2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Fast Marching Solution for the Social Path Planning Problem

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Abstract— **Traditional path planning for robots is a well-studied problem. However, the classical setting of the problem is simple to state: plan a path for a robot, starting from an initial point, and ending at a desired target point, given an environmental map, usually in the form of an occupancy grid. In this setting though, no special consideration is given to humans; they are thought of simply, as being obstacles in the environment, equivalent to chairs or walls. However, with more robots entering human spaces, special consideration needs to be given: humans need special treatment as obstacles, and furthermore humans can also serve the goal of goal points, towards starting a social interaction; either individual humans or groups of humans. Also, special mechanisms are required for engaging and disengaging in such interactions, taking into account psychological considerations of proxemics. In this paper, we first introduce our unifying theoretical framework for all the subproblems of social path planning; then, we propose an extended mode for engaging groups of people; and then, by using a special version of the fast-marching square planning method, we present and demonstrate actual algorithmic solutions for the social path planning subproblems. Our results prove the strengths of our approach and its generalizability. Finally, concrete further steps are discussed.**

I. INTRODUCTION

Although the motion planning problem has been studied for at least three decades, still there exist important aspects of it towards successful integration of robots in our everyday environments that have not been adequately covered in a general form. For instance, socially-aware path planning has just started to be touched upon only in the last years, and only in quite an ad-hoc way and only for special sub cases. In this new problem setting of social path planning, humans are not treated only as obstacles, in a way equivalent to environmental objects; in contrast, special considerations for them are taken in the algorithms since part of the objective can be to avoid them in a non-psychologically disturbing and friendly manner or to interact with them in a way they will find natural and not aggressive.

Therefore, many new variables need to be included into the classical path planning problem setting: for example, we need special representations for humans, including parameters such as human pose, intentions and movements. If the current path planning algorithms are applied to scenarios in which a human-friendly robot navigation is desired, the robot will most probably execute sharp movements, distracting humans and making them feeling uncomfortable.

The few existing papers representing previous work in this new field are quite diverse, very different ad-hoc approaches have been proposed, for specific subproblems, often with narrow domains of applicability. For example, there exist learning-based algorithms for robot human-friendly navigation [1], reactive and proactive navigation methods based on human imitation [2], cost-based planners [3], [4], etc. If one focuses though on the specific subproblem to be solved, and not on the actual methods employed, then another classificatory system of existing work is possible. In this fashion, [5] proposes a learning-based algorithm that enables the robot to follow a human while keeping an interaction. How to approach a human in order to start an interaction [6] and how to keep that interaction [7] are some of the recent problems that have been studied. The previous work appears to be quite ad-hoc, and most importantly, solving the social path planning problem only partially and in specific cases. Also, the problem formulation and notation in the existing papers is, most of the times, not uniform; and thus, juxtaposition, comparison, and benchmarking tasks are difficult.

To effectively address the above shortcomings, and to provide a rigid foundation for future work, in this paper we introduce our general formulation of social path planning, and most importantly we present and demonstrate a real-world solution with general coverage. Our social path planning problem formulation proposes 6 different sub-cases for human-robot interaction scenarios focusing on navigation tasks. By combining them, it is possible to model most of the cases a robot will find while navigating around humans. The proposed and demonstrated algorithmic solutions are based on the Fast Marching Square [8] method, which has many strengths as a underlying planner. Let us now proceed to the problem formulation:

II. PROBLEM FORMULATION

Let us assume that a robot is placed in a environment together with humans. Although the tasks the robot has to carry out might or might not imply the need for any explicit social interaction, just the fact of sharing the environment with humans effectively turns the robot into a social agent. Therefore, no matter whether the objective is to avoid humans or to interact with them, humans have to be taken into account in order to produce a socially acceptable, human-friendly behavior. In our previous work [9], the social path planning problem was formulated in detail, as the combination of 6 different subproblems, differentiating if the

This work is partially supported by the spanish Ministry of Science and Innovation under the projects DPI2010-17772 and CSD2009-00067 and the Greek General Secretariat for Research and Technology and from the European Regional Development Fund of the EC under the Operational Program "Competitiveness and Entrepreneurship" (OPCE II) - Priority Axis 1 "Promotion of innovation, supported by research and technological development" and under the Regional Operational Program Attica - Priority Axis 3 "Improving competitiveness, innovation and digital convergence".

