People's Adaptive Side-by-Side Model Evolved to Accompany Groups of People by Social Robots

Ely Repiso† Anaís Garrell† Alberto Sanfeliu†

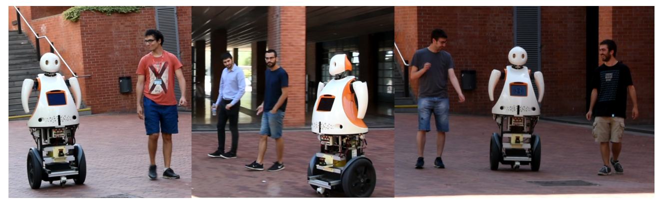

Fig. 1. **Real-life experiments in the Barcelona Robot Lab.** *Left*: Tibi accompanies one volunteer using the adaptive side-by-side. *Center*: Tibi accompanies the volunteers in the lateral of the side-by-side. *Right*: Tibi accompanies the volunteers in the middle of the Side-by-side formation

Abstract— **The presented method implements a robot accompaniment in a side-by-side formation of a single person or a group of people. The method enhances our previous robot adaptive side-by-side behavior allowing the robot to accompany a group of people, not only one person, doing an adaptive side-by-side behavior. The adaptive means that the robot is capable of adjusting its motion to the behavior of the person (or people) being accompanied (in position and velocity), without bothering other pedestrians in the environment, as well as avoiding colliding with static and dynamic obstacles. Furthermore, the robot can deal with the random factor of human behavior in several situations: if other people interfere the path of the companions, the robot leaves space to one of the accompanied person by approaching the other person, but without invading any personal space; if the people of the group changes their physical position inside the group formation, the robot adapts to them dynamically by changing from the lateral position inside the formation to the central position in the formation or otherwise; the robot adapts to the velocity changes of the companions and other people that interfere in the path of the group, in magnitude and direction of the movement; the robot can deal with occlusions of one accompanied person by the other. Finally, the method has been validated using synthetic experiments and real-life experiments with our robot. Furthermore, we developed a user study comparing the method with a Wizard of Oz.**

I. Introduction

The actual society is evolving to have social robots sharing our urban spaces with us, to do task by themselves or to collaborate with humans in daily tasks. These collaborative behaviors may include the accompaniment of individuals or groups of people to do some tasks like: go shopping, take care of elderly people, transport people, help people to walk, provide support for runners [1], etc. Also, these robots have to follow our social rules to be accepted by us [2]–[4], and understand and predict our behaviours to anticipate our movements [5].

Normally, people tend to group themselves in groups in order to perform daily tasks better and faster. This implies that robots will have to develop abilities to interact with individuals and groups of people. One of these collaborative abilities is to accompany people to any place following the social conventions to be accepted as part of the group, Fig. 1. Some studies in the social behaviour of groups [6]–[11] observed than groups of more that three components normally are divided in groups of two or three people that are interacting between them, and also that groups of two or three people are the more frequent and stable. In this work, we will focus on groups of two or three components, in order that the robot can interact with the accompanied people and the humans can interact among them in a more natural and easy way.

To be an active part of a group of people is not a trivial endeavor for robots, because the dynamic environments and humans movements are unpredictable and complex. For these reasons, when a robot accompanies a humans's group (for example a robot and two people), it has to perform several complex tasks at the same time, such as: predicts people movement and their final destinations; detects and predicts the position of the accompanied people; deals with occlusions of members of the group; adapts its velocity to the people velocity (accelerating, decelerating and even stopping when necessary); maintains, breaks or changes its physical position inside the group of the formation if necessary; facilitates the navigation of the group and other people; and does not invade the personal space of all people and does not collide with static obstacles. In this work we present a Side-by-Side navigation method which address all these problems to allow the robot to accompany one or more people in dynamic environments.

In the remainder of the paper, the related work is presented in Sec. II. Sec. III describes our method. The metrics of performances are introduced in Sec. IV. The synthetic results are described in Sec. V. The results of the real-life

Work supported by the Spanish Ministry of Science and Innovation under project ColRobTransp (DPI2016-78957-RAEI/FEDER EU), TERRINet (H2020-INFRAIA-2017-1-two-stage-730994), by the Spanish State Research Agency through the María de Maeztu Seal of Excellence to IRI (MDM-2016-0656). Ely Repiso is also suported by Spanish Ministry of Science and Innovation under a FPI-grant, BES-2014-067713.

†The authors are with the Institut de Robòtica i Informàtica Industrial (CSIC-UPC). Llorens Artigas 4-6, 08028 Barcelona, Spain. {erepiso,agarrell,sanfeliu}@iri.upc.edu

experiments and an user study are shown in Sec. VI. Finally, the conclusions are given in Sec. VII.

