted via action is introduced by Ostermann and Timpf [16] under the term *activity footprints*. Activity footprints are used for the analysis of space appropriation in public parks: The activity of playing football constitutes the space needed for playing football, the activity of running constitutes the space needed for running, etc. The authors further discuss relations of compatibility between different types of activity footprints, i.e., whether it is adequate to have different types of activity footprints overlap (e.g., kicking around in the park is antagonistic to reading a book, thus, overlaps of footprints of these kinds yield social conflicts).

Activity space resembles the concept of activity footprints, however, not every aspect of an activity footprint counts as an activity space, as discussed in subsequent sections. Moreover, activity spaces are formalized on a qualitative level (rather than quantitatively as in the case of activity footprints) and they contain representations of the respective space-constituting situations.

Another type of activity spaces has been described by Kendon [9]. Kendon's model of so called F-Formation results from studies conducted in human-human interactional settings with particular focus on the spatial patterns people produce while having conversations. F-Formations consist of three sub-regions: o-space, p-space, and r-space (see Fig. 2). The o-space is the region, in which the interaction actually takes place (subsequently denoted as *transactional region*), the p-space is the region where the interactants are located in (*agent region*), and the r-space separating the setting from the environment (*buffer region*). In our conception, every activity space yields a corresponding spatial structure.

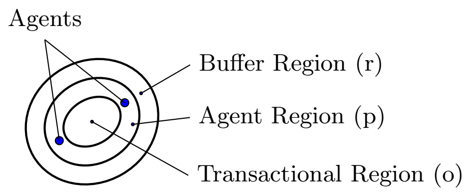

Fig. 2. Kendon's F-Formation of the Face-to-Face type

A robot should be aware of activity spaces, so that robot placement and motion does not conflict with activity spaces produced by other social agents.

2.3 Affordance Space

The affordance space is related to the concept of affordances as potential activities the environment provides to agents [5].

Galton [4] investigates and formalizes affordances with respect to space. He thereby explicitly notes the modal characteristics of affordances: A situation affords an action to an agent if and only if it is possible for the agent to perform the action in this situation.

In the context of robotics, Raubal and Moratz [19] introduce the notion of social-institutional affordances. Although it might be physically possible for an agent to perform an action in a particular situation, it might be socially inacceptable. Notably, the representations of affordances introduced in [19] support reasoning about affordances of different individual agents. This is particularly relevant in HRI, because in HRI, agents with very different capabilities (humans and robots) have to coordinate action.

In analogy to the notion of affordances as potential activities, affordance spaces are potential activity spaces. Consequently, affordance spaces are composed of a potential agent region, a potential transactional region, and a potential buffer region. A notion of potential activity spaces has been introduced by Ostermann and Timpf [16]. However, the internal structure of affordance spaces has not yet been discussed. In addition, it lacks a formal analysis of the implications affordance spaces have for acting and interacting social agents. For the pupose of planning social behavior, the conceptual distinction of activity spaces from affordance spaces is crucial. For instance, crossing an affordance space is generally unproblematic as compared to crossing an activity space.

To give an example, consider the affordance space constituted by the pressability affordance of a light switch. The spatial extension of this space depends on the abilities and the body shape of the agent. For a human with normal stature and motor abilities, the affordance space is as big as needed for the person to stand in front of the switch and to reach for it with her arm. For a robot without any means to press a light switch, consequently, there is no such affordance space. But even though a light switch might not afford pressing to a specific robot, to act socially aware, the robot should know that to other agents the light switch does afford pressing. Thus, the robot should not block affordance spaces for a longer period of time, for instance, by parking there or by placing objects in it.

2.4 Territory

In biology, the term *territory* denotes an area claimed by an animal or by a group of animals defending it against competitors. Most territorial animals mark the borders of the territory so that competing animals perceive the area as being already occupied by some other individual. In social sciences, the concept of territory is adapted to explain spatial behavior of humans owning, claiming, and defending space (e.g., [6, 11]).

Territories can be as big as a country or as small as a cup. Lawson [11] distinguishes national territory, city territory, and familiy territory. There is always a notion of possession and exclusive usage connected to a territory.

In many occasions, signs tell people that they are allowed or not allowed to enter a particular territory (e.g., "authorized personnel only"). Furthermore, territories can be prohibited for some species (e.g., "dogs have to stay outside") and behavior might be restricted for those that are located inside a territory (e.g., "no smoking").

Goffman [6] distinguishes three kinds of markers for territories: Boundary markers explicitly mark the territorial boundary (e.g., the armrest of a chair, the walls of a room, or the bar used in checkout counters to separate the articles of one customer from the next), central markers are located in the center region of a territory (e.g., a towel on the beach signaling occupancy), and ear markers are labels that signal the possession of an object or of a portion of space (e.g., a door-bell nameplate).

Territories call for different requirements on the robot's behavior (e.g., territories in a person's home vs. territories in a hospital vs. territories in a supermarket). Unauthorized intrusion of territories usually leads to social violations.

