From Body Space to Interaction Space - Modeling Spatial Cooperation for Virtual Humans

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ABSTRACT

This paper introduces a model which connects representations of the space surrounding a virtual humanoid's body with the space it shares with several interaction partners. This work intends to support virtual humans (or humanoid robots) in near space interaction and is inspired by studies from cognitive neurosciences on the one hand and social interaction studies on the other hand. We present our work on learning the body structure of an articulated virtual human by using data from virtual touch and proprioception sensors. The results are utilized for a representation of its reaching space, the so-called peripersonal space. In interpersonal interaction involving several partners, their peripersonal spaces may overlap and establish a shared reaching space. We define it as their *interaction space*, where cooperation takes place and where actions to claim or release spatial areas have to be adapted, to avoid obstructions of the other's movements. Our model of interaction space is developed as an extension of Kendon's F-formation system, a foundational theory of how humans orient themselves in space when communicating. Thus, interaction space allows for analyzing the spatial arrangement (i.e., body posture and orientation) between multiple interaction partners and the extent of space they share. Peripersonal and interaction space are modeled as potential fields to control the virtual human's behavior strategy. As an example we show how the virtual human can relocate object positions toward or away from locations reachable for all partners, and thus influencing the degree of cooperation in an interaction task.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous

General Terms

Algorithms, Design, Theory, Human Factors

Keywords

Virtual Humans, Peripersonal Space, Interaction Space, Body Schema, Spatial Arrangement, Multi-Person Interaction

1. INTRODUCTION

Improving articulated agents in actions carried out in the space immediately surrounding their body is a classic issue in building virtual humans. Even if they stay at one location and do not move around, near space interaction still holds lots of challenges. We will focus on two of these challenges. One issue is to improve the virtual human's sensory-motor and perceptual abilities, which are useful for body action/motion planning and control. The space where movements are carried out, the virtual human's *workspace*, is where sensory modalities have to focus on and where possible objects have to be observed or manipulated by reaching, grasping or avoiding them. Sharing parts of this space with others makes interaction only more challenging, which leads to the following, second issue. Interferences from other articulated agents or even humans also have to be considered. Not only for safety reasons, as in scenarios involving physical robots, but also in virtual environments when two or more partners are occupying or sharing parts of the same space. Work on this issue usually deals with scenarios where artificial agents move around in space, maintaining their global position. We focus on delimited near space arrangements (e.g., a table), involving mainly the virtual human's upper part of the body, where actions to claim or release spatial areas have to be adapted to avoid obstructions of the other's movements. Thus, the virtual human needs a representation of the shared near space in order to perform smooth, effective, and also cooperative interaction.

In our work we connect the two issues of first, modeling the space surrounding the body with regard to an individual virtual human and second, modeling the same space with regard to interpersonal interaction. Accordingly, our goal is to develop a virtual human that is able to

- learn and adapt to its reaching space, i.e., the virtual human knows from its sensory modalities whether objects are in its reaching distance or whether it has to lean forward.
- relocate objects to facilitate its actions in its own reaching space, i.e., putting objects into its own perceptual focus where they are easy to reach and easy to perceive with the virtual human's sensor modalities.
- relocate objects to facilitate cooperation in shared space, i.e., putting objects to locations reachable to all interaction partners.

In this paper we approve the recent work outlined by Lloyd [13] claiming that the principles underlying the individual representation of the space surrounding the human body also mediate the space between interacting human partners. This idea is also valuable to provide virtual humans with the abilities we aim to model. We present how our work on learning the reaching space of an individual articulated agent's body - the *peripersonal space*, is used to model the shared reaching space of cooperative interaction partners, that we define as *interaction space*.

Cite as: From Body Space to Interaction Space - Modeling Spatial Cooperation for Virtual Humans, Nhung Nguyen and Ipke Wachsmuth, *Proc. of 10th Int. Conf. on Autonomous Agents and Multiagent Systems (AAMAS 2011)*, Tumer, Yolum, Sonenberg and Stone (eds.), May, 2–6, 2011, Taipei, Taiwan, pp. 1047-1054.

Our work on peripersonal space is motivated by research from biology and cognitive neuroscience and takes input from the virtual human's sensor modalities to learn its reaching and lean-forward distances. Our work on interaction space is developed as a supplement to Kendon's F-formation system, a concept describing and analyzing spatial arrangements in human interaction [9]. The system describes how humans arrange their body orientation and position to each other when cooperating in physical space. In our work, we use potential field functions to control the virtual human's behavior strategies in peripersonal and interaction space. Depending on its own interaction goals, layout and position of the interaction space, the virtual human can plan its actions, e.g., relocating object positions toward or away from locations reachable for all partners. These actions demonstrate how the virtual human may influence the degree of cooperation in an interaction task.

The remaining paper is organized as follows. In the next Section we briefly explain the terms and concepts from other research disciplines on that we base our presented work and we describe related work in modeling artificial humanoids. In Section 3 we propose an interpretation of the concepts, suitable for a technical framework. In Section 4 the approach and results for a virtual human learning its peripersonal space are presented. Based on the learned reaching distances, we show how information from multiple sensor modalities is organized in spatial maps to help maintaining the virtual human's attentional focus and perception in peripersonal space. In Section 5 we present our novel approach on a computational model of interaction space by supplementing Kendon's F-Formation system using potential fields. Finally, in Section 6 we summarize the major aspects of our approach.

