A Qualitative Spatial Descriptor of Group-Robot Interactions

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Abstract

The problem of finding a suitable qualitative representation for robots to reason about activity spaces where they carry out tasks such as leading or interacting with a group of people is tackled in this paper. For that, a Qualitative Spatial model for Group Robot Interaction (QS-GRI) is proposed to define Kendon's F-formations [16] depending on: (i) the relative location of the robot with respect to other individuals involved in that interaction; (ii) the individuals' orientation; (iii) the shared peri-personal distance; and (iv) the role of the individuals (observer, main character or interactive). An iconic representation is provided and Kendon's formations are defined logically. The conceptual neighborhood of the evolution of Kendon formations is studied, that is, how one formation is transformed into another. These transformations can depend on the role that the robot have, and on the amount of people involved.

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1 Introduction

Robot tour guides appeared in the late 90s: Rhino [4] was located at the Deustche Museum in Bonn, Germany; Minerva [25] at the Smithsonian's National Museum of American History in Washington, etc. Nowadays flying quadcopters are used at MIT for personal guiding to labs (Skycall[1] project). Robots and other automats are getting gradually involved in human daily living activities, and in human environments, social robots must have the ability to communicate with people closely and fluidly both in a verbal and in a non-verbal way.

Spatial relationships are involved in human-robot interaction (HRI), e.g. combinations of distance, relative position and spatial arrangements that occur naturally when two or more people engage in an interaction [15, 20]. Empirical studies in robotics [17] identified spatial relations between people and a robot as a key issue to improve the quality of interaction noticing that interpersonal distances convey significant and relevant social information. Social interaction when navigating, specifically when robots pass people [22, 1] was also studied.

Qualitative descriptors for reasoning about moving objects appeared in the literature to represent HRIs in navigation situations where one robot and one human (or a group of

1 `http://senseable.mit.edu/skycall/`

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humans as a whole) are involved [11]. Qualitative spatial representations for activity spaces where a robot carry out a task or collaborate with more that one person are not available in the literature, as far as we are concerned. This paper refers to social interactions among humans and HRI in social environments, which may involve several individuals (sometimes arranged as a group) and one robot –from now on named as Group-Robot Interactions, GRI.

Few approaches in the literature have dealt with the challenge of formalizing social conventions for robots to behave more cognitively in human populated scenarios. The Qualitative Trajectory Calculus (QTC) was used to model HRI [8, 9, 2, 14]. QTC uses points as primitives to represent both the human and the robot, and their relative motion is expressed in a set of tuples of qualitative relationships. Qualitative social rules for robots to have a polite pedestrian behavior while navigating were proposed [10] using $OPRA_4$ calculus to formalize polite navigation rules (in situations as crossing, narrow passages, passing groups from the outside, etc.) and motion planning and pedestrian behavior were simulated using JWalkerS and SparQ toolbox[2] to investigate how traveling time is influenced by being polite. These pedestrian rules were also modeled in QLTL (Linear Temporal Logic with Qualitative Spatial Primitives) [11] and tested in a case study using a Kinect camera and a laser range scanner on a mobile robot. However, spatial arrangements of a robot interacting with a group of people (i.e. carrying a joint action) has not been studied yet.

The *Groups in Human-Robot Interaction* community discussed at IEEE Int. Symp. on Robot and Human Interactive Communication (RO-MAN 2016)[3] that inter-group interaction differs from inter-individual (dyadic) interaction. Ideally a robot should have different models of behavior depending on the number of people around it [18]. Thus, the first step is identifying the interactive situation a robot is facing.

This paper is organised as follows. Section 2 presents Kendon's [16] F-formations for group behavior. As these F-formations are described in a linguistic manner, next sections formalize them using qualitative representations and first order logics. Final sections provide an experiment for testing the logics defined, a discussion, conclusions and future work.

2 F-formations by Kendon

The *F-formation* system proposed by Kendon [16] studied spatial structures, both in position and orientation, generated when two or more people interact, and affirmed that *"behaviour of any sort occurs in a three dimensional world and any activity whatever requires space of some sort "* [ibid, p. 1.] This space allows an individual to perform any activity and it is differentiated from other spaces [20]. According to Kendon, in any scenario it is common that several individuals are co-present, but the way they are positioned and oriented in relation to the others reflects directly how they can be involved together. Based on his observations, Kendon defines a transactional space, *o-space*, as the space where people can interact and manipulate shared objects. In dyadic interactions, Kendon observed two types of formations: *vis-a-vis* (individuals are facing to each other) and *L-shape* (individuals are standing perpendicularly to each other facing an object). When the interaction occurs between two or more people, Kendon observed three types of formations: *circular form* (all people are looking at each other), *side-by-side* (people stand closely together and facing the same segment of the environment), and *horseshoe shape* (a kind of compromise between *side-by-side* and *circular form*). Typical spatial arrangements also happen in occasions where

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[2] SparQ toolbox: `http://www.sfbtr8.uni-bremen.de/project/r3/sparq/`
[3] `https://grouprobot.wordpress.com/home/`

there is an unequal distribution of rights to start a conversation or action, for example, in the *performer-audience* interaction. In contrast, if a group of people does not follow any spatial arrangement between them is known as *cluster*.

3 A Qualitative Spatial Descriptor of Group-Robot Interactions

This section presents a Qualitative Spatial descriptor for representing Group-Robot Interactions (QS-GRI). First, the representation for an individual is provided: an iconic representation is given, the location, orientation and distance reference systems used are defined and the first order logic statements generated are described (Section 3.1). Then the relations which can be obtained by QS-GRI between two individuals are described (Section 3.2).