II. Related Work

Regarding the accompaniment of individual people, several authors face this problem using fixed formations (followers, guiders and side-by-side) [1], [12]–[18]. However, few authors has worked in accompaniment of groups of people. In this topic, we can find several interesting works in the autonomous wheelchair field [19], where these approaches were focused on maintaining one or several exact formations between the members of the group to facilitate the communication between them, but without taken into account autonomous navigation in the environment neither avoiding obstacles or facilitating the navigation of other people. Another work [20] focused on the movement's prediction of the members of a group dance, to predict the dynamics of the group including the robot in the group, but without taken into account other interactions outside the group. The work of [21] analysed a concrete formation with a human guider, and the work of [22] studied the robot as a tour guider of a museum. Also, other works that guide people to places, but using more than one robot can be found in [12], [13].

Our previous work faced the same problem with a different accompaniment formation, V-formation, and hence, different robot behaviour. The main differences between the two methods are the methodologies used to obtain each different formation and the selection of the best paths regarding different formations. Also, the results of the experiments and the user study were different.

In this work, we present a method where the robot maintains an adaptive side-by-side formation with the companions to facilitate the communication between them, while facilitates the navigation of the group and other people in the environment.

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III. Method

This section describes the planning algorithm used to allow the robot to do an adaptive side-by-side group accompaniment, of several people at the same time. This method is based on our previous work of adaptive accompaniment of one person [23], however, in this case we extend it to do a side-by-side accompaniment of a group of people. We explain two different types of formations among one robot and two persons: lateral position, where the robot is in one side; and central position, where the robot is in the middle of the two persons being accompanied. When the robot is in the lateral position inside the group formation, we consider that the robot only interacts with the nearest person and the robot uses the adaptive companion of one human, but evaluates the side-by-side accompaniment of both people using the performance metrics. So we can check if only taking into account the closest person is enough to obtain a good accompaniment side-by-side with the further person from the robot. Moreover, we will introduce the improvements to achieve the side-by-side adaptive accompaniment of a group of two people, when the robot is in the central position of the group and can interact with both people. The method has two stages. In the first stage, Sub-sec. III-A, we explain how the robot infers the destination of the two people of the group (and all destinations for the other people) and infer both sub-goals for these accompanied people using their position inside the group. After that, the robot plans all the possible paths of these two people, and for each path position, it is obtained the respective robot position using the ESFM. To plan all the paths, we use the Anticipative Kinodynamic Planner (AKP) and the Extended Social Force Model (ESFM) improved to do the accompaniment of groups of people. In the second stage, Sub-sec. III-B, we do the evaluation of the planned paths using a new cost function and the selection of the best path to do the adaptive companion of groups.

A. Stage 1: Infer people destinations, and plan the paths for the group accompaniment

First of all, the robot needs to know the destinations and the predicted positions of all people to facilitate their navigation behaviour. Also, the robot has to predict the accompanied people destination and paths to perform an anticipatory and adaptive companion behaviour. Then, to know all the destinations that may change over time, the robot uses the Bayesian Human Motion Intentionally Predictor (BHMIP) method [5]. The BHMIP infers the final destination of all people in the environment by using a set of predefined known destinations of the environment, $D = \{D_1, D_2, ..., D_n, ..., D_m\}$, and a geometric-based long term prediction method that uses a Bayesian classifier to selects the best destination of the person. These destinations are places where people usually go, like entrances, exits or work places of the environment.

Also, using the BHMIP the robot selects the best destination of the group, ${D_n}^{goal}$, and the final position of this destination is dynamically modified to include the randomness factor of people, ${D_{n_d}}^{goal}$. The ${D_{n_d}}^{goal}$ is extracted from the selected destination of the environment, by using the predicted direction of the group and the position of both people inside the group. Each person of the group has its own dynamic goal. The predicted direction is computed by using the previous group positions saved during a past time window that allows the robot to know the mean of the group velocity during this time window. Always our time window is of 5 seconds. Furthermore, from the dynamic final destination of the group, ${D_{n_d}}^{goal}$, the robot extracts, using geometric properties, the dynamic final destinations of all the components of the group $\{D^{goal}_{n_{d_r}}, {D_{n_{d_{p_{c1}}}}}^{goal}, {D_{n_{d_{p_{c2}}}}}^{goal}\}$, were r, $c1$ and $c2$ means robot, companion one and two respectively. The computation of these dynamic destinations allows the robot to do a better side-by-side accompaniment and to compute all the possible paths for the two accompanied people that serves to compute all the possible robot paths. Finally, to allow the robot to avoid static and dynamic obstacles we use a local time window, that uses a time horizon $h = 5$ seconds, where the final destinations are translated to the region of exploration C_r that is a circle radius equal to $h \cdot v_{max}$, where v_{max} is the maximum velocity of the robot. Furthermore, these destinations include a random factor over this circle to compute all the possible paths to avoid obstacles. The random factor increases when the group has more obstacles inside the time window of the planner. For more information of the sampling procedure the reader is referred to [24].