2.5 Penetrated Space

There are circumstances, in which side effects of activities, such as noise, odor, dust, or light, make activities appear socially inadequate. The activity footprints by Ostermann and Timpf [16] consider this aspect: The activity footprint constituted by the activity of barbecuing extends to a wide area as fume spreads to a far distance away from the actual location of the barbecue, depending from where the wind blows. Keeping with this example, in the terminology developed in this article, we distinguish the activity space of barbecuing (i.e., the space actually needed for barbecuing) from the penetrated space (i.e., olfactory-penetrated space) of barbecuing.

The center of a penetrated space is the initiator situation of the penetration (i.e., agents and/or objects producing penetration). Usually, there is no claimant for such a penetrated space (i.e., nobody would claim to be the owner of a pentrated space). Nevertheless, there can be agents being to some extend responsible for its existance.

Penetrated spaces usually do not call for special permissions in order for an agent to act in it. This constitutes another argument for the separation of activity space and penetrated space for the purpose of reasoning about behavior, although, of course, most penetrated spaces co-occur with activity spaces.

A social robot might have to reason about the adaption of its behavior due to penetrated spaces. For instance, in noise-penetrated spaces, a robot might have to change its location to be recognized by the other interactants [14]. The actions of the robot in many cases produce penetrated spaces of which the robot should be aware, e.g., the robot should not vacuum-clean offices people are just working in.

3 Formalizing Social Spaces

This section provides formal specifications of the five types of social spaces regarding their constitution by agents and activities and their spatial structure, which is described using mereotopological concepts.

3.1 Spatial Framework

Our specifications make use of relations provided by several mereotopological frameworks such as the Region Connection Calculus (RCC) [18]. The following mereotopological relations that can hold between regions of arbitrary shape are needed:

$\mathrm{P}(r, r')$	r is part of r'
$\mathrm{TPP}r, r')$	r is a tangential proper part of r'
$\mathrm{NTPP}(r, r')$	r is a nontangential proper part of r'
$\mathrm{EC}(r, r')$	r is externally connected to r'
$\mathrm{O}(r, r')$	r overlaps r'

As social spaces constitute dynamic spatial structures that may move relative to physical space, the following mereotopological specifications of social spaces can also be understood in the sense of Donnelly's theory of relative places [3]. Taking this view, social space regions form location complexes that maintain an invariant internal topological structure but can coincide with different locations at different times.

Apart from the relations mentioned, the function $\mathrm{sum}(r, r')$ is needed to refer to the region that is the sum of r and r' [18].

In addition to that, the relation surrounds (SR) is defined as a special case of external connectedness (D1). A region r surrounds a region r' iff r is externally connected to r' and every region r'' externally connected to r' overlaps r.

(D1) $$\mathrm{SR}(r, r') \equiv_{def} \mathrm{EC}(r, r') \wedge \forall r'' \, [\mathrm{EC}(r'', r') \supset \mathrm{O}(r'', r)]$$

To state that the part relation holds between an agent or an object and a region, we write $\mathrm{P^O}$. This notation is an abbreviation for stating that the region occupied by an agent (first argument) is part of another region (second argument), cf. [4] for a similar treatment.

Both personal spaces and penetrated spaces exhibit a gradual structure with a center of high intimacy or intensity, fading towards the periphery. For this reason, we adapt a qualitative approach to modeling graded structures based on bundles of regions suggested by Kulik and colleagues [10]. We demonstrate in Sect. 4 that the specification of permissions regarding territories and activity spaces is supported by region bundles as well. As far as is neccessary to understand the gradual model, we replicate here the axiomatization of region bundles proposed in [10].

A region bundle is constituted by one or more regions. The relation Contains relates a region bundle to each constituting region. The extensionality assumption (ARB1) states that different region bundles contain different regions (SI1 in [10]).

$$\text{(ARB1)} \qquad \forall b, b' \, [[\text{RegionBundle}(b) \wedge \text{RegionBundle}(b')] \supset [\forall r \, [\text{Contains}(b, r) \equiv \text{Contains}(b, r)] \supset b = b']$$

A region bundle b defines a reflexive and transitive relation $\succeq_b$ of centrality for its regions (D2). Region r is at least as central as region r' relative to bundle b ($r \succeq_b r'$) iff r and r' both are contained in b and r is part of r' (D4 in [10]).

$$\text{(D2)} \qquad r \succeq_b r' \equiv_{def} \text{Contains}(b, r) \wedge \text{Contains}(b, r') \wedge \text{P}(r, r')$$

Axiom (ARB2) states that this order is total for the bundle regions, i.e., for every two bundle regions r and r', one is at least as central as the other (SB2 in [10]).

$$\text{(ARB2)} \qquad \forall r, r', b \, [\text{Contains}(b, r) \wedge \text{Contains}(b, r') \supset [(r \succeq_b r') \vee (r' \succeq_b r)]]$$

Based on a region bundle, arbitrary regions can be compared with respect to the gradient structure defined by the region bundle. One possibility (taken here) is to compare two regions with respect to the most central bundle region they overlap. An ordering for arbitrary regions can therefore be defined as (D3). A region r is at least as central as a region r' with regard to a region bundle b iff every bundle region r'' that overlaps r' also overlaps r (D7 in [10]). (D4) and (D5) introduce additional notions for the maximal symmetric and asymmetric subrelation of this partial order.