2. THEORETICAL FOUNDATIONS AND RELATED WORK

In this section we briefly highlight relevant definitions and valuable findings from technical as well as non-technical research areas on the space immediately surrounding a body. In the following we use the term *body space* when generally refering to this space, to avoid misunderstandings. It can be observed that individual body space is often analyzed in terms of sensor-motor and perceptual characteristics, and commonly termed as peripersonal space, e.g., in engineering, cognitive neurosciences or biology. In contrast, when body space co-occurs in interaction with others, it is usually analyzed as a social phenomenon and treated in terms of social relationships depending on body distances and orientations. Of particular interest is one work that aims at merging the two areas into one neurophilosophical framework.

2.1 Body Schema and Peripersonal Space

Holmes and Spence [7] presented evidence of a neural multisensory representation of peripersonal space that codes objects in body-centered reference frames and defines humans' actions in near space: "Objects within peripersonal space can be grasped and manipulated; objects located beyond this space (in what is often termed 'extrapersonal space') cannot normally be reached without moving toward them [...]"([7], p. 94). A comprehensive theoretical model of humans' 3D spatial interactions containing four different realms was presented by Previc. His model is a synthesis of existing models and neuroscientific findings [16]. In addition to peripersonal space (PrP) he distinguishes three extrapersonal spaces differing in function and extent. Of particular interest is that he defines PrP's lateral extent as being 60° central in front of the body, corresponding to the extent of human stereoscopic vision. PrP together with one of the extrapersonal spaces also include movements of the upper torso, e.g., leaning forward to reach for objects, which Holmes and Spence assign to extrapersonal space. Work on using peripersonal space as a way to naturally structuring visual object recognition tasks in artificial systems has been conducted by Goerick et al. [4]. We use peripersonal space to structure the space covered by multiple sensor modalities.

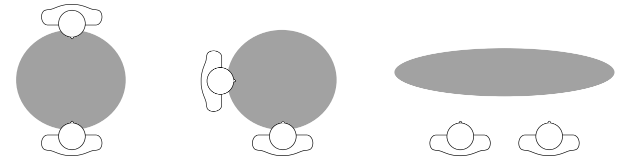

Figure 1: Spatial arrangements typical in F-formations. From left to right: A vis-a-vis, L- and side-by-side arrangement.

In humans, the representation of peripersonal space is intimately connected to the representation of the body structure, namely the body schema. A comprehensive discussion on body schema, as a neural representation, which integrates sensor modalities, such as touch, vision, and proprioception, was provided by Gallagher [2]. This integration or mapping across the different modalities is adaptive to changes of the body, i.e., if the structure of the body changes, the representation also changes. A lot of research was inspired by this finding, offering a mechanism to save engineers from laborious work on predefining an articulated agent's - possibly changing body structure [1]. More recently, work with different approaches on connecting body schema learning with peripersonal space for articulated agents have also been presented [6], [14]. This aspect is also covered in our work.

2.2 Interpersonal Space

In this Section we introduce how body space is defined when occurring in interpersonal interaction.

A prominent model on interpersonal space is Hall's model of proxemics [5], which describes interpersonal distances starting from what he calls *intimate distance* of a few inches to large-scale distances of 25 feet and more. The range of peripersonal space falls roughly into the scope of intimate and personal distance. Hall's theory is a taxonomy which maps interpersonal distances to human social relationships. Therefore, it does not aim at analyzing the cognitive structure of the spaces. An example of robots changing their locomotion in presence of humans, depending on social spaces, has been presented by Sisbot et al. [17]. As mentioned previously, we will not focus on locomotion, but instead focus only on how a virtual human changes its motor actions depending on the space it shares with others.

Aware of the two isolated fields of neural analysis of peripersonal space and research on interpersonal behavior, Lloyd proposes a framework that aims at investigating and interpreting the "neural mechanisms of 'social space'" ([13], p. 298). In her hypothesis she argues that the mechanism explaining how interactions with inanimate objects affect body space, can be applied to interactions with e.g., human partners. This idea is a major aspect in our framework.

Kendon [9] presented a notably relevant work on observable patterns, called *formations*, when humans orient and group themselves in physical space. He defines an *F-formation* as a pattern, which "arises whenever two or more people sustain a spatial and orientational relationship in which the space between them is one to which they have equal, direct, and exclusive access." ([9], p. 209). He describes in particular three typical F-formations, namely vis-a-vis, L- and side-by-side arrangements, depicted in Figure 1. Kendon also mentions an activity space in front of a single interactant,

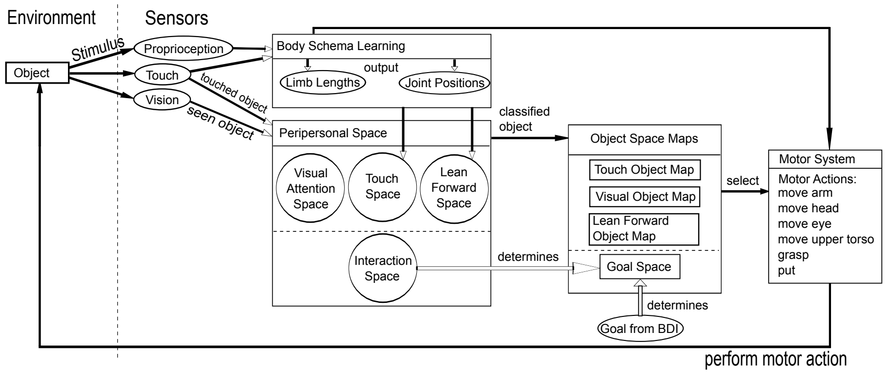

Figure 2: Technical Framework Overview. Information from body schema learning is utilized to build peripersonal subspaces. Objects perceived from different sensor modalities are classified into the subspaces and are maintained in object space maps. Objects outside the goal space induce a motor action, leading to a new sensor input.