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978-1-4799-3685-4/14/$31.00 ©2014 IEEE

humans in the environment are individuals walking around or groups of people engaged in an interaction:

1) Single human, individual:
   a. Robot to point. Regular path planning considering humans as obstacles.
   b. Full interaction: 1) approach human, 2) interact, keep interaction, 3) disengage.
   c. Follow human.
2) Group of humans:
   a. Robot to point. Regular path planning considering group of humans as obstacles.
   b. Observe group, ask for permission to enter.
   c. Full interaction: 1) enter the group, 2) interact, keep interaction, 3) disengage.

Also, a harmonious human-robot interaction should satisfy the following rules [10]:

1) *Collision-free:* Maintain safety.
2) *Interference-free:* the robot should not enter the personal space of any human unless it is its objective.
3) *Waiting:* If the robot enters the personal space of a human, it has to stop a fixed amount of time.
4) *Human priority:* Humans always have the highest priority.
5) *Robot intrusion:* If a robot enters the workspace of other robot, it should leave this space as soon as possible, while the other robots should stop their activities.
6) *Robot priority:* Robots with lower priority should yield to robots with higher priority.

Let us start our formalization by considering a bi-dimensional, euclidean space $\mathcal{C}$, corresponding with the floor. This space is composed by the union of the obstacle-occupied space $\mathcal{C}_{obs}$ and the obstacles-free space $\mathcal{C}_{free}$ where humans can be located. We denote as $H = \langle H_i, \ldots, H_N \rangle$ the set composed by N humans in the environment. The state of a given human i is composed by its position, heading and velocity: $H_i = \langle x^i_H, y^i_H, \theta^i_H, v^i_H \rangle$. The set of humans can be splitted into two different subsets: H_{group} composed by those humans which are engaged in a social interaction, and H_{ind} the rest of individuals (walking around).

The influence of individuals in H_{ind} is modeled with their personal spaces Φ_i. On the other hand, people belonging to H_{group} will be arranged in F-formations[11]. Therefore, we denote the social influence created by the group of humans $H_{group,j}$ as Φ_j.

The robot state is denoted as $R = \langle x_R, y_R, \theta_R, v_R \rangle$. The robot will navigate through a path Γ_R, in a human-friendly manner, following the aforementioned rules.

This formulation is summarized in figure 1.

III. INTUITIVE INTRODUCTION TO THE FAST MARCHING SQUARE PATH PLANNING METHOD

The Fast Marching Square method (FM^2) is a robust, efficient algorithm to compute safe and smooth trajectories [12]. The powerfulness of this algorithm has been shown during the last years since it has been successfully applied to many different motion planning problems such as robot formations planning, motion learning, roadmap generation, etc. [8], [13]. Since this method is well described in the literature, we will outline the basis in the following lines.

The FM^2 method consists on applying twice the Fast Marching Method (FMM) proposed by J. A. Sethian [14]. The objective of the FMM is to approximate distances map in manifolds. In other words, given a point in a space, it computes the distance of the rest of the points in the space to the initial point. It provides a fast, approximated solution by simulating the propagation of a wave through a non-homogenenous medium, in which the wave propagation depends on the current position of the wavefront. The environment is modeled as a binary occupancy gridcell.

The first step of FM^2 is to compute a velocities map $\mathbf{W}_{FM^2}$. In this case, we assign to each point of the space a relative velocity directly proportional to the distance to the closest obstacle. For that, we apply the FMM method to the whole workspace, using as wave sources the obstacles. In fact, we are computing an approximation to the distance transform by applying the FMM. Although any other method to compute the distance transform can be applied, we consider that using FMM makes the implementation easier but there are other advantages, i.e. continuous velocities map.

The second step is to apply the FMM from the goal point and expand the wave until it reaches the current robot position (initial point). In this case, the distances map created is interpreted as a time-of-arrival map, $\mathbf{D}$, in which every point of the space is assigned a value which represents the time it took to the wave to reach this point from the source point while restricted to the velocities map computed.

Once this time-of-arrival path has been computed, the final path is obtained by applying gradient descent from the initial point until the goal point (only local minimum) is reached. Figure 2 illustrates the different steps of the proposed algorithm.

Among the desirable properties of the FM^2 method, the smoothness of the computed paths has been observed, as well as close-to-optimal obstacle clearance, and quite importantly, the time optimality property: assuming that the robot moves at a relative speed according to the velocities map, the provided path is optimal in terms of execution time [8].

Also, in FM^2, the velocities map can be used to generate the velocity profiles of the computed trajectories, just by extracting the velocities value for every point of the path. This is very useful for our purpose, as we shall discuss in the next section.