Once the robot knows the final destinations of both accompanied people, with the random factor included to avoid other people and static obstacles, it has to compute all the possible paths for the robot. To do it the robot employs the AKP that uses the ESFM, but this force model is modified to do the side-by-side accompaniment of two people. Then, we proceed to define the improved resultant force of the robot, F_r, used to plan all the paths of the adaptive side-by-side method to accompany groups of people.

$$\mathbf{F}_r = \alpha\, \mathbf{f}_{r,d_c}^{goal}({D_{d_c}}^{goal}) + \gamma\,(\mathbf{F}_r^{ped} + \mathbf{F}_{p_c}^{ped}) + \delta\,(\mathbf{F}_r^{obs} + \mathbf{F}_{p_c}^{obs}) \quad (1)$$

Where, α, γ and δ are the corresponding weights of the forces and were learned in [25]. These weights were obtained through two steps: a first approximation of the weights were computed by means of the MCMC-MH method using data of thousands of simulations of the accompaniment task, and second, these weights were refined by means of an Interactive Learning [26] using data of the real life experiments. For more information about this procedure the reader is referred to [25].

The, $\mathbf{f}_{r,d_c}^{goal}({D_{d_c}}^{goal})$ is the attractive force of the robot to accompany the people using the adaptive side-by-side accompaniment of groups, and to go through the final destination of the group, see Eq. 2. Now, the final destination is implicitly included in the paths of the accompanied people, generated previously, and these paths uses the AKP-planner with the dynamic destinations calculated before.

$$\mathbf{f}_{r,d_c}^{goal}({D_{d_c}}^{goal}) = \mathbf{f}_{r,p_{c_1}}^{goal}({D_{p_{c_1}}}^{goal}) + \mathbf{f}_{r,p_{c_2}}^{goal}({D_{p_{c_2}}}^{goal}), \quad (2)$$

$\mathbf{f}_{r,p_{c_i}}^{goal}({D_{p_{c_i}}}^{goal})$, $i = 1, 2$, are the two attractive forces until the next planned positions of each of the accompanied persons, P_{c_1} and P_{c_2}. Furthermore, these forces are computed using Eq. 3, and assumes that the person, p_{c_i}, tries to adapt its velocity with a relaxation time k^{-1} to arrive to the final destination for this person, ${D_{d_{c_i}}}^{goal}$, to do the plan.

$$\begin{aligned} \mathbf{f}_{r,p_{c_i}}^{goal}({D_{p_{c_i}}}^{goal}) = \quad & \mathbf{f}_{r,d_{c_i}}^{goal}({D_{d_{c_i}}}^{goal}) = \\ = \quad & k(\mathbf{v}_r^0(D_{n_{d_{p_{c_i}}}}{}^{goal}) - \mathbf{v}_{p_{c_i}}), \end{aligned} \quad (3)$$

$(\mathbf{F}_r^{ped} + \mathbf{F}_{p_c}^{ped})$ and $(\mathbf{F}_r^{obs} + \mathbf{F}_{p_c}^{obs})$ are repulsive forces from pedestrians and obstacles. The first ones, $\mathbf{F}_r^{ped}$ and $\mathbf{F}_r^{obs}$, are the repulsive forces directly applied to the robot; and, $\mathbf{F}_{p_c}^{ped}$ and $\mathbf{F}_{p_c}^{obs}$ are the repulsive forces that feel each person that is accompanied by the robot. As the robot is part of the group, it also feels these forces but reduced, since they are not applied directly to the robot. These forces are used by the robot to overcome persons movements in the accompaniment and allow that them do not collide or interfere in the walking path of other people of the environment Let us start defining the direct repulsive forces from pedestrians and obstacles to the robot. These repulsive forces are the summation of all the repulsive forces between the robot and all the pedestrians and obstacles.

$$\mathbf{F}_r^{ped} = \sum_{j \in P} \mathbf{f}_{r,j}^{int} + \mathbf{f}_{r,p_{c_1}}^{int} + \mathbf{f}_{r,p_{c_2}}^{int}, \quad (4)$$

where $\mathbf{f}_{r,j}^{int}$ are the interaction forces among the robot and other people and $\mathbf{f}_{r,p_{c_i}}^{int}$ are the interaction forces between the robot and the two accompanied people.