3.1 QS-GRI Iconic Representation for an Individual

QS-GRI defines interactions between robots and people depending on: location, orientation and distance. Robots must be aware that people's personal space usually is not interfered by other people unless they are family, and this space is not allowed to be interfered by robots. So, an interactive distance for a robot is that distance which is not too close to any person but not too far away for them. Kendon [16] defined the *o-space* as the space where people can interact and manipulate shared objects. Similarly, in psychology, peri-personal space is defined as the space wherein individuals manipulate objects, whereas extra-personal space –which extends beyond the peri-personal space– is defined as the portion of space relevant for locomotion and orienting [12, 6]. Therefore, let us determine that two individuals that share their peri-personal space can be considered to have an interaction.

Moreover, any person distinguishes spatial orientations inside his/her personal and peri-personal space. These areas are usually named as: *front, back, right* and *left*. A person is also an oriented entity in space, defined by his/her *front*, indicated by their eyes.

The iconic representation of an individual (robot or person) used in QS-GRI is shown in Figure 1. That is, any individual fills an area in space (in blue), and (s)he has a personal space (in red) which is private, and a peri-personal space (in green) which is that space that (s)he can reach using their body or a tool. The white space is the extra-personal space.

These locations are defined using a Location interval Reference System, that is, Lo_{RS}= $\{\alpha$, Lo_n, $\mathrm{Lo}_{int(\alpha)}\}$ where α is the angular amplitude starting from 0 –located following the unit circle convention in trigonometry, that is, on the right-hand of an individual– to a range of $[0, 2\pi]$ measured in radians; Lo_n refers to the set of names given as locations; and $\mathrm{Lo}_{int(\alpha)}$ refers to a function which returns the corresponding Lo_n depending on α. In general:

$$\begin{aligned}\mathrm{Lo}_n &= \{\mathrm{Lo}_1, \mathrm{Lo}_2, \dots, \mathrm{Lo}_K\}\,,\\ \mathrm{Lo}_{int(\alpha)} &= \{[\mathrm{lo}_0, \mathrm{lo}_1], (\mathrm{lo}_1, \mathrm{lo}_2], \dots, (\mathrm{lo}_{K-1}, \mathrm{lo}_K]\}\,,\end{aligned}$$

where K is the number of concepts used for defining orientations. The Lo_n and $\mathrm{Lo}_{int(\alpha)}$ can be defined for the QS-GRI adapting to the case of study. Therefore, for modeling Kendon F-formations, the following Lo_{RS} can be selected:

$$\begin{aligned}\mathrm{Lo}_n &= \{\mathit{right}, \mathit{front}, \mathit{left}, \mathit{back}\}\,,\\ \mathrm{Lo}_{int(\alpha)} &= \{(-\pi/4, \pi/4], (\pi/4, 3/4\pi], (-\pi/4, -3/4\pi](3/4\pi, -3/4\pi]\}\,.\end{aligned}$$

An individual can rotate its *front* towards any direction in the space. Thus, the orientation of an individual is also taken into account by QS-GRI, which is calculated with respect to its *front* defined in the Lo_{RS}, and can be determined by the following RS: $\mathrm{O}_{RS}= \{\sigma, \mathrm{O}_i, \mathrm{O}_{g(\sigma)}\}$ where σ is the angle of rotation measured from the *front* with a range of $[0, 2\pi]$ in radians; O_i refers to the set of names (n) given to the orientations; and $\mathrm{O}_{g(\sigma)}$ refers to the function which relates the σ with a given name. In general:

$$\mathrm{O}_i = \{\mathrm{O}_1, \mathrm{O}_2, \ldots, \mathrm{O}_M\},$$
$$\mathrm{O}_{g(\sigma)} = \{\mathrm{o}_1(\sigma), \mathrm{o}_2(\sigma), \ldots, \mathrm{o}_M(\sigma)\},$$

where M is the number of concepts used for defining orientations. The O_i and O_g can be adapted to the case of study. Therefore, for QS-GRI, the following O_{RS} is selected:

$$\begin{aligned}\mathrm{O}_i = \{&\textit{towards-front}(tf), \textit{towards-front-right}(tfr), \textit{towards-right}(tr),\\ &\textit{towards-back-right}(tbr), \textit{towards-back}(tb), \textit{towards-back-left}(tbl),\\ &\textit{towards-left}(tl), \textit{towards-front-left}(tfl)\},\end{aligned}$$
$$\mathrm{O}_{g(\sigma)} = \{0, (0, \pi/2), \pi/2, (\pi/2, \pi), \pi, (\pi, 3/2\pi), 3/2\pi, (3/2\pi, 2\pi)\}.$$

In order to define the spaces surrounding an individual, QS-GRI uses a Distance Reference System or $\mathrm{D}_{RS} = \{d, \mathrm{D}_n, \mathrm{D}_f\}$, where d refers to a distance measured in meters (m), D_n refers to the set of names corresponding to the spaces defined; and D_f refers to the values of d related to each label. In general,

$$\mathrm{D}_n = \{\mathrm{d}_1, \mathrm{d}_2, \ldots, \mathrm{d}_Q\},$$
$$\mathrm{D}_f = \{[0, \mathrm{d}_1], (\mathrm{d}_1, \mathrm{d}_2], \ldots, (\mathrm{d}_{Q-1}, \mathrm{d}_Q]\},$$

where Q is the quantity of concepts defined. Both D_n and D_f can be parameterized depending on the case of study. For QS-GRI:

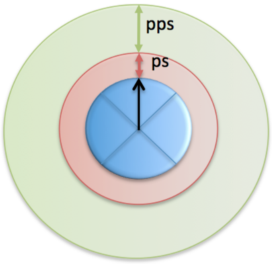
$$\mathrm{D}_n = \{\textit{ps}, \textit{pp}, \textit{eps}\},$$
$$\mathrm{D}_f = \{[0, 0.46], (0.46, 0.46 + ToolLength], (0.46 + ToolLength, \infty)\},$$

where *ps* is the personal space, *pps* is the peripersonal space, and *eps* is the extra-personal space. The width of the *ps* depends on the person, their social abilities and culture. Some people would need a wider personal space than other people. The *pps* is dynamic and adaptable, depending on the tool used by the person/robot and their abilities (i.e. flexibility of legs/arms for a person, actuator possibilities in a robot, etc). Thus, these areas can be customized for an individual but also parameterized based on psychological experimental studies [3]. For example, Hall [13] defined 4 kinds of interpersonal distances, each with its own significance in a social context: intimate ($0 - 0.46$ m), personal ($0.46 - 1.22$ m), social ($1.22 - 3.66$ m) and public (> 3.66 m). In QS-GRI, the *ps* may correspond to Hall's intimate distance, and the peripersonal space may involve the personal and social distance.