which he calls *transactional segment*. This space somehow corresponds to peripersonal space, as defined previously. In arrangements, where several interactants' transactional segments overlap, the intersection is called *o-space* (see grey regions in Figure 1). Kendon mentions, but does not elaborate on the two spaces. We will amend these aspects by focussing on the space between F-formations in Section 4.3 and 5.

Other work has been presented, using Kendon's F-formation system for proximity control of robots which move along in space in the presence of humans ([8], [18]). Another work by [15] showed how avatars in virtual worlds can keep social distances among each other in face-to-face interaction. In contrast to these works, we will not deal with creating an F-formation, but with extending o-space and sustaining cooperation, once an F-formation is established.

3. TECHNICAL FRAMEWORK

We first present an overview of the architecture to realize a technical system which models peripersonal space and interpersonal space at the same time (see Figure 2). In the next Sections we will describe the different parts in more detail. The findings from other research fields, presented in the previous Section, are incorporated into our framework.

Body Schema The virtual human learns its body structure and the kinematic functions of the limbs by means of a recalibration approach involving tactile and proprioceptive sensor data. Thus, the limb lengths and joint positions of the kinematic skeleton are learned. This part is described in Section 4 and corresponds to the findings in humans, stating that body schema is learned from sensor-motor information, coding the body's kinematic structure and is adaptive to bodily changes.

Peripersonal Space In the technical framework, we divide the realm of peripersonal space into different subspaces. Extracted from the learned body schema they differ in spatial range and frames of reference. The core spaces are determined by their predominant sensor modality and comprise of a *touch space*, a *lean-forward space* and a *visual attention space*. The subspaces are in line with the finding of a multi-sensory representation of peripersonal space. For a technical system, where sensor modalities do not necessarily cover the same spatial regions, this finding proposes a comprehensive and robust representation of peripersonal space. More details are described in Section 4.3.

Object Space Maps Since an object can be perceived with different sensor modalities, it can be represented in different peripersonal subspaces. Each perceived object is maintained in object space maps, corresponding to the sensor modalities it was perceived from. The advantage is that the virtual human can keep track of whether objects are within its visual or touch space. Thus, the virtual human can select its next movement, e.g., forward-leaning or reaching for an object. As an additional spatial map we define a *goal space* within the peripersonal space. This space defines a region in peripersonal space, which the virtual human should direct its attention to, for example to objects related to a task on a table in front of the torso. The extent and location of the goal space can be determined through different factors, for instance a new goal from the virtual human's Belief-Desire-Intention framework. The maintenance of the object space maps will be described in Section 4.3.2.

Motor System Information about object positions from the object space maps is used to choose an appropriate motor action. For example, if an object has been touched, but not seen so far, the motor system will generate a head or eye movement in direction of the touched object. By means of this, the visual attention space is shifted to cover the new object. If the object is located outside the goal space, a motor action is generated to grasp the object and put it into the current goal space.

Interaction space If one or more articulated agents are entering the virtual human's peripersonal space, it assumes that they are also surrounded by a peripersonal space. The peripersonal spaces, in a first simple approach, are simulated as large as the peripersonal space of the virtual human. The overlapping spaces form the space reachable to all participants. In cooperative interaction this space is then marked as a new *goal space*. The virtual human would now center its attention to the new space and would place objects into it, supporting the interaction. We describe this issue in Section 5.

4. A COMPUTATIONAL MODEL OF PERIPERSONAL SPACE FOR A HUMANOID

In this section we present our computational model of peripersonal space for Max, a virtual human. Multisensory abilities are a crucial factor in our framework, thus the demands we make on a virtual human's sensor system are described in Section 4.1. On the one hand sensor data is used to learn Max's kinematic structure using data from virtual touch and proprioception sensors, described in 4.2. On the other hand, since sensor modalities do not necessarily cover the same space, their combination accounts for establishing a comprehensive perception of Max's peripersonal space, described in 4.3.

In our scenarios we assume that peripersonal space interaction with objects usually involves a plane, lateral in front of a virtual human's body, e.g., a table. In order to decrease the complexity of the model, we therefore focus on peripersonal space on a 2-D plane lateral, in front of Max's upper torso. The range of the spaces defined in Section 4.3 is thus projected on this 2-D plane.

4.1 Sensory Requirements for a Virtual Human

Touch receptors were developed and technically realized for Max's whole virtual body [14]. These receptors allow for differentiating between different qualities of tactile stimulation. Biological findings on the human tactile system were incorporated to build an artificial sense of touch for Max. The virtual skin consists of flat quadrangle geometries varying in size, each representing a single skin receptor. Altogether the virtual skin consists of more than 200 virtual skin receptors. Max's tactile system provides information on which body limb a virtual skin receptor is attached to, together with the position in the limb's frame of reference (FOR), allowing for determining where Max is being touched.