Then, the repulsive force respect to the obstacles in the environment is defined by:

$$\mathbf{F}_r^{obs} = \sum_{o \in O} \mathbf{f}_{r,o}^{int}, \quad (5)$$

where $\mathbf{f}_{r,j}^{int}$ and $\mathbf{f}_{r,o}^{int}$ are defined in Eq. 6, where $e = p, o$ for people and obstacles, respectively, and the iterators among all people or obstacles are represented by s of subject.

$$\mathbf{f}_{r,s}^{int} = A_{re} e^{(d_{re} - d_{r,s})/B_{re}} w(\varphi_{r,s}, \lambda_{re}) \quad (6)$$

A_{re}, B_{re}, λ_{re} and d_{re} are the parameters of the robot-person or robot-obstacle repulsive interaction. A_{re} and B_{re} denote respectively the strength and range of interaction force, d_{re} is the sum of the radii of a robot and an entity, person or obstacle, and $d_{r,s} = r_s - r_r$ is the distance between the centers of the robot and the subject, that can be person or robot. $w(\varphi_{r,s}, \lambda_{re})$ is the factor that considers the direction of the force and the fact that the human's field of view is limited and the influences might not be isotropic. We define this last factor and how these force parameters were learned in the case of the interaction force between the robot and the accompanied person, in [27].

Finally, we describe the repulsive forces respect to obstacles and other people, that feel each of the people who are accompanied by the robot.

$$\mathbf{F}_{p_c}^{ped} = \sum_{j \in P} \sum_{i \in C} \mathbf{f}_{p_{c_i},j}^{int}, \quad \mathbf{F}_{p_c}^{obs} = \sum_{o \in O} \sum_{i \in C} \mathbf{f}_{p_{c_i},o}^{int}, \quad (7)$$

where C contains all the accompanied people. Then, these forces are the repulsive interaction forces between the accompanied people to all the other people and obstacles of the environment. $\mathbf{f}_{p_{c_i},j}^{int}$ and $\mathbf{f}_{p_{c_i},o}^{int}$ have the same structure than the robot repulsive forces in Eq. 6, but now applied to the accompanied people.

B. Stage 2: Evaluation of the planned paths using an improved cost function

Once all the possible paths of the robot to accompany the group are computed, the robot has to select the best one. The evaluation of all the paths is done using a cost function that considers several sub-cost related to some characteristics of the paths, Eq. 8. The sub-costs of Eq. 8 evaluate: the distance between the robot and the final dynamic destination of the group; the orientation of the robot respect to the orientation to arrive to the dynamic final destination; the attractive force of the robot; and the repulsive interaction forces respect to people an obstacles, and the accompaniment cost respectively.

$$\mathbf{J}(S, s_{goal}, U) = [J_d, J_{or}, J_r, J_p, J_o, J_c] \quad (8)$$

The costs related with the distance and angle were introduced in [24]. The companion cost was introduced in [23].Here, we reformulate the costs related with the forces, to include the attractive interaction between the robot and the two people and to include the feeling of the repulsive forces of the partners in the robot behaviour. Then, the formulas of these cost are:

$$J_r(U) = \sum_{t_{ini}}^{t_{end}} ||u_r(t)||^2, \quad (9)$$

where now $u_r(t)$ is not only the force due to the final goal, but it is composed by the sum of the two attractive forces to both accompanied people. $u_r(t) = u_{r-p_{c_1}}(t) + u_{r-p_{c_2}}(t)$.

The next equations are the costs related to the repulsive forces respect people and obstacles, that are also modified.

$$J_p(U) = \sum_{t_{ini}}^{t_{end}} \sum_{j=1}^{P} ||u_{r-p_j}(t)||^2 + \sum_{t_{ini}}^{t_{end}} \sum_{j=1}^{P} \sum_{i=1}^{C} ||u_{p_{c_i}-p_j}(t)||^2 \quad (10)$$

$$J_o(U) = \sum_{t_{ini}}^{t_{end}} \sum_{j=1}^{O} ||u_{r-o_j}(t)||^2 + \sum_{t_{ini}}^{t_{end}} \sum_{j=1}^{O} \sum_{i=1}^{C} ||u_{p_{c_i}-o_j}(t)||^2, \quad (11)$$

where the first component of the previous costs are related to the forces between the robot and all the people and obstacles of the environment, respectively; and the second components of the previous costs are related with the forces between the accompanied people and the other people and obstacles of the environment, $C \in \{p_{c_1}, p_{c_2}\}$.

Furthermore, the companion cost also is modified to include the accompaniment cost of the second person, obtaining $J_c(U) = J_{c1}(U) + J_{c2}(U)$. Please refer to [23] for the equation that computes the companion cost.

Finally, the computation of the cost needs three steps. First, the robot computes each individual cost in each step of the path. Second, to avoid the scaling effect of the weighted sum method, each cost function is normalized between $(-1, 1)$ using the mean and variance of an erf function, that are calculated after the computation of all the paths. Third, a projection via weighted sum $J : R^I \rightarrow R$ is obtained giving the weighted cost formula (see [28] for additional explanation).

Then, with the reformulation of these individual costs we ensure that the robot selects the best path (the path with minimum cost). The best path allows the robot to do the adaptive side-by-side accompaniment of people, while avoiding the static and dynamic obstacles, and also leaves space for the group people to avoid their static and dynamic obstacles.