$$\text{(D3)} \qquad r \geq_b r' \equiv_{def} \forall r'' [\text{Contains}(b, r'') \supset [\text{O}(r', r'') \supset \text{O}(r, r'')]$$

$$\text{(D4)} \qquad r =_b r' \equiv_{def} [(r >_b r') \wedge (r' >_b r)]$$

$$\text{(D5)} \qquad r >_b r' \equiv_{def} [(r >_b r') \wedge \neg(r' >_b r)]$$

As a consequence (T1), any two regions r and r'' can be compared with respect to every region bundle b (T5 in [10]).

$$\text{(T1)} \qquad \forall r, r', b \, [(r \geq_b r') \vee (r' \geq_b r)]$$

A notion of betweenness of regions with regard to a region bundle is defined by (D6): A region r is said to be located between two regions r' and r'' w.r.t. a region bundle b iff r is more central than r' and r'' is more central than r (or the same but r' and r'' change roles).

$$\text{(D6)} \qquad \text{Btw}(b, r', r, r'') \equiv_{def} [[(r' >_b r) \wedge (r >_b r'')] \vee [(r'' >_b r) \wedge (r >_b r')]]$$

To give an example, in Fig. 3 there are several regions located relatively to a region bundle b consisting of three ellipsoid regions. The regions $R1$ to $R5$ are located within this gradient structure. With the relations defined above it holds that $R4 >_b R2 =_b R3 >_b R1 >_b R5$, and $\text{Btw}(b, R5, R3, R4)$.

The formalization of region bundles does not restrict the number of regions defining a region bundle. Region bundles can contain an infinite or a finite number of regions. Even one or two regions can be sufficient for a region bundle.

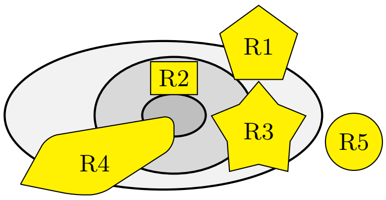

Fig. 3. Regions located relatively to a region bundle

3.2 Modeling Penetrated Space

A penetrated space *sp* consists of a physical situation *p* producing it and a group of agents[1] *ag* that is responsible for *p* (APS1).

(APS1) $\forall sp\, [\text{PenetratedSpace}(sp) \supset$
$\exists p, ag\, [\text{PhysicalSituation}(p) \wedge \text{Constitutes}(p, sp) \wedge$
$\text{AgentGroup}(ag) \wedge \text{hasResponsibleAgents}(p, ag)]]$

Usually, the physical situation produces a penetration of space such that the intensity of penetration is highest in the vicinity of the space-initiating situation and diffuses along the way to the periphery. This gradient of different degrees of penetration is modeled by associating a bundle of regions *b* (APS2).

(APS2) $\forall sp\, [\text{PenetratedSpace}(sp) \supset \exists b\, [\text{RegionBundle}(b) \wedge \text{hasGradient}(sp, b)]]$

The shape of the regions is a consequence of the underlying physical process that produce the penetrated space. It is not restricted by the model in any way.

3.3 Modeling Personal Space

At the social level, Hall's personal space is represented as a social space having a constituting human. Every personal space *sp* is constituted by a human *h* and every human constitutes a personal space:

(AHPS1) $\forall sp\, [\text{PersonalSpace}(sp) \supset \exists h\, [\text{Human}(h) \wedge \text{Constitutes}(h, sp)]]$

(AHPS2) $\forall h\, [\text{Human}(h) \supset \exists s\, [\text{PersonalSpace}(sp) \wedge \text{Constitutes}(h, sp)]]$

On the spatial dimension, personal space constitutes a region bundle representing the intimacy gradient which underlies the personal space regions discussed in Sect. 2.1. Within this region bundle, the elementary ring-like regions of a personal space (intimate region, personal region, etc.) can be embedded, such that the intimacy relation between these regions matches Hall's model of personal space (see Fig. 1).

Depending on the level of granularity, there are four or eight such *elementary personal space regions*. For the sake of simplicity but without loss of generality, we

[1] A group of agents may consist of just one agent.

consider the four-region version. Hence, a personal space constitutes an intimate region, a personal region, a social region, and a public region (AHPS3).

$$\text{(AHPS3)} \quad \forall sp\,[\text{PersonalSpace}(sp) \supset [\exists r\,[\text{IntimateRegion}(sp,r)] \wedge \exists r\,[\text{PersonalRegion}(sp,r)] \wedge \exists r\,[\text{SocialRegion}(sp,r)] \wedge \exists r\,[\text{PublicRegion}(sp,r)]]$$

The intimacy gradient of the personal space corresponds to a region bundle related to the personal space (AHPS4). The intimacy gradient conforms to the specification of the personal space regions as the intimate region and the regions derived by successively accumulating the other elementary personal space regions all are regions that constitute the region bundle (AHPS5). Consequently, the intimate region is more intimate than the personal region, which is more intimate than the social region, which is more intimate than the public region (T2).