The QS-GRI can represent any individual using Horn clause logic [19] and Prolog programming language [23]. A possible description for an individual is given in Figure 1.

3.2 Relations between Individuals Inferred by QS-GRI

According to the previous definitions given for QS-GRI, relations of location, topology and distance can be inferred with respect to (wrt.) each individual. In this section, the logical rules for these inferences are provided.




```
has_location_xy(ind, 10,10).
has_orientation(ind, pi/2, towards-front).
has_width(ind,1).
has_ps(ind, 0.46).
has_tool_length(ind, stick, 0.2).
has_area(ind, right, -pi/4, pi/4).
has_area(ind, front, pi/4, 3/4*pi).
has_area(ind, left, 3/4*pi, 5/4*pi).
has_area(ind, back, 5/4*pi, 7/4*pi).
```

Figure 1 Iconic and logic representation of an individual.

Topological relation A wrt. B. An individual B, is inside the peripersonal space of another individual A, if the distance between the location of B and the location of A is smaller than their peri-personal limits. Moreover, if A is in the peri-personal space of B, B is also in the peri-personal space of A.

```
in_pps(A,B):-
  has_location_xy(A,X,Y), has_location_xy(B,X2,Y2),
  has_pps(A,LimitA), has_pps(B,LimitB),
  distance(X,Y,X2,Y2,D), D < LimitA+LimitB.
```

```
in_pps(A,B):-
  in_pps(B,A).
```

Relative Location of A wrt. B. The area around any individual is divided in locations according to the Lo_{RS}. So, the location of an individual A wrt. another individual B, is computed. For that, the rL_{RS} is built: $\mathrm{rL}_{RS}=\{\alpha, \mathrm{rLo}_j, \mathrm{rL}_{f(\alpha)}\}$ where α is the angle of location of A wrt. B in radians; rLo_j refers to the set of names (n) defined as locations in Lo_n and its combinations; and $\mathrm{Lo}_{f(\alpha)}$ takes the values in radians as parameters in a belonging function ($h(\sigma)$) which returns the corresponding location in rLo_j and a value of certainty ($Grade$). This $Grade$ is needed to evaluate how to the $front$, for example, is an individual located. It depends on the relative angle between the individuals as indicated below.

$$\mathrm{rLo}_j = \mathrm{Lo}_n \cup \{\textit{front-right}, \textit{front-left}, \textit{back-right}, \textit{back-left}\}\,,$$
$$\mathrm{rLo}_{h(\sigma,grade)} = \mathrm{rLo}_h(\mathrm{Lo}_{int(\sigma)}, \mathrm{grade})\,.$$

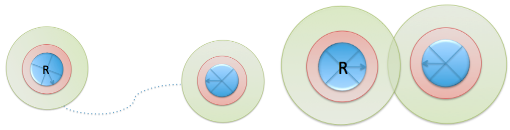
```
located(Lon,A,B,Grade):-
  relative_coordinates_to_A(A,B,Xr,Yr),
  location(Lon,Xr,Yr,Grade).

relative_coordinates_to_A(A,B,Xr2,Yr2):-
  has_location_xy(A,X,Y),
  has_location_xy(B,X2,Y2),
  has_orientation(A,RAngle, _),
  Xr is X2-X, Yr is Y2-Y,
  Xr2 is round((Xr*cos(RAngle))-(Yr*sin(RAngle))),
  Yr2 is round((Xr*sin(RAngle))+(Yr*cos(RAngle))).
```

```
location(front,0,Yr,Grade):-
  Yr >= 0, Grade is 1.
location(front,Xr,Yr,GradeS2):-
  Xr <> 0,
  Yr > 0,
  GradeS is sin(Yr/Xr),
  GradeC is cos(Yr/Xr),
  GradeC2 is abs(GradeC),
  GradeS2 is abs(GradeS),
  GradeS2 > GradeC2.
```

Similarly, the rest of the locations (*right, left, back*) of an individual B wrt. another individual A are obtained. And the combined location relations (*front-right, front-left, back-right, back-left*) are inferred. Note that, as individuals have a *ps* area, then the points on the boundary of this *ps* must be used to obtain correct locations.

```
located(front-right,A,B,Grade):-
  boundary_point_loc(front,A,B,GradeF),
  boundary_point_loc(right,A,B,GradeR),
  Grade is GradeF * GradeR.
```

```
located(back-left,A,B,Grade):-
  boundary_point_loc(back,A,B,GradeB),
  boundary_point_loc(left,A,B,GradeL),
  Grade is GradeB * GradeL.
```




```
vis_a_vis(A, B):-
  facing_each_other(A,B, _),
  in_pps(A, B).

facing_each_other(A,B, GradeResult):-
  located(front,A,B, GradeA),
  located(front,B,A, GradeB),
  GradeResult is (GradeA+GradeB)/2.
```

Figure 2 Vis-a-vis formation. Note that A and B are variables which can refer to any individual.