IV. Performance Metrics

This section describes the metrics used to evaluate the adaptive side-by-side accompaniment of the robot when it accompanies two people in the central and in the lateral position of the group. The metrics to evaluate the adaptive side-by-side accompaniment of the robot when it accompanies one person where described in [23]. All of the metrics are based on previous studies on humans [3] and the proxemic rules, proposed by Hall. [2]. Furthermore, the limits of the interaction distances used were based on a previous work of our institute [4].

Mainly, the robot's accompaniment is evaluated using three types of metrics. The first metric is the Area performance metric to evaluate if the robot is in the appropriate companion area respect to each person. The second and third performance metrics serve to differentiate if the companion task is failing on the distance or ideal angle of companion between person and robot. The images of the three types of performances for the two companion behaviours, central and lateral, can be seen in the web: `http://www.iri.upc.edu/people/erepiso/ICRA2020.html`. We analyze the performance of the robot respect to each accompanied person in a separate way, and the final robot's performance is the average of all the performances for each person that accompanies the robot, Eq. 12.

$$\begin{cases} \mathrm{P}(r, p_{ctot}) & = & \frac{\mathrm{P}(r,p_{c1})+\mathrm{P}(r,p_{c2})}{C} \\ P_{2R_i\,ctot} & = & \frac{P_{2R_i\,c1}+P_{2R_i\,c2}}{C} \\ P_{\theta_{diff}\,ctot} & = & \frac{P_{\theta_{diff}\,c1}+P_{\theta_{diff}\,c2}}{C} \end{cases} \quad (12)$$

were $\mathrm{P}(r, p_{ctot})$, $P_{2R_i ctot}$ and $P_{\theta_{diff} ctot}$ are the robot's performance in area, distance and angle of the accompaniment task, $\mathrm{P}(r, p_{c1})$ and $\mathrm{P}(r, p_{c2})$ are the individual values of area performance for each accompanied person, $P_{2R_i c1}$ and $P_{2R_i c2}$ are the individual values of distance performance for each accompanied person, $P_{\theta_{diff} c1}$ and $P_{\theta_{diff} c2}$ are the individual values of angle performance for each accompanied person, and C is the number of people accompanied by the robot, in our case two.

A. Performance metrics for the companion task where the robot is in the central position

In the case of the robot in the central position, the performance metrics evaluated for each individual person follows the same procedure that in the case of one person [23], because the performances are calculated for each of the companions independently. The reader is referred to [23] for a better explanation of how are calculated these performances and Fig. 2 shows the performances in the case that the robot is situated in the central position of the group. Finally, when we have the accompaniment performances of each individual person, we use Eqs. 12 to obtain the final performance for the robot, regarding Area, distance and angle, respectively.

B. Performance metrics for the companion task where the robot is in the lateral position

In the case of the robot in the lateral position it needs a new definition of the performances respect to the lateral person of the group because there is an increase of distances between them. The performances respect to the central person are the same as in the paper [23].

Regarding the metric of performance for the area, it is defined by three areas. The Human's personal space $\mathcal{C}$, and a new redefinition of the Social distance Area $\mathcal{A}$ and the Human's Companion Area $\mathcal{B}$, now with name $\mathcal{A}'$ and $\mathcal{B}'$. For a further explanation of the meaning of these areas the reader is refereed to [23]. In the area $\mathcal{A}'$, we consider that if the distance is greater than 6 meters, twice the normal social distance which is 3 meters, a person does not feel that the robot part of the group. This increment in distance is due to the person in the middle of the group between the robot and the lateral person. $\mathcal{B}'$ is the best robot position to accompany the lateral person, it changes following the Eq. 13.

$$\begin{aligned} \hat{x}^r(t+1) &= \hat{x}^p(t+1) + d_{r-c2}\cos\left(\theta_p - \operatorname{sgn}\left(\theta_p - \theta_c\right)\theta\right) \\ \hat{y}^r(t+1) &= \hat{y}^p(t+1) + d_{r-c2}\sin(\theta_p - \operatorname{sgn}(\theta_p - \theta_c)\theta) \end{aligned} \tag{13}$$

Where $(\hat{x}^r(t+1), \hat{y}^r(t+1))$ and $(\hat{x}^p(t+1), \hat{y}^p(t+1))$ are the robot position and person position in the next instant of time. Then, the performances of this instant of time will be calculated in the next iteration. θ_p is the person orientation to the final destination. θ_c is the actual companion angle between the person and robot positions. Finally, θ is the ideal companion angle between robot and person calculated in the same way of [23]. d_{r-c2} is the distance between the robot and the lateral person. Furthermore, to be related with [23], the reader needs to know that the distance between the central position of the robot and the nearest accompanied person is $d_{r-c1} = 2R_i = 1.5$ m in the ideal side-by-side, and the distance between the robot and the lateral person is $d_{r-c2} = 2 \cdot 2R_i = 3$ m. For further details regarding the obtaining of the ideal distance of accompaniment see [23].