A very interesting modification of the FM^2 method is the saturation variation. Assuming that the velocities map contains relative velocities between 0 and 1, it is possible to *trim* (saturate) this velocities map. With this small modification, the safety and smoothness of the computed paths is still ensured (except for saturation values close to 0), while obtaining trajectories closer to the optimal in terms of distance. Examples are shown in figure 3.

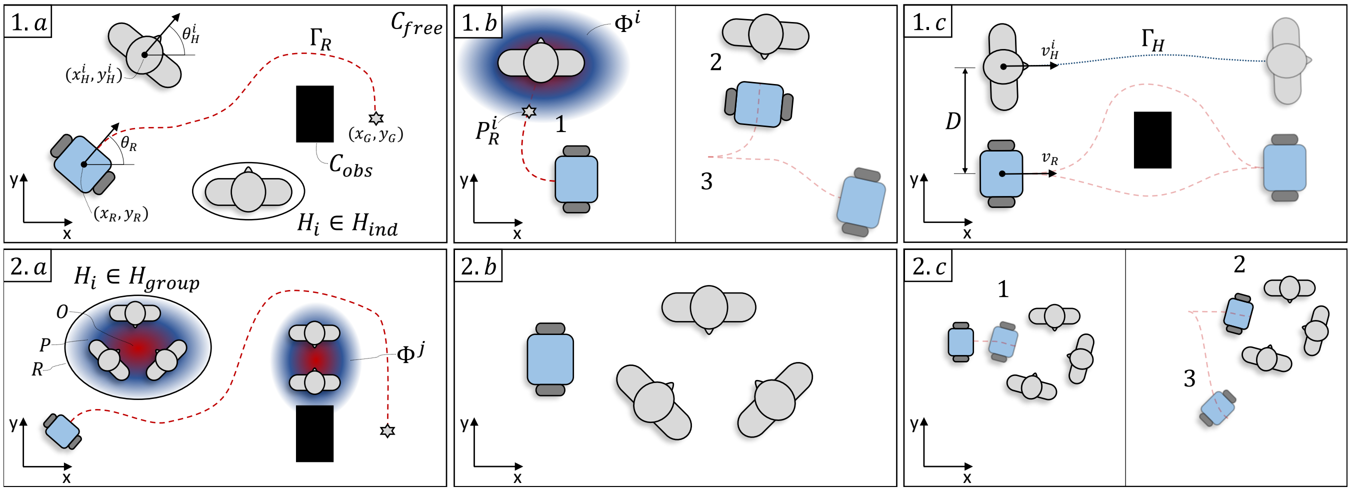
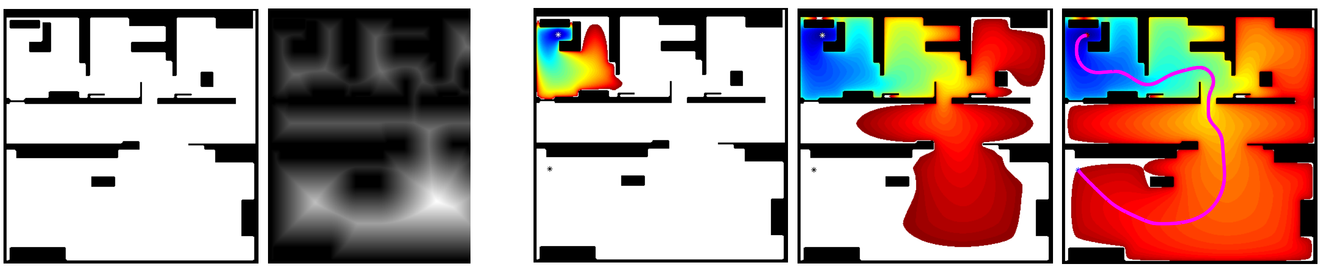


Fig. 1: Top: subproblems for a single human. Bottom: subproblems for group of humans.



(a) (b) (c) (d) (e)

Fig. 2: Steps of the FM^2 algorithm. a) Initial binary map. b) Velocities map generated with FMM. c),d) Wave propagation from the goal point. e) Final path shown over the time-of-arrival map.

IV. FM^2 APPLIED TO THE SOCIAL PATH PLANNING PROBLEM

The velocities map of the FM^2 is a very powerful tool in the path planning algorithm. By its proper modification, higher-level problems can be easily solved in a uniform way, without clumsy modifications, and without increasing the algorithm complexity. If a static environment is given, it has to be calculated once. But for dynamic environments, the velocities map can be locally updated. Therefore, our solution is based on modifying the velocities map according to models of the personal space of humans. In the following subsections we detail the application of the FM^2 method to each one of the subproblems described in II.