Location-neighbourhood relations that can help us to define the F-formations (i.e. *next to*, *in middle*, *neighbour*) and are inferred using QS-GRI as follows. Note that other relations (i.e. *behind*, *in front*) are also possible to define.

```
next_to(A,B):-
  in_pps(A,B),
  located(right,A,B,GradeR),
  located(left,B,A,GradeL).
in_middle(A,B,C):-
  next_to(A,C), next_to(C,B).
```

```
neighbour(A,B):-
  in_pps(A,B),
  located(front-right,A,B,GradeR),
  located(front-left,B,A,GradeL).
```

Orientation relation A wrt. B. By expressing the orientation of an object A wrt. another object B, relations of opposition (*towards-right* vs. *towards-left*, *towards-front* vs. *towards-back*, *towards-front-left* vs. *towards-back-right*, and *towards-front-right* vs. *towards-back-left*) and relations of perpendicularity (*towards-right* vs. *towards-front*, *towards-left* vs. *towards-down*, *towards-left* vs. *towards-front*, and *towards-right* vs. *towards-down*) can be extracted, which are useful to identify individual group formations. Logically, these relations can be written as the following examples:

```
opposed_orientation(A,B):-
  has_orientation(A,_, towards-right),
  has_orientation(B,_, towards-left).
```

```
perpendicular_orientation(A,B):-
  has_orientation(A,_, towards-down),
  has_orientation(B,_, towards-right).
```

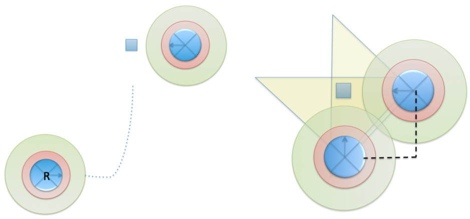
4 Recognizing Social Formations in Groups of Individuals

In this Section the F-formations defined by Kendon [16] are described logically using the predicates defined by QS-GRI: vis-a-vis, L-shape, circular, horse-shoe, side-by-side, performer-audience or cluster formation.

Vis-a-vis Formation: Individuals are facing each other and their *pps* intersect in the *front* area of both individuals, as Figure 2 shows. Note that the *front* of each individual must be oriented to each other relative *front* and that their orientations are opposite.

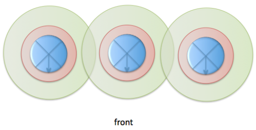
L-shape Formation: Two individuals are facing an object (Figure 3). This object is located in the front area of both individuals. The object observed is not animated, so it has no personal and no peri-personal space. These two individuals must share some peri-personal space. The intersection of this peri-personal space intersects at their *front-left* area of one individual and at the *front-right* area of the other individual.

The individuals are observers, they are not carrying out any physical activity together, otherwise they would face each other (e.g., they may be talking about the object). The roles of speaker and listener can be taken in turns. Note that the orientation of each individual is perpendicular to each other.




```
l-shape(A, B):-
  in_pps(A, B),
  located(front,A,object,_),
  located(front,B,object,_),
  dif(A,B).
```

Figure 3 L-shape formation.




```
side_by_side(A,B):-
  next_to(A,B),
  has_orientation(A,_,O),
  has_orientation(B,_,O).
```

```
side_by_side_group(A,[]).
side_by_side_group(A,[B|L]):-
  side_by_side(A,B),
  side_by_side_group(B,L).
```

Figure 4 Side-by-side formation.

Side-by-side formation: Individuals have the same orientation. They share their peri-personal space with the individuals *next to* them on their *left* and on their *right*.

In the queuing variation, individuals have also the same orientation, but they share their peri-personal space with their neighbors at their *front* and at their *back*. In both cases, individuals' role is passive. They are listeners-observers. Usually, they do not take the speaker role unless they are given permission for (i.e. for the queuing variation, until they reach the head of the queue). Note that, in both *side-by-side* and *queuing* formations, individuals only must change their orientation to establish a *facing each other* relation.

Horse-shoe formation: Individuals share their peri-personal space with their neighbors, in the *right* and *left* area. They all share their *front* area. All the individuals are observers: they are displaced to listen to somebody or to see some object (Figure 6).

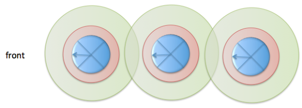
Hence, they hold the role of listeners. This is a passive role which can be changed with permission of the speaker, which is usually located at the shared *front*. Note that, the first and last individuals in the group-chain are *facing each other*.

Circular formation: Individuals are displaced in a triangular spatial formation sharing a common peri-personal space (Figure 8) on their right, and on their left. They are oriented towards a shared front.

In the general circular formation, each member of the group shares her personal space on her $right$ and also on her $left$, so each of the members in the group have two neighbors at the mentioned locations.

The individuals in the group are not only observers, they can interact with each other. The roles of speaker and listener can be exchanged constantly. Therefore, in order to maintain a circular shape, each member of the group has at least one other member located at its $front$ or facing each other in the distance (not sharing peri-personal space).

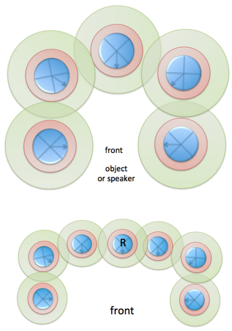
Performer-audience or cluster formation: All the individuals have the same perspective and they share their *pps* with their neighbors at their *front*, *right*, *left* and at their *back*, that is, they are *next to* someone and also *cueing* with someone (Figure 9). Their role is passive since they are listeners-observers. They do not take the speaker roll unless they are given permission.




```
cueing(A,B):-
  in_pps(A,B),
  located(back,A,B,GradeF),
  located(front,B,A,GradeB).
```

```
cueing_group(A,[]).
cueing_group(A,[B|L]):-
  cueing(A,B),
  cueing_group(B,L).
```

Figure 5 Cueing formation.




```
horse_shoe_form([Head|L]):-
  length(L,NumInd),
  NumInd >= 3,
  last(L,Tail),
  facing_each_other(Head,Tail,_),
  horse_shoe(Head,L).

horse_shoe(_,[Tail]):-
  located(front,Tail,obj2,_).
```

```
horse_shoe(H,[X|L]):-
  located(front,H,obj2,_),
  (next_to(X,H);
  neighbour(X,H)),
  horse_shoe(X,L).
```

Figure 6 Horse-shoe formation: individuals observe someone/ something while sharing its left/right peripersonal space and its front.