The equation to compute the final area performance in this case is the same that in [23] for the companion, but the definition of the $\mathcal{A}$ and $\mathcal{B}$ areas changes to $\mathcal{A}'$ and $\mathcal{B}'$ areas definition.

The metric has the maximum performance when the robot is in the area described by $\mathcal{B}'$, since it is the best position to accompany the human in each instant of time. Additionally, if the robot is in the area $\mathcal{A}'$, but outside of area $\mathcal{B}'$, is a partial success, since the robot is inside the social distance for the group to accompany this human. Finally, if the robot is further than six meters from the human's position, then we consider that there is no group companionship interaction between robot and person, and therefore its performance is zero. Also, if the robot invades any human's personal space is penalized with zero performance.

The functions of the distance performance metric of the accompaniment task in the lateral position are shown in Eqs. 14. The distance metric considers that the robot achieves a good distance performance if it keeps its central position inside the interval of distances $[2.75 - 3.5]$ m, and we decrease the performance in both sides of this margin until arrive to 0. The metric follows the same procedure than in [23], but with the increased distance to take into account that the robot is in one lateral of the group. Where d_{r-c2} corresponds to the real distance between person and robot to compute the performance.

$$P_{d_{r-c2}\,c2} = \\ = \begin{cases} 0 & if \quad d_{r-c2} < 2.25m \\ 2(d_{r-c2}) - \frac{9}{2} & if \quad 2.25m \leq d_{r-c2} < 2.75m \\ 1 & if \quad 2.75m \leq d_{r-c2} \leq 3.5m \\ -(d_{r-c2}) + \frac{9}{2} & if \quad 3.5m < d_{r-c2} \leq 4.5m \\ 0 & if \quad d_{r-c2} > 4.5m \end{cases} \tag{14}$$

Regarding the angle performance metric it is the same that in [23], because the angle between person and robot is not affected by the respective position between them inside the group.

Finally, we use the equations described in Eqs. 12 to do the mean of the performances of the central person of the group and the lateral one, to obtain the final performances of the task for the robot.

V. SYNTHETIC EXPERIMENTS

This section address the synthetic experiments developed to test and evaluate the implemented method. The method was tested using a complex simulation environment developed in past works. The simulation environment includes the robot, represented by the model of Tibi, that now uses the implemented method to be able to do the adaptive side-by-side accompaniment of groups. Our robot is non-holonomic and has a maximum speed of 1m/s, for security reasons. Then, the robot is able to adapt its velocity and accompany a group of people that walks below the 0.8m/s, as if they were taking a leisurely stroll. Furthermore, this environment includes two simulated people that forms the group accompanied by the robot, these people use the AKP planner to obtain a more realistic behavior, because the planner allows the two people to avoid static and dynamic obstacles, and also turn a corner or go through a door together as a group of people would. Besides, the environment includes static obstacles and other people that uses the ESFM to move randomly from one destination to another, while they avoid other people and obstacles. All of the people in the environment, including the accompanied ones, walk at random speed inside the interval of [0-8] m/s.

More than 3,400 simulations were performed to test and evaluate the method. These simulations include situations