In addition to the tactile system the virtual agent's body has an underlying anthropomorphic kinematic skeleton which consists of 57 joints with 103 Degrees of Freedom altogether [12]. Everytime Max executes a movement, the joint angle information of the involved joints is output. Synchronously with the tactile information, the proprioceptive information can be observed.

In this work, Max's virtual visual field of view corresponds to human stereoscopic vision [16], required for effective hand-eye coordination and thus is limited to an angle of 60°, lateral attached to his head. Head and torso movements are translated to the virtual visual field, changing its position. The angle of view is projected onto a 2-D Plane, when he is sitting or standing at a table. Objects perceived in its virtual view are represented in head centered coordinates.

4.2 Tactile Body Schema Learning for a Humanoid

The model for learning the body structure takes input data given by touch sensors and joint angle data given by the proprioception sensors. In a first step, Max executes random motor actions resulting in random body postures. For each posture he perceives proprioceptive data from his joints and tactile stimuli when touching himself (see Figure 3).

As described by [14] we consider the body schema as a tree of rigid transformations. In our case this kinematic tree is prescribed by the skeleton of the virtual human Max. In the initial tree the number of joints linked in their respective order with the number of limbs are known, but the joint orientation and positions are unknown. In our model the touch receptors are attached to the limbs and their position is represented in the limb's FOR. In the kinematic tree representation, the touch receptors can therefore be represented as located along the edges.

In order to learn the real positions and orientations of the joints which also determine the limb lenghts, we make use of the algorithm proposed by Hersch et al. [6]. It is a novel and general approach in online adapting joint orientations and positions in joint manipulator transformations. Our challenge in using this algorithm was to adapt it to a case different from the one it was originally applied to. In our case we did not use visual and joint angle data, but instead replaced all visual by tactile information in order to update all the rigid transformations along the generated kinematic chains.

The original idea is to observe a rigid transformation carried out by a manipulator. Knowing the rotation angles of the manipulator's joints and a position, given in the FOR of the root segment as a vector **v'**, and that same position given in the FOR of the end-segment

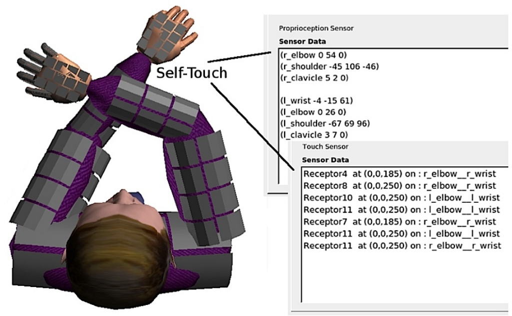

Figure 3: Tactile body schema learning: For each random posture, sensory consequences are output by the sensory systems. The touch sensor provides an ID of the receptor, the limb it is attached to, and the position in the frame of reference (FOR) of the corresponding limb. Angle data for the involved joints are output by the motor system, representing the proprioceptive information.

as a vector **v**, we can guess the parameters of the rigid transformation. A gradient descent on the squared distance between **v'** and its guessed transform vector $\mathscr{T}$ (**v**) is used in order to update the parameters, consisting of the joint positions ($\mathbf{l_i}$ at joint i) and the unit rotation axis ($\mathbf{a_i}$ at joint i).

$\mathscr{T}$(**v**) contains the transformations along the kinematic chain of a multisegment manipulator. In our case the kinematic chains can be generated using the kinematic tree representing Max's body skeleton. Each time Max touches himself, the two skin receptors' positions in a limb-centered FOR are used as **v'** and **v**. Since we use this learning method as a fast way to learn peripersonal space's boundaries, we do not elaborate on learning the unit rotation axis of the joints, but focus on learning the limb lengths. For more details on learning both parameters see [14] and [6]. Thus, we extracted the unit rotation axis from the available proprioception data, i.e., the rotation angles. The translation vectors of joint i are updated by using the Equation (1) with a small positive scalar ε, and rotation matrix $\mathbf{R}_i$ at joint i.

$$\Delta \mathbf{l}_i = \varepsilon (\mathbf{v}'_n - \mathscr{T}(\mathbf{v}_n))^T \prod_{j=1}^{i-1} \mathbf{R}_j \qquad (1)$$

4.2.1 Results

The results of the algorithm used with tactile and proprioception data are shown in Figure 4. Since we focused on learning the limb lengths, the number of iterations is much lower (approx. 6-10 times) than for learning all parameters . However, due to fact that the proposed approach takes knowledge from the body structure in advance and does not learn sensor-motor mapping, this learning method is in the strict sense a recalibration mechanism, which corresponds to the definition of body schema which adapts to changing body limbs. By means of this, the limb lengths of Max's articulated skeleton were learned, which are used to calculate Max's reaching distances. This aspect is described in the next Section.