$$\text{(AHPS4)} \quad \forall sp\,[\text{PersonalSpace}(sp) \supset \exists b\,[\text{RegionBundle}(b) \wedge \text{hasIntimacyGradient}(sp,b)]]$$

$$\text{(AHPS5)} \quad \forall sp,b,r,r',r'',r'''\,[[\text{PersonalSpace}(sp) \wedge \text{hasIntimacyGradient}(sp,b) \wedge \text{IntimateRegion}(sp,r) \wedge \text{PersonalRegion}(sp,r') \wedge \text{SocialRegion}(sp,r'') \wedge \text{PublicRegion}(sp,r''')] \supset [\text{Contains}(b,r) \wedge \text{Contains}(b,\text{sum}(r,r')) \wedge \text{Contains}(b,\text{sum}(\text{sum}(r,r'),r'')) \wedge \text{Contains}(b,\text{sum}(\text{sum}(\text{sum}(r,r'),r''),r'''))]]$$

$$\text{(T2)} \quad \forall sp,b,r,r',r'',r'''\,[[\text{PersonalSpace}(sp) \wedge \text{hasIntimacyGradient}(sp,b) \wedge \text{IntimateRegion}(sp,r) \wedge \text{PersonalRegion}(sp,r') \wedge \text{SocialRegion}(sp,r'') \wedge \text{PublicRegion}(sp,r''')] \supset [(r >_b r') \wedge (r' >_b r'') \wedge (r'' >_b r''')]]$$

In the following, the region denoted by "$\geq$ personal" is the region that is the sum of the intimate and the personal region, i.e., the maximal region that is at least as intimate as the personal region. Similarly, the sum of the social region and the public region "$\leq$ social" is the maximal region that is at most as intimate as the social region. The elementary personal space regions together with the six sum regions depicted in Fig. 4 will be referred to as *personal space regions*.

Finally, it can be stated that the human h constituting the personal space sp is always located in the intimate region:

$$\text{(AHPS6)} \quad \forall h,sp,r\,[[\text{Human}(h) \wedge \text{PersonalSpace}(sp) \wedge \text{Constitutes}(h,sp) \wedge \text{IntimateRegion}(sp,r)] \supset \text{P}^{\text{O}}(h,r)]$$

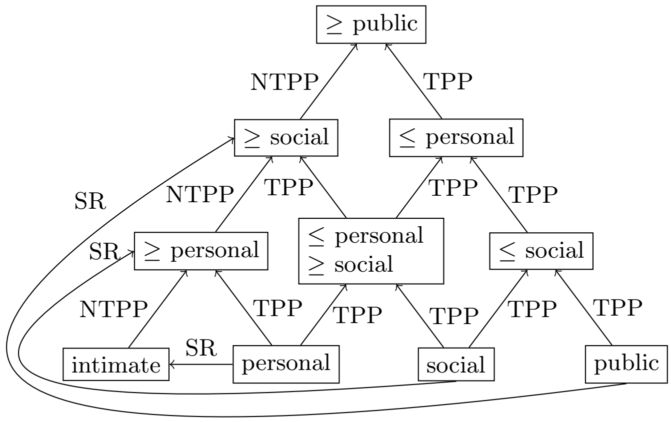

Fig. 4. The topology of personal space

3.4 Modeling Activity Space and Affordance Space

Activity spaces are constituted by activities performed by groups of agents (AACS1). At the topological level, activity space is characterized by three designated regions: the agent region, the transactional region, and the buffer region (AACS2). The group of agents performing an activity constituting an activity space is located in the agent region that belongs to that activity space (AACS3).

(AACS1) $\forall sp\,[\text{ActivitySpace}(sp) \supset \exists ag, ac\,[\text{Activity}(ac) \wedge \text{AgentGroup}(ag) \wedge \text{Constitutes}(ac, sp) \wedge \text{performs}(ag, ac)]]$

(AACS2) $\forall sp\,[\text{ActivitySpace}(sp) \supset [\exists r\,[\text{AgentRegion}(sp, r)] \wedge \exists r\,[\text{TransactionalRegion}(sp, r)] \wedge \exists r\,[\text{BufferRegion}(sp, r)]]]$

(AACS3) $\forall sp, ag, ac, r\,[[\text{ActivitySpace}(sp) \wedge \text{AgentGroup}(ag) \wedge \text{Activity}(ac) \wedge \text{performs}(ag, ac) \wedge \text{Constitutes}(ac, sp) \wedge \text{AgentRegion}(sp, r)] \supset \text{P}^{\text{O}}(ag, r)]$

The model of affordance spaces is quite similar. This is straightforward, because affordance spaces are potential activity spaces. Affordance spaces are constituted by affordances[2] (AAFS1). In analogy to activity spaces, an affordance space has a potential agent region, a potential transactional region, and a po-

[2] As this discussion focusses on the spatial effect of affordances, we remain silent as to what an affordance is.

tential buffer region (AAFS2).

$$\text{(AAFS1)} \quad \forall sp\, [\text{AffordanceSpace}(sp) \supset \exists af\, [\text{Affordance}(af) \wedge \text{Constitutes}(af, sp)]]$$

$$\text{(AAFS2)} \quad \forall sp\, [\text{AffordanceSpace}(sp) \supset [\exists r\, [\text{PotentialAgentRegion}(sp, r)] \wedge \exists r\, [\text{PotentialTransactionalRegion}(sp, r)] \wedge \exists r\, [\text{PotentialBufferRegion}(sp, r)]]]$$

Figure 5(a) depicts the topology of *activity space regions* and of *affordance spaces regions*. The region labeled A is the (potential) agent region, the region labeled T is the (potential) transactional region, and the region labled B is the (potential) buffer region. The sum of the regions A and T establish the (potential) core region AT. ATB is the whole activity/affordance space region being the sum of AT and B.