5 Dynamics of Social Formations: Exploring QS-GRI Neighbourhoods

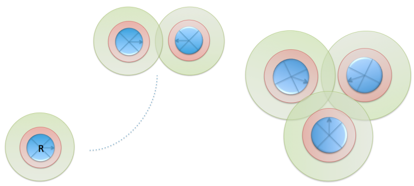
This section deals with the following challenge: *where the robot should locate itself to be included in a group? and towards which direction should it be oriented?* The first step towards the solution is to identify which kind of F-formation is the group taking. Then, for some F-formations, the role of the robot is relevant because it determines the location where the robot should place itself. For example, in the *horse-shoe* formation, most of the individuals have an *observer* role, while the individual at the front has a *leading* role. If the situation evolves so that the one leading allow others to lead and their roles are exchanged, then an interactive situation is happening and the *horse-shoe* formation evolves to a *circular* formation. For this reason, how a F-formation can evolve by including individuals is studied depending on the roles involved: leading, observer or interactive.

If the robot has an interactive goal, and detects:

- a person, it can select the vis-a-vis formation to locate itself and start this interaction. For that, it must be located in front of the person, oriented towards the person, and it must share that person's *pps* but their *ps* must not intersect (Figure 2).
- two people in a vis-a-vis formation, then the robot can select the triangular formation to locate itself to try to start an interaction.
- a group of more than 3 people who interact among themselves, then the robot can select a circular formation. The evolving formations are those where the circle is getting bigger: 4-circular formation, 5-circular formation, n-circular-formation (Figure 8).

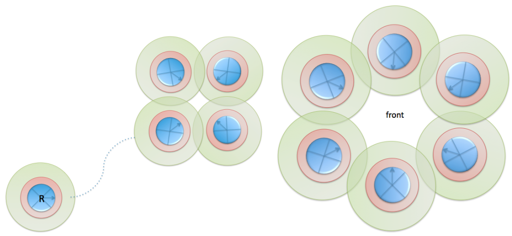
Let us explain how the rest of F-formations are useful for the robot to place itself depending on its goal, which may be:

- interacting with one person while observing an object, then the robot selects the L-shape formation to start this interaction (Figure 3).
- leading, i.e. performing a speech to a group of people located in a horse-shoe formation (Figure 6). The robot must locate itself at the front. While if the robot takes an observer




```
triangular_form(A,B,C):-
  both_sides_neighbours(A,B,C),
  both_sides_neighbours(B,A,C),
  both_sides_neighbours(C,A,B).

both_sides_neighbours(A,B,C):-
  in_pps(A,B),
  in_pps(A,C),
  (located(front-left,A,B,_);
   located(front-right,A,B,_)),
  (located(front-right,A,C,_);
  located(front-left,A,C,_)).
```

Figure 7 Minimal circular or triangular formation.




```
circular(Group):-
  length(Group,NumInd),
  NumInd > 3,
  some_members_loc(front,Group,Group),
  two_neighbours_for_each(Group,Group).

two_neighbours_for_each([Head|L],Group):-
  last(Group,Tail),
  nextto(Head,Next,Group),
  ( neighbour(Head,Tail);
    next_to(Head,Tail)),
  ( neighbour(Head,Next);
    next_to(Head,Next)),
  two_neighbours_middle(L,Group).
```

Figure 8 General circular formation. The complete definition is available[5].

role, then the robot chooses to locate itself among the people. The robot shares its left and right peri-personal space with its neighbors.

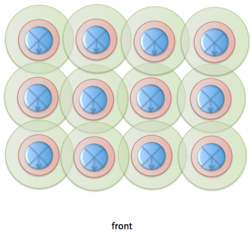
- leading, i.e. performing some speech to a group of people who are located in a side-by-side formation or in a cluster formation (i.e. performance), then the robot chooses to locate itself at the front, not in the crowd.
- observing, i.e. observing a performance with a group of people. These people are located in a side-by-side formation, and the robot incorporates itself in this side-by-side or cluster formation (Figure 4). In the cluster formation, the robot can have more than 2 left-right-neighbours and up to 4. In the situation depicted, the robot must also share its front *pps* with the person in front of it while they are sitting.

This relations among the F-formations have been summarized in Table 1. Note that a change of the robot activity/role involves a change in its location in the corresponding formation (see lines in Table 1), while adding a new person in the group also makes the formation to evolve to a different one (change in columns in Table 1).

6 Experimentation

In order to test the QS-GRI, we selected Prolog programming language [23], which is based on Horn clause logic [19]. Swi-Prolog[4] was the testing platform. Figure 10 presents the experimental world used to test QS-GRI logic algorithms[5] in an envisioned museum scenario

[4] SWI-Prolog: `http://www.swi-prolog.org/`
[5] Download from CogQDA project website: `https://sites.google.com/site/cogqda/publications`




```
cluster(L):-
  all_in_cluster(L,L).

all_in_cluster([],_).
all_in_cluster([X|L],Cluster):-
  in_cluster(X,Cluster).
```

```
in_cluster(A,L):-
  side_by_side_with_sb(A,L,LNext),
  cueing_with_sb(A,L,LCue),
  length(LNext,NumNext),
  length(LCue,NumInCue),
  NumNext > 0, NumInCue > 0.
```

Figure 9 Performer-audience formation or cluster formation[5].