4.3 Structuring Peripersonal Space

According to Previc, each realm surrounding a human is associated with certain predominant behavioral interactions, e.g., visuomotor object-manipulation is predominant in peripersonal space and locomotion in action extrapersonal space. More precisely, in his model he defines a set of sensory-perceptual and motor operations and a predominant FOR to each realm. In order to technically

Table 1: **Characteristics of sensory subspaces of a virtual human's peripersonal space.**

	Visual Attention Space	**Touch Space**	**Lean-Forward Space**
Function	Visual search, visual control	Grasping, placing, manipulation	Grasping, placing
2D location, extent			
Vertical	Lower field, Projection on frontal 2D plane		
Origin	Head	Shoulder, Trunk	Shoulder, Trunk
Lateral	Central 60°	360°	Frontal 180°
Radial	0-2m	Length: shoulder joint to hand palm	Length: hip to hand palm
Frames of Reference	Head centered	Limb centered	Limb centered
Motor Action	Head, eye movements	Arm movements	Upper Torso movements

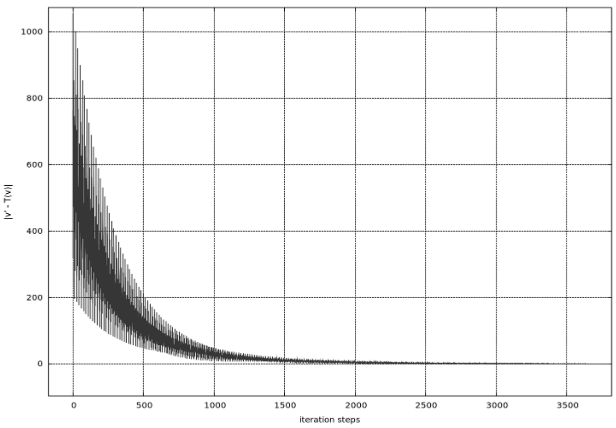

Figure 4: The x-axis shows the number of iteration steps the algorithm needed to learn the real limb lengths of the kinematic chain consisting of 6 joints. The Y-Axis shows the error $\|\mathbf{v}'_n - \mathscr{T}(\mathbf{v}_n)\|$ [mm] of the calculated limb lengths.

realize this idea, and focussing on peripersonal space only, we decomposed his definition of peripersonal space into three major sensor components, namely vision, touch, and proprioception. Each of them spans a realm with a specific extent, FOR and predominant motor actions.

In this Section the technical framework outlined in Section 3 and in Figure 2 is specified in more detail. In Table 1 characteristics of the spanned three subspaces of peripersonal space are presented. The results from the learning algorithm described in the previous Section determine the boundaries of the subspaces. In the next Section we explain the content of the table and will describe in Section 4.3.2 how the subspaces influence spatial object maps. Finally, we show how the object maps together with motor actions, delineated in Section 4.3.4, satisfy a defined goal realm, which is specified in Section 4.3.3.

4.3.1 Subspaces in Peripersonal Space

The subspaces we define within peripersonal space are deduced from Previc's work [16] and adopted to the technical conditions determined by Max's sensory system. The major sensory modalities assumed to be involved in peripersonal space are determining the three subspaces. Vision is mainly utilized in object search and visual manipulation control and determines a *visual attention space*. Touch is mainly utilized in object manipulation and grasping, determining a *touch space*. The function of proprioception is always utilized in peripersonal space, but plays a particular role in placing and grasping of objects at the boundaries of peripersonal space when efforts have to be made by leaning forward, therefore it determines an additional *lean-forward space*.

The characteristics are listed in Table 1. Their technical counterparts are shown in Figure 2. Each subspace defined here is associated to a main function determining the predominant motor actions carried out in the specific subspace. As mentioned at the beginning of this Section, the boundaries of the subspaces are projected on an assumed 2-D plane on a table in front of Max. Hence, the vertical extent of each subspace is projected on a lower radial 180° 2-D plane. A schematic layout is depicted in Figure 5.

The *visual attention space*'s origin lies in the center of the head. Its lateral extent is projected to the touch and lean-forward spaces. Stimuli perceived in Max's 60° field of view are represented in a head centered frame of reference.

The *touch space*'s boundary is limited to the lengths of the arm limbs which are extracted from the body schema. It radiates from the trunk's center with the maximal distance covering the range between shoulder joints and the palms of the hands. The lateral extent covers 360° around the trunk's center, since tactile stimuli may also effect the back of the body. (Although, in the following scenarios only the frontal 180° are examined.)

The *lean-forward space*'s boundary is limited to the maximal reaching realm of the upper torso, when bending forward. From the body schema we extract the maximum range achieved with the arm limbs together with the spine joints which begin above the hip joint. This space thus extends touch space. Objects and stimuli perceived in both subspaces are represented in a limb-centered frame of reference. Compared to touch space, the function of object manipulation is not predominant in lean-forward space.

In addition to the mentioned spaces, other subspaces which potentially structure Max's peripersonal space can be established in our framework. As soon as other virtual or real human(s) enter Max's proximity, we assume that they are also surrounded by peripersonal spaces. The intersection of their overlapping peripersonal spaces are registered as an *interaction space*. Depending on the sensor modality an object was perceived from, it is evaluated in which subspaces the object is located in. The classified object is then registered to the according object space maps (see Figure 2).

4.3.2 Object Space Maps

An example of objects being located in different peripersonal subspaces is shown in Figure 5. In order to keep track of the objects in Max's peripersonal space, the sensory modalities have to cover the objects, depending on a predefined sensor hierarchy. Since not all objects need to be touched or grasped, but all need to be seen, in our framework, visual search is preferred over tactile manipulation, and tactile manipulation is preferred over leaning forward.