The model so far is very generic. More detailed topological descriptions spelling out subregions of the various activity or affordance spaces, as well as the geometric shape, depend on the type of activity or affordance generating it.

3.5 Modeling Territory

Territories are constituted by claims asserted by groups of agents (AT1). Topologically, territories consist of a center region and a margin region (AT2).

$$\text{(AT1)} \quad \forall sp\, [\text{Territory}(sp) \supset \exists c, ag\, [\text{Claim}(c) \wedge \text{Constitutes}(c, sp) \wedge \text{AgentGroup}(ag) \wedge \text{hasClaimant}(c, ag)]]$$

$$\text{(AT2)} \quad \forall sp\, [\text{Territory}(sp) \supset [\exists r\, [\text{CenterRegion}(sp, r)] \wedge \exists r\, [\text{MarginRegion}(sp, r)]]]$$

The topological structure of territories is depicted in Fig. 5(b). The three regions identified are referred to as the *territory space regions*.

The topological structure of territories can be found as a building block in the other topologies of the previously mentioned social spaces (i.e., an inner region

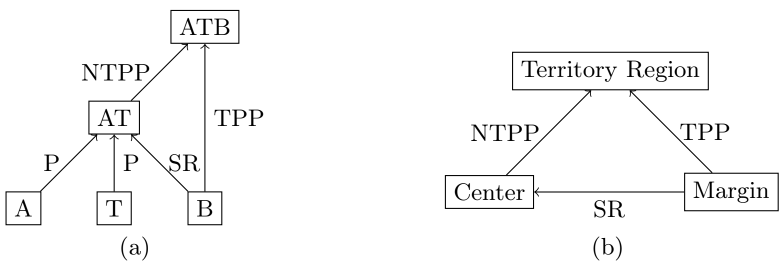

Fig. 5. The topological specifications of both activity spaces and of affordance spaces (a), and of territories (b).

surrounded by another region). However, the social role of the regions depends on the type of social space.

Because no agent is required to be present for a territory to be constituted, no general statement about the topological situation with regard to the location of agents can be made. But the claim asserted by the agent group can be made explicit by markers: Boundary markers are located in the margin region, whereas central markers are located in the center region; ear markers can be located in the sum of these regions (cf. Sect. 2.4). However, markers are a time-variant feature, as location and type of markers can change during a territory's life span.

4 Reasoning about Permissions in Social Spaces

The course of actions of a social agent is constrained by the presence of social spaces. For instance, a social agent needs authorization to enter a territory and it should ask for permission to cross the more intimate regions of a personal space. Reasoning about normative behavior in social spaces requires knowledge about the social adequacy of actions, i.e., knowing which kind of behavior is permissible and how to acquire permissions if necessary. Our goal is to specify an agent that has the capability to reason about appropriateness of actions. Therefore, an axiomatization is introduced as a basis for reasoning about permissions with regard to the performance of actions in social spaces. This axiomatization entails the social rules by which we want a socially aware robot to think and act.

In the following, the situation calculus with Reiter's solution to the frame problem [20] is used for specifying actions that affect permissions. A basic action theory in the situation calculus contains, among others, a set of first-order sentences that describe the initial situation S_0, and a set of successor state axioms describing the effects of actions. A binary function $\mathrm{do}(a, s)$ denotes the successor situation to s that results from performing the action a in s.

The scenario depicted here is that a social robot perceives a situation and reasons about which regions it is allowed to enter or to park in. Therefore, the spatial actions entering a region r, $\mathrm{enter}(r)$, and parking in a region r, $\mathrm{park}(r)$, are introduced. Crossing as a third type of spatial action occurs if the agent enters a region and enters another region subsequently without having parked. Thus, crossing is considered a composite action. To acquire a permission to enter or to park in a social region, two signalling actions are specified: $\mathrm{signal}(\mathrm{enter}(r))$ and $\mathrm{signal}(\mathrm{park}(r))$.

The possibility to gain permission for actions in regions demonstrates that social spaces are, to a planner, more than just obstacles that are to be avoided. Instead, social restrictions *ought not* to be violated but they *could*, and if so, the robot should signal this violation appropriately to appear more transparent and socially aware to the human interactants. Humans use to act in a similar way, for instance, if they duck down and speed up when they walk in front of the screen in the cinema.

In the remainder of this section, we specify requirements a simplified domain theory for socially aware path planning should fulfill and provide corresponding successor state axioms.

4.1 Preliminaries

The model is based on some simplifying assumptions. First, it is always permissible to signal any action (APSig). We add this assumption to the axioms of our action theory, as nothing more needs to be said about the permissibility of signalling actions. The other two assumptions are formulated as requirements and will be derivable as theorems of the following specification of spatial actions. First, we require that permissions that hold in some situation s cannot be deprived in a subsequent situation do(a', s) (RP1). Second, if the robot appropriately signals its intention to perform an action a , then it acquires the permission to do so (RP2).