Table 1 Table of conceptual neighborhood situations.

	Leading	**Observer**	**Interactive**
1 person	vis-a-vis	L-shape	vis-a-vis
2 people	at front in: side-by-side or minimal circular	L-shape	minimal circular
3 people	at front in: side-by-side or horse-shoe	observer in: side-by-side	circular
4 people	at front in: side-by-side or horse-shoe	observer in: side-by-side horse-shoe	circular
5 people	at front in: side-by-side or horse-shoe	observer in: side-by-side horse-shoe	circular
N people	at front in: side-by-side, horse-shoe or performance	observer in: side-by-side horse-shoe or performance	circular

where the surveillance camera helps the robot to take a general perspective to identify human formations and to identify where should it stand to start the interaction.

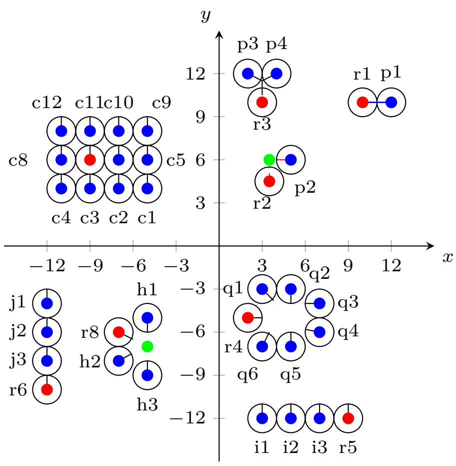
The following simulated environment has been implemented as facts in a close world. The elements showed are:

```
?- facing_each_other(R, P, G).
  R = r1,
  P = p1,
  G = 1 .

?- vis_a_vis(R,Ind).
  R = r1,
  Ind = p1 .

?- l-shape(A,B).
  A = r2,
  B = p2 ;
  A = p2,
  B = r2 ;
```

```
?- side_by_side_group(A,L).
L = [] ;
A = i1, L = [i2] ;
A = i1, L = [i2, i3] ;
A = i1, L = [i2, i3, r5] ;

?- cueing_group(A,L).
L = [] ;
A = j1, L = [j2] ;
A = j1, L = [j2, j3] ;
A = j1, L = [j2, j3, r6] ;
```

```
?- triangular_form(p3,p4,r3).
  true .

?- circular([r4,q1,q2,q3,q4,q5,q6]).
  true .

?- horse_shoe_form([h1,r8,h2,h3]).
  true .

?- cluster([c1,c2,c3,c4,c5,c6,
   r7,c8,c9,c10,c11,c12]).
  true .
```

- robot *r1*, located on the coordinates (10,10) in the simulated world and which is oriented *towards-right* and a person *p1*, who is located in the coordinates (12,10) and who is facing *towards-left*. According to these facts and the Lo_{RS}, it is inferred that *p1* is *in front of r1* and viceversa, and therefore, they are located in a *vis-a-vis* F-formation.
- robot *r2*, located on the coordinates (3.5,4.5) and which is oriented *towards-front* and a person *p2*, who is located in the coordinates (5,6) and who is facing towards-left. There is also a non-oriented *object* located on (3.5, 6). According to these facts and the Lo_{RS}, it is inferred that the *object* is *in front of r2* and *in front of p2*, sharing some peri-personal space, thus it is inferred that they are in a *L-shape* formation.
- individual *i1*, which is oriented *towards-front* has another individual *i2 next to*, which has another individual, *i3* also *next to*, which also has *r5 next to*, thus it is inferred that they are in a *side-by-side* formation.




```
has_loc_xy(r1, 10,10).              has_orient(r1,pi/2,tr).
has_loc_xy(p1, 12,10).              has_orient(p1,-pi/2,tl).
has_loc_xy(object, 3.5,6).          has_orient(p2,-pi/2,tl).
has_loc_xy(object2,-5,-7).          has_orient(r2,0,tf).
has_loc_xy(r2, 3.5,4.5).            has_orient(object,0,none).
has_loc_xy(p2, 5,6).                has_orient(object2,0,none).
has_loc_xy(p3, 2,12).               has_orient(p3,3/4*pi,tbr).
has_loc_xy(r3,3,10).                has_orient(p4,5/4*pi,tbl).
has_loc_xy(p4,4,12).                has_orientation(r3, 0, tf).
has_loc_xy(q1,3,-3).                has_orient(q1,3/4*pi,tbr).
has_loc_xy(q2,5,-3).                has_orient(q2,pi,tb).
has_loc_xy(q3,7,-4).                has_orient(q3,3/2*pi,tl).
has_loc_xy(q4,7,-6).                has_orient(q4,7/4*pi,tfr).
has_loc_xy(q5,5,-7).                has_orient(q5,0,tf).
has_loc_xy(q6,3,-7).                has_orient(q6,pi/4,tfr).
has_loc_xy(i1,3,-12).               has_orient(r5,0,tf).
has_loc_xy(i2,5,-12).               has_orient(i1,0,tf).
has_loc_xy(i3,7,-12).               has_orient(i2,0,tf).
has_loc_xy(r5,9,-12).               has_orient(i3,0,tf).
has_loc_xy(j1,-12,-4).              has_orient(j1,0,tf).
has_loc_xy(j2,-12,-6).              has_orient(j2,0,tf).
has_loc_xy(j3,-12,-8).              has_orient(j3,0,tf).
has_loc_xy(h1,-5,-5).               has_orient(h1, pi, tb).
has_loc_xy(r8,-7,-6).               has_orient(r8, 7/12*pi, tbr).
has_loc_xy(h2,-7,-8).               has_orient(h2, 5/12*pi, tfr).
has_loc_xy(h3,-5,-9). (...)         has_orient(h3, 0, tf). (...)
```

Figure 10 Virtual world created for testing QS-GRI logic algorithms in Prolog. These predicates and orientations (see O_{RS}) have been abbreviated for saving space.