In the example a virtual human like Max is accidentally touching, but not seeing a virtual object, since its visual attention space at that moment is not covering the object behind its arm. In our framework, the object would be listed in the *touch*-, but not in the *visual*- or *lean-forward object map*. Due to the mentioned hierarchy, a motor action would be triggered to sense the object with the visual modality. In this case a motor action is selected to turn the virtual human's head to the location where it touched the object, which leads the visual attention space to shift to the object location. Then the object is additionally registered to the visual map.

4.3.3 Goal Space

In order to avoid collisions with objects when interacting, the virtual human may reorganize the object positions in its peripersonal space. For this purpose an additional spatial map, a *goal space* is defined, which describes his region of attention. In the example shown in Figure 5, we assume that the goal space is set to a default spatial region on the table, with an angle of 60° central in front of the virtual human, so that objects are easy to see, reach and touch, and the virtual human's motions are less prone to hindrances. All sensory modalities have a preference to cover the goal space as long as no external spatial interferences or constraints are given. Each time an object is perceived, the goal space map is compared to the object space maps. If differences between the maps are found, a motor action is selected to bring the virtual objects into Max's current goal space. In the schematic layout on the left in Figure 5 the default goal space is the space where visual attention and touch space overlap. Due to the preferences defined for the sensor modalities, the virtual human would turn its head to the location where the touch stimulus occurred. In a next step, due to the goal space definition, described in detail in Section 4.4, another motor action is triggered to grasp and put the object into the goal space.

4.3.4 Motor Actions

As outlined in the previous example, motor actions are selected depending on the subspaces. Another factor in the selection of the appropriate motor action is the superposed potential fields, which is the topic of the next Section. In touch space arm movements are predominant motor actions for fullfilling the functions of grasping, placing and manipulation. In lean-forward space, arm movements are combined with upper torso movements, like leaning forward, in order to grasp for or place an object. Object manipulation is not predominant in this space, since objects are more likely to be brought to touch space. Visual attention space relies on motor actions like eye movements to control the gaze and head movements to shift the entire space. Furthermore, the replacement of objects relies on the information of the potential fields defined by the goal spaces. The information from the body schema is used to translate object positions from one frame of reference to another, since the subspaces code objects in different coordinate systems.

4.4 Modeling Peripersonal Space with Potential Fields

In order to trigger appropriate motor actions with regard to objects at each location in peripersonal space we used the method of artificial potential fields. This method is very common in obstacle avoidance and path planning for artificial agents [11]. A potential field is an array of vectors, which defines a spatial region in which each location of the field is exposed to a force vector, describing the direction and the strength of the radiating force. For example an object's direction and velocity of a motion can be controlled depending on the length and the direction of the force vector. Multiple potential fields can be defined for the same spatial region. By adding the fields together, a new field with attenuated or amplified forces is built.

Goal space and Max's peripersonal space are modeled as artificial potential fields. The peripersonal space is described as a repulsive field F_{peri}, defined by Equation 2 with tangential directions covering a semicircle, defined by Equation 3. The field is visu-

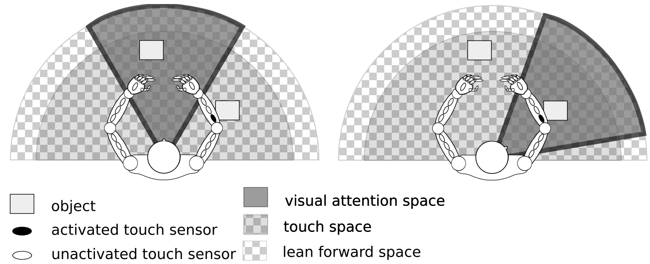

Figure 5: The virtual human directs its sensory attention toward an object. Left: the virtual human perceives an object with the skin sensors beyond its visual attention space. The object is registered in the touch object map. Right: A motor action is selected and shifts the head and the visual attention space toward the touch-location . The object elicits a visual stimulus and is then registered to the visual object map.

alized in Figure 6, left. A vector between the center of peripersonal space and any location in space is denoted by position vector $\mathbf{p}$. We calculate the force vector $\mathbf{v}_{peri}(\mathbf{p})$, that is currently affecting $\mathbf{p}$, using Equation 3. The paramter ξ denotes a positive scalar which influences the length of the resulting force vector. The force vectors $\mathbf{v}_{peri}(\mathbf{p})$ point to the frontal, sagittal midline, described by vector $\mathbf{r}_{perimid}$. The field covers all $\mathbf{p}$'s within an angle of 90° to both sides of this midline. The regions beyond the radius r_{peri} of peripersonal space are not affected by the potential field. Therefore any $\|\mathbf{p}\|$ that is greater than r_{peri} results in a zero force vector.

The default goal space is modeled as a selective attractive field F_{goal} defined by Equation 4. The field covers the angle Θ_{goal} with an angle bisector denoted by $\mathbf{r}_{goalmid}$, and force vectors pointing away from the center in (see Equation 5). The default goal space has an angle of Θ_{goal} = 60°, and is visualized in Figure 6, middle. The sum of the two fields are shown in Figure 6, right.

Each time Max perceives an object, the current force vector $\mathbf{v}_{res}$ impacting on the object is calculated using Equation 6. Objects outside the goal space, that have to be relocated, would be affected by force vectors, describing a path which leads in the direction of the inside of the goal space. With decreasing distance to the center, the strength of the potential field disappears, ending the path.