(APSig) $\forall s, a\, [\text{Permissible}(\text{signal}(a), s)]$

(RP1) $\forall s, a, a'\, [\text{Permissible}(a, s) \supset \text{Permissible}(a, \text{do}(a', s))]$

(RP2) $\forall s, a\, [\text{Permissible}(a, \text{do}(\text{signal}(a), s))]$

The last assumption simplifies social actions of permission acquisition enormously. Signal actions are placeholders for action sequences that acquire permissions, such as dialogs. In realistic settings, attempts to gain permissions by dialogs can also fail. However, dialogs are not easily modeled in the situation calculus and they are not in the scope of this paper. Another strategy for a robot might be to wait until situations change. For instance, if an activity space constituted by people having a chat in a hallway blocks the path, a robot might also decide to wait until the chat is over. Since the change of social spaces over time is not yet modeled, this kind of reasoning is currently out of scope, as well. Thus, another important assumption of our model is that the spatial layout is stable, i.e., we take a snapshot view. While the robot perceives, reasons, and acts, no changes occur in the environment.

4.2 Gradual Structure for Permissions

There are two ways to propagate action permissions. The characterization of personal spaces by Hall already expresses that the gradual structure of the personal space regions fits a gradual structure regarding the permissions to enter these regions. Correspondingly, the intimacy gradient is exploited in the following regarding the transfer of permissions between those regions (AHPS7).

When the agent holds the permission to enter a personal space region it is also allowed to enter the regions that are between (regarding the intimacy gradient) that region and its current location. For instance, if the robot is located in the public region and has the permission to enter the personal region, then it also has the permission to enter the social region, but not necessarily the intimate region. However, if the robot is located in the intimate region of a personal space and has the permission to enter the social region, then it also has the permission to enter the personal region, but not necessarily the public region. Both directions are relevant for social behavior: On the one hand, the robot should not violate personal spaces. On the other hand, it could also be the case that the robot has the obligation to stay near to its owner and thus not to move beyond a certain personal space region, e.g., to preserve the withness (see Sect. 2.1). Using betweenness, requirement (RP3) covers both cases: If a robot located in the social space region r_{loc} of a social space sp has the permission to enter a region r of sp, then the robot is also allowed to enter all social space regions r' in sp which are between r_{loc} and r.[3]

(AHPS7) $\forall sp\,[\text{PersonalSpace}(sp) \supset$
$\quad\forall b\,[\text{hasPermissionGradient}(sp,b) \equiv \text{hasIntimacyGradient}(sp,b)]]$

(RP3) $\forall sp, b, r, r_{loc}, s\,[[\text{SocialSpace}(sp) \wedge \text{SocialSpaceRegion}(sp,r) \wedge$
$\text{hasPermissionGradient}(sp,b) \wedge \text{Permissible}(\text{enter}(r),s) \wedge$
$\text{CurrentLocation}(sp,r_{loc},s)] \supset$
$\quad\forall r'\,[[\text{SocialSpaceRegion}(sp,r') \wedge \text{Btw}(b,r,r',r_{loc})] \supset$
$\quad\quad\text{Permissible}(\text{enter}(r'),s)]]$

A similar gradual structure can be found regarding activity spaces and territories. In these cases, there is a core region and a boundary region, such that the permission to enter the core implies the permission to enter the boundary. Correspondingly, we associate a gradual permission structure to activity spaces and territories. We provide axioms (AT3) and (AT4) for the case of territories (one can impose corresponding axioms for activity spaces). (AT4) states the correspondence between the social regions and the permission gradient for the case of territories, i.e., the permission gradient contains the center region and the sum of the center region and the margin region. Specific activity space types and territory types might make it necessary to define finer-grained permission gradients. Therefore, axioms (AT3&4) are open for additional regions to be contained in the respective region bundles.

(AT3) $\forall sp\,[[\text{Territory}(sp)] \supset$
$\quad\exists b\,[\text{RegionBundle}(b) \wedge \text{hasPermissionGradient}(sp,b)]]$

(AT4) $\forall sp, b, r, r'\,[[\text{Territory}(sp) \wedge \text{hasPermissionGradient}(sp,b) \wedge$
$\quad\text{CenterRegion}(sp,\,r) \wedge \text{MarginRegion}(sp,\,r')] \supset$
$\quad\text{Contains}(b,r) \wedge \text{Contains}(b,\text{sum}(r,r'))]$

The second type of permission propagation exploits the fact that actions can presuppose other actions, e.g., to park in a region presupposes entering that

[3] The current location of the robot is defined relative to location-complexes of social spaces. For instance, the robot is located in the social region of a particular personal space and in the agents region of a particular activity space at the same time iff at that time, both social space regions partially coincide (cf. [3]) with the robot.

region. Therefore, we assume that the permission to park in a region generally entails the permission to enter that region (RP4). As a consequence, if our robot intends to enter a region in order to park there, it is sufficient to signal parking.

$$\text{(RP4)} \qquad \forall sp, r, s\ [[\text{SocialSpace}(sp) \wedge \text{SocialSpaceRegion}(sp, r) \wedge \text{Permissible}(\text{park}(r), s] \supset \text{Permissible}(\text{enter}(r), s)]$$

The formulae labeled (RP3) and (RP4) express requirements that should be met by the specification of the initial situation S_0 and situations derived from S_0 by any sequence of actions. As a complete specification of S_0 requires a detailed modelling of the social spaces present and the permissions initially granted, we restrict the further discussion to formulating succcessor state axioms that guarantee that permissions are propagated along action sequences respecting (RP3) and (RP4).