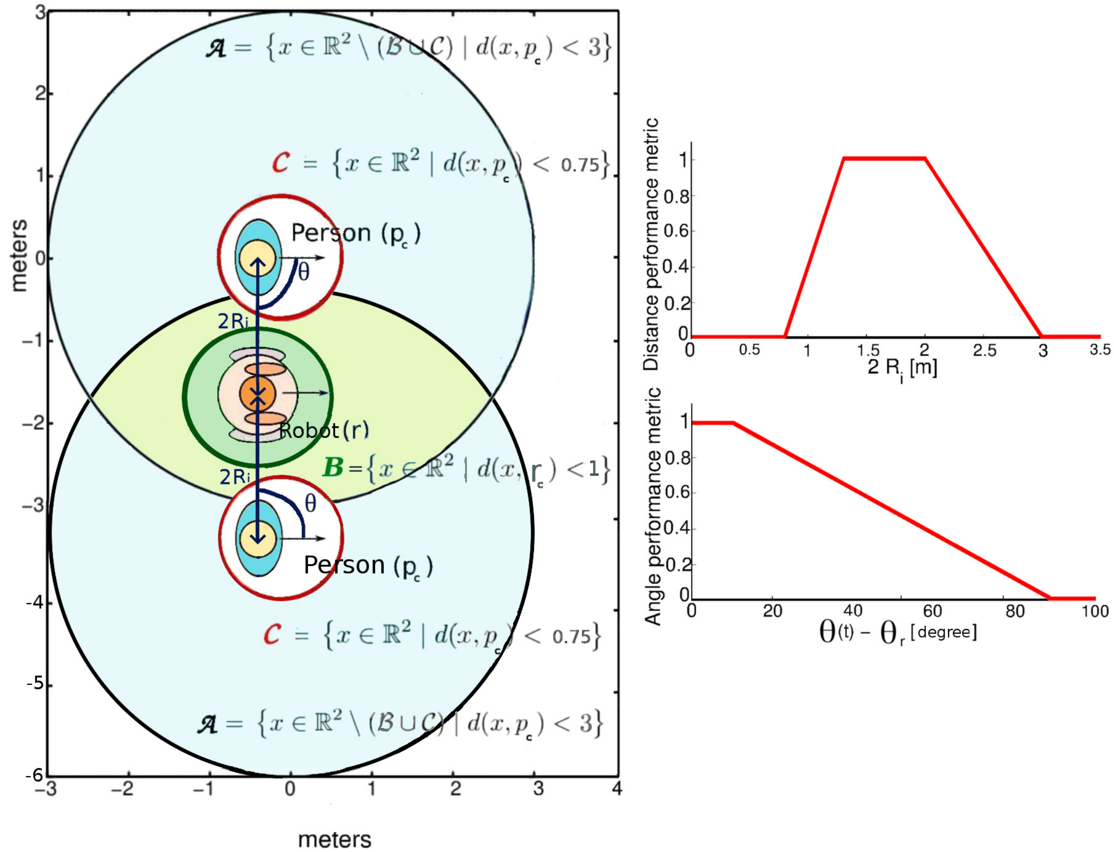

Fig. 2. **Performance metrics of area, distance and angle for side-by-side accompaniment with the robot located in the central position of the group formation**

where the robot accompanies a single person or a group of people, starting in the central position or in the lateral one. We say that it starts in that position, since the robot position may change inside the group, depending on the environment situations, because the accompaniment is adaptive and we allow the components of the group to change its positions if they want, like in the real-life.

Firstly, the robot walks with the group without any obstacle in the environment. Secondly, we include other people in the environment that walks to different destinations. We perform several types of people behaviours: random people crossing in diagonal the frontal path of the group; a flow of people in the contrary direction of the group (left, right and both sides at the same time); and people crossing in diagonal the group and other people walking in the sides in contrary direction at the same time. Also these people can walk passing between two of the members of the group, demonstrating that the robot can deal with small occlusions of one of the group members. Furthermore, the method includes a generation of a fake person if the robot loses the detection/track of one of the two members, by the occlusion of the other. This is for the case that the robot is in the lateral position, that one of the group people can be occluded by the other, and the fake person allows the robot to continue performing a good side-by-side accompaniment. Thirdly, we include static obstacles, at the left and right side of the group, and also a simulated door. Fourthly, we joint the cases of people and static obstacles at the same time.

From all these experiments, we obtain the results of performance of the Table. I. The performances are expressed in a scale between 0 and 1, where 1 is the best performance value. As you could see the performances of the cases without obstacles are the best ones and the performances that include people have a lower performance value, but always over 0.5. This is due by the random factor of people and also because our simulated people are more aggressive walking than the robot. These people has less repulsive force to the robot, to simulate the worst cases where people do not have the robot in mind. Then in these cases, we expect that the robot also avoids them and disturbs the minimum the people's way.

VI. Real-life Experiments and User study

The side-by-side method to accompany groups of people was also tested and evaluated in real-life experiments performed in the Facultat de Matematicas y Estadistica (FME) of the Universitat Politecnica de Catalunya (UPC) and in the Barcelona Robot Laboratory (BRL) situated in the Campus Nord of UPC. The FME is a square area of 15x15 meters and the BRL is a university campus area of $10,000\ m^2$. The best experiments were done in the BRL, where people can go to different destinations, then we focus the images and videos

	Performance of simulations		
	Distance	Angle	Area
One person Side-by-side without obstacles	0.95 (± 0.04)	0.92 (± 0.07)	0.94 (± 0.04)
two person Side-by-side lateral robot without obstacles	0.91 (± 0.06)	0.75 (± 0.04)	0.81 (± 0.07)
two person Side-by-side central robot without obstacles	0.89 (± 0.07)	0.74 (± 0.05)	0.88 (± 0.1)
One person Side-by-side with static obstacles	0.91 (± 0.07)	0.87 (± 0.08)	0.87 (± 0.07)
two person Side-by-side lateral robot with static obstacles	0.94 (± 0.03)	0.77 (± 0.03)	0.81 (± 0.03)
two person Side-by-side central robot with static obstacles	0.78 (± 0.15)	0.74 (± 0.08)	0.74 (± 0.15)
One person Side-by-side with dynamic obstacles (people)	0.86 (± 0.11)	0.85 (± 0.12)	0.84 (± 0.1)
Two person Side-by-side lateral robot with dynamic obstacles (people)	0.81 (± 0.11)	0.82 (± 0.09)	0.77 (± 0.09)
Two person Side-by-side central robot with dynamic obstacles (people)	0.72 (± 0.12)	0.66 (± 0.09)	0.7 (± 0.14)
One person Side-by-side with static and dynamic obstacles	0.81 (± 0.12)	0.88 (± 0.11)	0.78 (± 0.11)
two person Side-by-side lateral robot with static and dynamic obstacles	0.8 (± 0.1)	0.78 (± 0.1)	0.76 (± 0.08)
two person Side-by-side central robot with static and dynamic obstacles	0.84 (± 0.08)	0.79 (± 0.09)	0.78 (± 0.12)