Max is not exactly following the path, but uses the force vectors as a trigger to select a grasping motion. The end position of the path is used as a target position for a placing motion. Objects located within goal space are represented with repulsive potential fields, which prevents new objects being placed at their location. This example shows that potential fields are a suitable method to associate each point in peripersonal space to a specific behavior, in this case motor actions. By superposing several potential fields, behaviors can be combined, allowing for more sophisticated actions.

$$\mathbf{F}_{peri}(\mathbf{p}) = \begin{cases} \xi\left(\frac{1}{\|\mathbf{p}\|} - \frac{1}{r_{peri}}\right)\frac{\mathbf{p}}{\|\mathbf{p}\|^3} & \|\mathbf{p}\| \leq r_{peri}, \\ 0 & \|\mathbf{p}\| > r_{peri} \end{cases} \tag{2}$$

$$\mathbf{v}_{peri}(\mathbf{p}) = \begin{cases} -(\frac{\pi}{2}) * \mathbf{F}_{peri}(\mathbf{p}) & \forall \mathbf{p} | \measuredangle(\mathbf{r}_{perimid}, \mathbf{p}) \leq -(\frac{\pi}{2}), \\ (\frac{\pi}{2}) * \mathbf{F}_{peri}(\mathbf{p}) & \forall \mathbf{p} | \measuredangle(\mathbf{r}_{perimid}, \mathbf{p}) \leq (\frac{\pi}{2}), \\ 0 & else \end{cases} \tag{3}$$

$$\mathbf{F}_{goal}(\mathbf{p}) = -\xi \frac{\mathbf{p}}{\|\mathbf{p}\|} \tag{4}$$

$$\mathbf{v}_{goal}(\mathbf{p}) = \begin{cases} \mathbf{F}_{goal}(\mathbf{p}) & \forall \mathbf{p} | \measuredangle(\mathbf{r}_{goalmid}, \mathbf{p}) \leq (\frac{\Theta_{goal}}{2}), \\ 0 & else \end{cases} \tag{5}$$

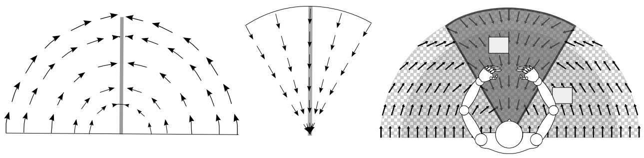

Figure 6: Left: Peripersonal space modeled as tangential potential field with $\mathbf{r}_{perimid}$ depicted as a grey line. Middle: Default goal space modeled as selective attraction field with an angle Θ_{goal} of 60° and $\mathbf{r}_{goalmid}$ depicted as a grey line. Right: Addition of the two fields shows the resulting peripersonal space field.

$$\mathbf{v}_{res}(\mathbf{p}) = \mathbf{v}_{peri}(\mathbf{p}) + \mathbf{v}_{goal}(\mathbf{p}) \tag{6}$$

Goal spaces in general can be determined by a new goal, raised by the Belief-Desire-Intention system or by a newly established subspace of the peripersonal space. In particular a new established interaction space as described in Section 4.3.1 holds interesting potential field combinations and associated motor actions that we describe in Section 5.2.

5. A COMPUTATIONAL MODEL FOR A HUMANOID'S INTERACTION SPACE

So far, we modeled the individual peripersonal space for a virtual human with potential fields. We will now propose how to computationally model the space between a virtual human and its interaction partners. As mentioned previously, we base our work on Kendon's F-formation system.

5.1 Extending the F-formation System

With our model we aim at supplementing the F-formation system by adding the aspect of a measurable shared space, suitable for computational applications. In Figure 7 we show how we modeled the space between interactants. Compared to Figure 1, Kendon's o-space is now defined as the intersection of the interactants' overlapping peripersonal spaces (Figure 7, striped regions). We define this space as their *interaction space*. Since our definition refers to the intersection of all interactants' reaching realm, it is conform to Kendon's definition of the space as being equally and exclusively reachable to all interactants, and in which they cooperate. In order for a virtual human to sustain an F-formation arrangement, once established, we incorporate interaction space into our described framework.

When Max perceives an interactant within an F-formation, he projects his own peripersonal space onto the partner, in order to model the partner's reaching space. This process is similar to a mechanism which is usually referred to as *spatial perspective taking*. The fact that Max simulates the partner's perspective by using his own body structure is commonly known as *embodied simulation* [3] and is a hypothesis of how humans understand others. Studies by [10] state that spatial perspective taking might still be rooted in embodied representations, which supports our approach. However, at the current stage of the framework, Max's peripersonal boundaries are pojected onto another partner's body structure manually, since the current focus lies on modeling interaction space.