- robot *r3* is sharing its peri-personal space and its *front-right* and *front-left* areas with two individuals *p3* and *p4*, which also have the same relation between them. Thus, they are located in a *triangular* formation.
- robot *r4* and individuals *q1-q6* are located in a *circular* formation, whereas robot *r8* and individuals *h1-h3* is located forming a *horse shoe*.
- finally, robot *r7* and individuals *c1-c12* are located in a cluster formation.

7 Discussion

In robotics, research works usually analyze spatial interactions from a quantitative point of view, expressing spatial relationships in terms of numerical distances and absolute orientations. Since distances and directions are constantly changing, the representation of the interaction based on these primitives is complex. A qualitative descriptor such as QS-GRI can abstract the necessary information, while dealing with incomplete or uncertain data to define HRI in a more cognitive way.

In the literature, $\mathcal{EPRA}_m$ calculus [21] integrated cardinal absolute direction information and local distances. Other works focused on HRI [22, 10] divided the robot space following proxemics using: intimate, personal, social and public. This paper proposes a more psychological point of view by dividing space in personal and peri-personal, which is more related to Kendon definition of o-space [16], where people can interact and manipulate shared objects.

Exploratory studies in robotics [7] for evaluating HRI in terms of spatial relationships observed that it is possible to distinguish different types of spatial arrangements and group sizes, and to chose a discretization of group individuals to points/regions in space (see Figure 11).

Other studies in psychology and linguistics [24] observed that, in a communicative process, the capabilities assumed for the addresse depend if they are a human or a robot since speakers usually conceptualized a robot as *“a communication partner who needs comparably simple instructions”* (p.22), e.g. humans usually took the robot’s perspective when giving instructions

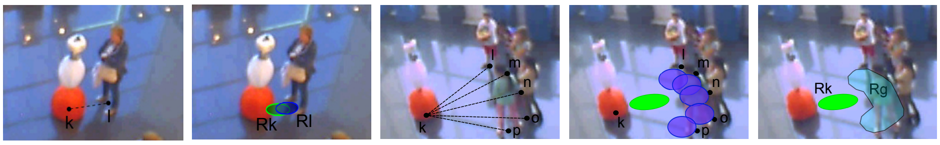


Figure 11 Real scenario: a *vis-a-vis* formation representing individuals as points/regions, a *horse-shoe* formation representing individuals as points/regions.

to it. The capacity of adaptation in humans in interactive situations facilitates HRI, which does not need to be so sophisticated as interaction among humans. However, the more the robot can reproduce human-similar utterances and behaviors, the more natural the interaction will get.

As far as we are concerned, there are not previous works in the literature that define Kendon's F-formations logically using qualitative descriptors and study their change/evolution as conceptual neighborhood. This evolution of F-formations may help robots to locate themselves following a social convention depending on the role they are assigned (main character/guide, observer/listener, or interactive). Further tests are intended for the QS-GRI logics I are aimed to be tested in a real scenario, where the robot perspective will substitute the general surveillance camera perspective with real human test subjects as future work.

8 Conclusions and Future Work

This paper presents a Qualitative Spatial model for Group Robot Interaction (QS-GRI) based on a location, orientation and a distance descriptor for representing individuals interacting in space. These descriptors are defined as first order logic statements and are used to infer relations of location, orientation and topology between individuals.

The QS-GRI identifies also Kendon's F-formations depending on: (i) the relative location of the robot with respect to other individuals involved in the interaction; (ii) the orientation of the individuals (shared front) or not; (iii) the shared peri-personal distance; and (iv) the role of the individuals (observer, main character or interactive). The recognition of these situations has been tested in a simulated world using Swi-Prolog.

Moreover, the evolution of Kendon-formations between them has also been studied to extract conceptual neighbourhood relations. That is, how one formation is transformed into another. These transformations depend on the robot role (i.e. interactive or observer), and on the number of people in the group.

As future work we intend to validate QS-GRI using the data available from the exploratory study carried out in a cultural centre where a robot guide is interacting to people [7]. QS-GRI is also envisioned to be applied in other human-robot collaboration (HRC) scenarios [5].

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References

1 P. Althaus, H. Ishiguro, T. Kanda, T. Miyashita, and H. I. Christensen. Navigation for human-robot interaction tasks. In *Robotics and Automation, 2004. Proceedings. ICRA'04. 2004 IEEE Int. Conf. on*, volume 2, pages 1894–1900 Vol.2, April 2004. doi:10.1109/ROBOT.2004.1308100.

2 N. Bellotto, M. Hanheide, and N. Van de Weghe. Qualitative design and implementation of human-robot spatial interactions. In G. Herrmann et al., editor, *Social Robotics*, volume 8239 of *LNCS*, pages 331–340. Springer International Publishing, 2013.

3 R. J. Bufacchi, M. Liang, L. D. Griffin, and G. D. Iannetti. A geometric model of defensive peripersonal space. *Journal of Neurophysiology*, 115:218–225, 2016. `doi:10.1152/jn.00691.2015`.

4 W. Burgard, A. B. Cremers, D. Fox, D. Hähnel, G. Lakemeyer, D. Schulz, W. Steiner, and S. Thrun. Experiences with an interactive museum tour-guide robot. *Artificial Intelligence*, 114(1):3–55, 1999. `doi:10.1016/S0004-3702(99)00070-3`.