4.3 Successor State Axioms

Successor state axioms describe how the world changes due to actions that have been performed. While planning action sequences, the robot simulates how the world might change. Because we assume a static environment, change is limited to the location of the robot and to permissions.

As the situation evolves, reasoning about appropriateness of actions in social spaces should be guaranteed. Therefore, the axiomatization should meet two requirements: First, the requirements (RP3&4) are to be preserved over time. Second, the robot should be able to systematically plan signal actions to acquire permissions (currently, only the acquisition but not the withdrawal of permissions is considered).

The successor state axiom (APSS1) states that after performing an action a in situation s, the robot has the permission to park in region r iff it had the permission before (according to (RP1)) or if a is signalling its intention to park in r (according to (RP2)).

$$\text{(APSS1)} \qquad \forall s, sp, r, a\ [[\text{SocialSpace}(sp) \wedge \text{SocialSpaceRegion}(sp, r)] \supset [\text{Permissible}(\text{park}(r), \text{do}(a, s)) \equiv [\text{Permissible}(\text{park}(r), s) \vee a = \text{signal}(\text{park}(r))]]]$$

The successor state axiom for entering is more complex, because it must also preserve permission propagation, i.e., that less restrictive actions are allowed to be performed if the permission to perform the more restrictive actions is granted. To meet this requirement, again beetweenness is used. After performing action a in s, the robot being located in region r_{loc} has the permission to enter the social space region r iff one of the three conditions holds: First, the robot already had the permission to perform a in situation s, or, second, the robot signals its intention to enter a social space region r (or park there), or, lastly, the robot signals its intention to enter a social space region r' (or park there), which is located such that r is between r_{loc} and r' (APSS2). The last condition presupposes that the social space under consideration has a permission gradient.

$$\text{(APSS2)} \quad \forall s, sp, r, a\ [[\text{SocialSpace}(sp) \wedge \text{SocialSpaceRegion}(sp, r)] \supset [\text{Permissible}(\text{enter}(r), \text{do}(a, s)) \equiv [\text{Permissible}(\text{enter}(r), s) \vee [a = \text{signal}(\text{enter}(r)) \vee a = \text{signal}(\text{park}(r))] \vee \exists b, r', r_{loc}\ [\text{hasPermissionGradient}(sp, b)] \wedge \text{SocialSpaceRegion}(sp, r') \wedge \text{CurrentLocation}(sp, r_{loc}, s) \wedge [a = \text{signal}(\text{enter}(r')) \vee a = \text{signal}(\text{park}(r'))] \wedge \text{Btw}(b, r_{loc}, r, r')]]]$$

4.4 A Simple Golog Planner

The situation-calculus-based model developed so far builds the foundation for generating socially acceptable action sequences that can be executed by an artificial agent. An implementation of a simple action planner is provided in Listing 1.1. It is written in Golog [12], which is a programming language that directly uses situation calculus domain theories.

The program in Listing 1.1 generates courses of actions leading the robot from its current location to a destination without ruthlessly violating social restrictions. An action sequence can be described as a sequence of transitions between self-connected regions [18] having a homogeneous social meaning enriched with signalling actions.

Definition (D7) makes clear what is meant by the notion of regions having a homogeneous social meaning: A region r is called socially homogeneous (SH) iff every region r' that is part of r is overlapped by exactly the same social space regions as r.[4]

$$\text{(D7)} \quad \text{SH}(r) \equiv_{def} \forall r'\ [\text{P}(r', r) \supset \forall r''[\text{SocialSpaceRegion}(r'') \supset [\text{O}(r'', r') \equiv \text{O}(r'', r)]]]$$

Before an action is added to the plan (i.e., entering or parking), it is checked whether the robot has the permissions to perform the action in the target region under consideration. As the target region could be overlapped by arbitrarily many social spaces, the planner has to determine whether it is permissible to perform the intended action with respect to all overlapping social space regions. Therefore, if there is a social space region overlapping the target region in which the action at hand is not permissible, the planner selects an adaquate signal (due to our simplifying assumtions, every signal action results in the acquisition of the respective permission).