TABLE I

The results of Performance of the accompaniment of the robot of the simulation experiments for all the simulated cases. The performance value equal to 1 is considered the best value and the values between brackets are the standard errors of each mean.

to these ones. The initialization time that needs the robot to start from 0 m/s to reach people's velocity, 0.8 m/s, is a small percentage of the total interaction with the robot.

In these experiments, Tibi accompanied 148 people using a side-by-side formation from one to another destination of the environment, and a survey was fulfilled by each one to know their feelings about the accompaniment behaviour. During the experiments, it was selected randomly if the robot uses teleoperation or the implemented method. Most of them were performed with two people taking into account that the method using one person was tested in [23], but we have some cases of only one person being accompanied. In the case of two people the robot accompanied them in the lateral or in the central position. Fig. 1 shows several moments of the real life-experiments, where Tibi accompanies one person or a group of two using a side-by-side formation in the central position and in the lateral one. The results of the experiments using the method in terms of performances are included in Table. II.

The range, mean and standard deviation of the participant age was [11-56] years old, $M = 23.44$, $SD = 8.5$ (mainly students and few workers of the campus), and 32% were females and 68% were males. Also, we included the level of knowledge in robotics in the questioner, obtaining a mean of 3.7 and a standard deviation of 1.66. Then, we can conclude that the huge amount of participants were potential users. We used a 7-point scale in all the questions, from ”Not at all” to ”Very much”. To analyse the results we grouped the questions in two scales: robot's sociability and robot's comfortableness. Both scales surpassed the 0.75 level of reliability, Cronbach's alpha. We calculated a ANOVA for each scale to highlight similitude's or differences between the two robot behaviours, teleoperation and method. Pairwise comparison with Bonferroni demonstrated no statistical difference $p > 0.05$, results can be seen in Fig 3. Therefore, seems that the method has a largest acceptance, because inexperienced people perceive the same comfort and sociability with respect to the robot when it is teleoperated by an expert than when it is using the method. Furthermore, we attach a video of the real-life experiments in the web link of the paper: `http://www.iri.upc.edu/people/erepiso/ICRA2020.html`.

	Performance real experiments on BRL and FME of the side-by-side adaptive accompaniment		
	Distance	Angle	Area
one person	0.83 (± 0.17)	0.77 (± 0.14)	0.79 (± 0.15)
two people lateral robot	0.87 (± 0.13)	0.8 (± 0.1)	0.84 (± 0.14)
two people central robot	0.8 (± 0.18)	0.66 (± 0.12)	0.77 (± 0.13)

TABLE II

Performance results of the real-life experiments for all the possible formations. These results include cases without other people and with other people, as dynamic obstacles for the robot. The performance value equal to 1 is considered the best value and the values between brackets are the standard errors of each mean.

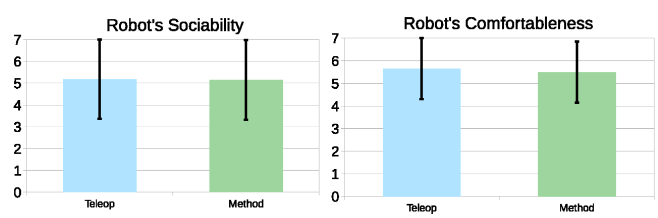

Fig. 3. **User study results.** *Left:* Robot's Sociability. *Right:* Robot's Comfortableness.

VII. Conclusions

The implemented method allows a robot to accompany one person or a group of people using an adaptive side-by-side formation. The major contributions of this paper are three-fold: First, we obtained an accompaniment behaviour for the robot to accompany groups of people. This behaviour includes a formation that allows people to interact between them and also the robot's behaviour facilitates the navigation in dynamic environments of the group and other people. Second, we included solutions to deal with the randomness factor of people behaviour, by adapting the robot behaviour to the changes in velocity and direction of movement of accompanied people, the changes in position inside the group and the possible occlusions between them. Third, the method was tested in a huge amount of simulations and real-life experiments, as well as an user study of a comparison between the method and teleoperation with non-trained volunteers was developed to demonstrate the people acceptability of the method.

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