5 P. Bustos, L. J. Manso, J. P. Bandera Rubio, A. Romero-Garcés, L. V. Calderita, R. Marfil, and A. Bandera. A unified internal representation of the outer world for social robotics. In L. P. Reis et al., editor, *Robot 2015: Second Iberian Robotics Conference – Advances in Robotics, Lisbon, Portugal*, volume 418 of *Advances in Intelligent Systems and Computing*, pages 733–744. Springer, 2015. `doi:10.1007/978-3-319-27149-1_57`.

6 A. Couyoumdjian, F. Di Nocera, and F. Ferlazzo. Functional representation of 3D space in endogenous attention shifts. *The Quarterly Journal of Experimental Psychology Section A*, 56(1):155–183, 2003. `doi:10.1080/02724980244000215`.

7 M. Díaz-Boladeras, D. Paillacho, C. Angulo, O. Torres, J. Gonzalez, and J. Albo-Canals. Evaluating group-robot interaction in crowded public spaces: A week-long exploratory study in the wild with a humanoid robot guiding visitors through a science museum. *Int. Journal of Humanoid Robotics*, 12(04):1550022, 2015. `doi:10.1142/S021984361550022X`.

8 C. Dondrup, N. Bellotto, and M. Hanheide. A probabilistic model of human-robot spatial interaction using a qualitative trajectory calculus. In *AAAI Spring Symposium*, 2014.

9 C. Dondrup, N. Bellotto, and M. Hanheide. Social distance augmented qualitative trajectory calculus for human-robot spatial interaction. In *Robot and Human Interactive Communication, 2014 RO-MAN: The 23rd IEEE International Symposium on*, pages 519–524, Aug 2014. `doi:10.1109/ROMAN.2014.6926305`.

10 F. Dylla, M. Coors, and M. Bhatt. Socially compliant navigation in crowded environments. In *Spatial and Temporal Dynamics (STeDy) Workshop at ECAI 2012*, pages 9–17, 2012.

11 F. Dylla, A. Kreutzmann, and D. Wolter. A qualitative representation of social conventions for application in robotics. In *2014 AAAI Spring Symposium – Qualitative Representations for Robots*, number SS-14-06 in Papers from the 2014 AAAI Spring Symposium, 2014.

12 C. Goerick. Towards cognitive robotics. In B. et al. Sendhoff, editor, *Creating Brain-Like Intelligence: From Basic Principles to Complex Intelligent Systems*, pages 192–214. Springer, Berlin, Heidelberg, 2009. `doi:10.1007/978-3-642-00616-6_10`.

13 E. Hall. *The hidden dimension: Man's Use of Space in Public and Private*. The Bodley Head Ltd, London, UK, 1966.

14 M. Hanheide, A. Peters, and N. Bellotto. Analysis of human-robot spatial behaviour applying a qualitative trajectory calculus. In *RO-MAN, 2012 IEEE*, pages 689–694, 2012.

15 H. Huettenrauch, K. S. Eklundh, A. Green, and A. T. Elin. Investigating spatial relationships in human-robot interaction. In *Int. Conf. on Intelligent Robots and Systems*, pages 5052–5059, 2006.

16 A. Kendon. Spacing and orientation in co-present interaction. In A. Esposito, N. Campbell, C. Vogel, A. Hussain, and A. Nijholt, editors, *Development of Multimodal Interfaces: Active Listening and Synchrony*, volume 5967 of *LNCS*, pages 1–15. Springer, Berlin, 2010.

17 A. Kristoffersson, K. Severinson-Eklundh, and A. Loutfi. Measuring the quality of interaction in mobile robotic telepresence: A pilots perspective. *Int. Journal of Social Robotics*, pages 1–13, 2012.

18 I. Leite, M. McCoy, D. Ullman, N. Salomons, and B. Scassellati. Comparing models of disengagement in individual and group interactions. In *Proc. of 10th Annual ACM/IEEE*

Int. Conf. on Human-Robot Interaction, HRI'15, pages 99–105, New York, NY, USA, 2015. ACM. doi:10.1145/2696454.2696466.

19 J. W. Lloyd. *Foundations of logic programming. Symbolic computation: Artificial intelligence*. Springer-Verlag, 2nd, extended edition edition, 1987.

20 P. Marshall, Y. Rogers, and N. Pantidi. Using F-formations to analyse spatial patterns of interaction in physical environments. In *Proc. of the ACM 2011 Conf. on Computer Supported Cooperative Work*, CSCW'11, pages 445–454, New York, NY, USA, 2011. ACM. doi:10.1145/1958824.1958893.

21 R. Moratz and J. O. Wallgrün. Spatial reasoning with augmented points: Extending cardinal directions with local distances. *J. Spatial Information Science*, 5(1):1–30, 2012. doi:10.5311/JOSIS.2012.5.84.

22 E. Pacchierotti, H. I. Christensen, and P. Jensfelt. Embodied social interaction for service robots in hallway environments. In *Proc. of the International Conference on Field and Service Robotics (FSR'05)*, July 2005.

23 L. Sterling and E. Shapiro. *The Art of Prolog (2nd Ed.): Advanced Programming Techniques*. MIT Press, Cambridge, MA, USA, 1994.

24 T. Tenbrink, K. Fischer, and R. Moratz. Spatial strategies in linguistic human-robot communication. In Christian Freksa, editor, *KI-Themenheft 4/02 Spatial Cognition*, pages 19–23. arenDTaP Verlag, 2002.

25 S. Thrun, M. Bennewitz, W. Burgard, A. B. Cremers, F. Dellaert, D. Fox, D. Hähnel, C. R. Rosenberg, N. Roy, J. Schulte, and D. Schulz. MINERVA: A second-generation museum tour-guide robot. In *1999 IEEE Int. Conf. on Robotics and Automation, Proc.*, pages 1999–2005, 1999. doi:10.1109/ROBOT.1999.770401.