5.2 Modeling Interaction Space with Potential Fields

As soon as an interaction space is established, it is defined as the new goal space. Therefore Max directs his sensory attention to this

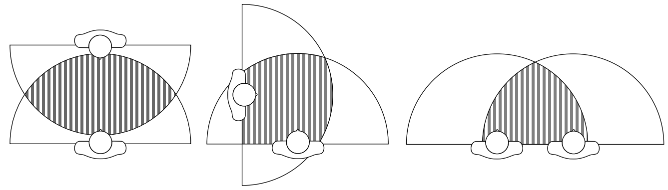

Figure 7: Kendon's o-spaces modeled as interaction spaces (striped regions). Interaction spaces are established by the intersection of the interactants' overlapping peripersonal spaces.

space. Max's and the interactants' peripersonal spaces are modeled as selective repulsive potential fields, as shown in Equation 3. Their interaction space is modeled as an attractive potential field F_{inter}, as described in Equation 4, with its center being the center of a circle, which approximates interaction space. The range of the F_{inter} covers all interactants' potential fields. Thus, each force vector within their peripersonal spaces is distracted in the direction of the interaction space, as depicted in Figure 8, right. As described in Section 4.3.3 a motor action to put objects into the new goal space is selected, i.e., Max would now put perceived objects into the interaction space, so that every interactant may reach the objects. Figure 8 (left) shows a vis-a-vis F-formation between Max and another articulated humanoid in a virtual reality scenario. In this scenario both partners are standing at a table and cooperate in an object manipulation task, e.g., building a tower with toy blocks. Their peripersonal subspaces overlap (see Figure 8, middle) and establish an interaction space. The calculated resulting potential fields are displayed in Figure 8, right. The force vectors of the peripersonal spaces lead in the direction of the interaction space. Within interaction space, the field strength disappears so that objects are placed within the space.

5.2.1 Modeling Cooperation and Competition in F-formations

In the scenario described so far, Max acts in a cooperative way as soon as an F-formation with an interaction space is established. The fact that Max's peripersonal space is modeled as a repulsive potential field, can be interpreted as his potential to *share* objects with others, i.e., to put objects into interaction space, where it is accessible to all involved interactants. However, Max's cooperative behavior can be modulated or also be inverted to competitive behavior. This can be achieved by modifying the parameter ξ in the peripersonal space field Equation 3. Decreasing ξ makes the field less repulsive, therefore Max might not put every object into interaction space. Increasing ξ makes the field more repulsive, which might lead him to be more cooperative than his partners. Finally, changing the repulsive field into an attraction field may reveal Max's competitive behavior by taking all objects from interaction space to his peripersonal space, where only he can access them.

6. CONCLUSIONS

In this work we presented our approach to model first, the representation of the space which immediately surrounds an articulated agent's body, second, the representation of the same space when it is shared with others and third, the articulated agent's behavior depending on interaction in the individual and in the shared space. The approach is therefore applicable for virtual humans as well as physical robots.

In a first step we realized individual body space in terms of a multi-sensory representation, involving touch, vision and proprioception. This concept, commonly known as peripersonal space, takes its information from the body structure, known as body schema.

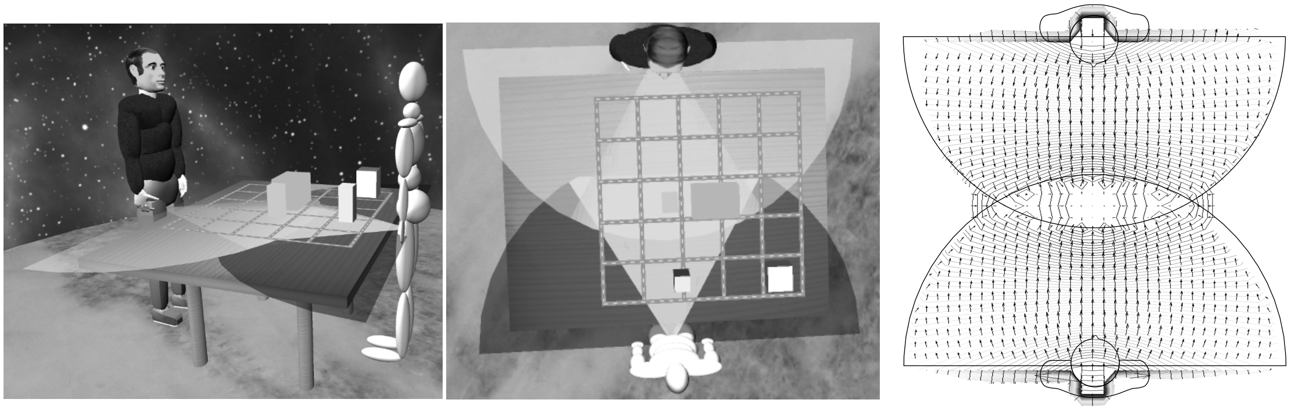

Figure 8: Left: Max (left) and an articulated humanoid (right) interacting in a virtual environment with visualized peripersonal subspaces. Middle: Bird-view perspective in the vis-a-vis arrangement with interaction space between the interactants. Right: The resulting potential field as a superposition of interactants' selective repulsive fields and one attractive potential field within interaction space.

Changes in body schema also affect peripersonal space, which we realized by a recalibration algorithm. In a second step we divided peripersonal space into subspaces corresponding to each sensory modality. This approach allows for naturally structuring the behavior, i.e., motor actions, and multimodal perception of the virtual human. In a third step we modeled the behavior within peripersonal space and interaction space. The method of potential fields proves to be applicable for modeling not only the peripersonal space of a virtual human, but also for modeling the space it shares with others. This aspect goes in line with the idea of Lloyd [13], who proposes that individual and interpersonal space share the same underlying representation. Finally, we showed how our model of interaction space for virtual humans supports their cooperative behavior in shared space and also implies a broader range of social behavior.

7. ACKNOWLEDGEMENTS

This work has been kindly supported by the Collaborative Research Center 673 Alignment in Communication, funded by the German Research Foundation (DFG). We thank Kim-Anh Tran for assisting in the research project and this publication.

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