Selecting a proper signal is nontrivial. For instance, being located in the public region of a personal space and intending to park in the social region,

[4] Because we take a snapshot view throughout this article, we use the time-independend relation O. If considering that location-complexes of social spaces can move, we suggest to substitute O with Donnelly's relation PCOIN (cf. [3]).

it could signal the park action with respect to the social region, but also with respect to the personal region, or with respect to the intimate region. It is also possible to ask for parking directly or, alternatively, to ask for entering first and then to ask for parking afterwards. After all permissions have been successfully acquired, the intended action is added to the plan.

```
proc(simpleSociallyAwarePathPlanner(r),
 if(CurrentRegion(r),
  acquirePermissionAndPerformAction(park, r),
 /* else */
   pi(r', ?(CurrentRegion(r'))
        : pi(r'', ?(EC(r', r'') & SH(r''))
          : acquirePermissionAndPerformAction(enter, r'')
          : simpleSociallyAwarePathPlanner(r)
        ) ) ) )

proc(acquirePermissionAndPerformAction(actionType, r),
 if(overlappingSocialRegionImpermissible(actionType, r),
  pi(r', ?(SocialSpaceRegion(r') & O(r, r')
           & impermissible(actionType, r'))
   : selectAndPerformSignal(actionType, r')
   : acquirePermissionAndPerformAction(actionType, r)
    ),
  /* else */
  perform(actionType, r)
 ) )
```

Listing 1.1. Simple Golog Planner

To give an example, we consider a museum-tour guide robot that has the task to provide information to visitors. Figure 6 depicts an example situation such a robot could encounter. First, there is a personal space constituted by a visitor viewing the painting. Second, there is an activity space that is constituted by the visitor's activity of viewing the painting. It is composed of an agents region, in which the visitor is located. The transactional region is spanned according to the field of view between the visitor and the painting. Third, there are two affordance spaces constituted by the affordance of viewing the painting (by other visitors) and the affordance of talking to the visitor, respectively. Buffer regions are skipped for simplicity.

By default, it is not permissible to enter activity space regions. So, if the planner generated a path through the transactional region of an activity space region (as in Figure 6), the plan should also contain actions that compensate for this violation. Therefore, a socially acceptable action sequence generated by the the procedure in Listing 1.1 is to cross the affordance space regions of the first affordance space, then to signal the entrance into the transactional region of the activity space, crossing it, and finally move into the goal region.

$$[\text{enter}(r_2); \text{enter}(r_3); \ldots; \text{signal}(\text{enter}(r_6)); \text{enter}(r_6); \text{enter}(r_7); \text{enter}(r_8)]$$

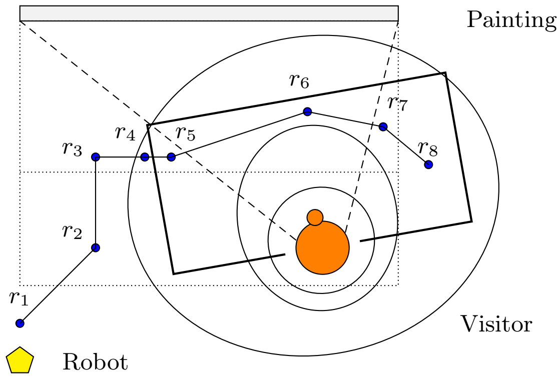

Fig. 6. A social-space aware action sequence

5 Related Work

The work by Sisbot and colleagues [21] considers two social contraints for planning trajectories: safety and visibility. Their approach is based on a weighted occupancy map. Motivated by Hall's notion of personal space, grid cells near to a person receive higher weights, so do cells in the back of a person to punish locations with poor visibility. The planning process is specified as an optimization process searching for a trajectory along the grid cells minimizing the weight of the overall trajectory. Our focus is on the constitution of social spaces and on permissions attached to them. This involves the avoidance of personal space intrusion, if it is inadequate, but also to allow entering a personal space, if this is appropriate.

Cirillo and colleagues [2] integrate social constraints in a symbolic action planner using temporal logics to avoid socially inacceptable actions. However, they do not discuss the spatial dimension of social behavior and do not consider the concept of social space as a means to constrain actions in human-robot encounters.

Pommerening and colleagues [17] integrate a qualitative spatial calculus with Golog to realize spatial coordination of agent-controlled vehicles. The agents are to act according to normative right-of-way rules as written in law code in order to avoid collisions. While the rules considered by Pommerening and colleagues must be followed to derive crash-free behaviors, the rules related to social spaces ought to be followed but might be neglected in cases of urgency or danger. Nevertheless, the communication structure between different components of a simulating system combining Golog and qualitative spatial reasoning proposed by Pommerening and colleagues might be reusable for a similar simulation system of socially aware behavior.

6 Conclusions

The spatial behavior of service robots that are meant to interact with humans should match people's expectations. We think that the concept of social spaces provides a promising basis for the analysis of people's expectations, as well as for the modeling and implementation of socially aware robots. On the one hand, robots are faced with social spaces produced by other agents, most notably by humans. On the other hand, they are actively involved in the social space production as they act in a physical environment.

The taxonomy of social spaces introduced in this article provides a generic framework upon which a wide range of social spatial situations can be modeled. Based on qualitative representations of social spaces and on knowledge about action permissions, an artificial agent can systematically reason about the social adequacy of spatial actions and about the acquisition of permissions. This can be exploited for the generation of socially adequate courses of actions.

Future research will deal with an analysis of the temporal characteristics of social spaces in order to cope with the fact that location-complexes of social spaces can move relative to physical space. We will also explore the geometric embedding of social spaces in concrete situations. We expect a high diversity of factors determining the respective geometries. Finally, deontic ought-to-do reasoning about spatial actions with respect to social spaces will be a matter of deeper investigation.

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