A. Single Human Cases

When humans are present in the environment as individuals, not taking part into social interactions, the robot should treat each one of them as a separate entity. [1] For the three subproblems identified within this category, we model the personal spaces of each human as a mixture of two Gaussian functions as detailed in [15]. The model of the personal space is included in the FM^2 velocities as follows:

- Compute the personal space Φ_i for each human i and normalize it in order to have values between 0 and 1.
- Obtain the complementary of each Φ_i: $\Phi_i' = 1 - \Phi_i$.
- Create a map $\mathbf{W}_\Phi$ in which all Φ_i' are included.
- Calculate the final velocities map as:

$$\mathbf{W} = min(\mathbf{W}_{FM^2}, \mathbf{W}_\Phi) \tag{1}$$

Before the minimum operation of the last step, it is possible to add to the model the *personal space* of the robot. In our case, we applied to gray scale dilation operation to the $\mathbf{W}_\Phi$ map. The structuring element is a disk which radius is the maximum radius of the robot.

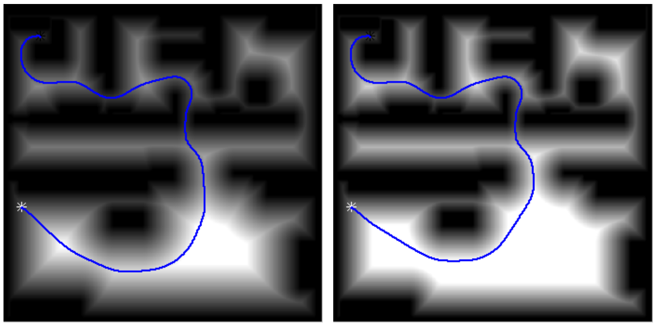
With these simple steps the humans are taken into account as non-regular obstacles in which the personal space of each human is avoided when possible. Note that the positions of the humans have a value 0 in the final velocities map $\mathbf{W}$. This means that, in absence of a high-level layer, when the goal point is a human, the algorithm will not be able to reach that point since it has 0 velocity (the wave will reach this point in infinite time). One easy way to solve this problem is to modify the personal spaces map as follows:

$$\mathbf{W}_{PS} := \mathbf{W}_\Phi + \delta \tag{2}$$

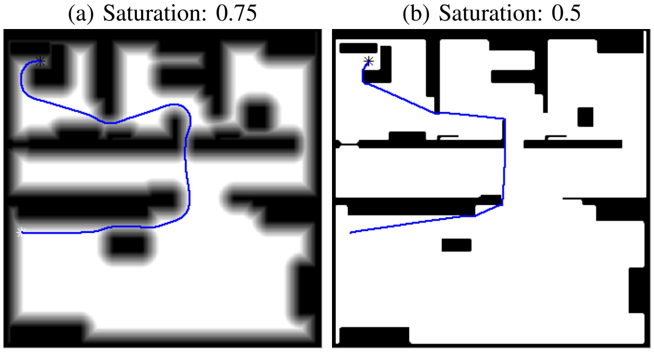
where $\delta \to 0^+$. This way, the behavior of the algorithm will no be influenced and no errors will appear. Note that we are assuming static humans for the following subsections (except for the follow human case).

1) 1.a Robot to point: To solve this subproblem, the individuals are included in the velocities map as aforementioned and a simple path planning query is done to the

[1]However, as we shall see, when a group of humans is engaged in interaction, they will be treated on the basis of their joint personal spaces.



(a) Saturation: 0.75 (b) Saturation: 0.5



(c) Saturation: 0.25 (d) Saturation: 0

Fig. 3: FM^2 saturated variation: modification of the path depending on the saturation value.

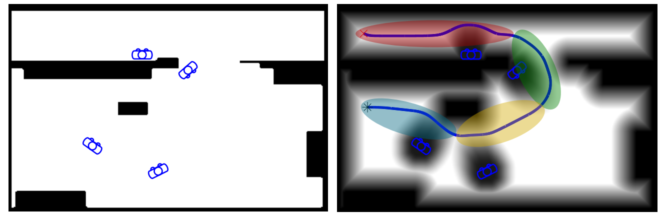
robot (to reach one point from the current position). Thanks to the design of the FM^2 and the personal space model used, the robot will create safe, smooth and human-friendly trajectories while reaching the goal, as shown in figure 4.

2) 1.b Full interaction: approach, interact, disengage: This case is divided in three different steps. First one, approaching to the human, exactly the same algorithm as mentioned before is applied. However, in this case the goal point for the robot is a human. Therefore, once the path is computed, it is processed in order to automatically select a new goal point 0.5 meters away from the human while keeping the initial path.

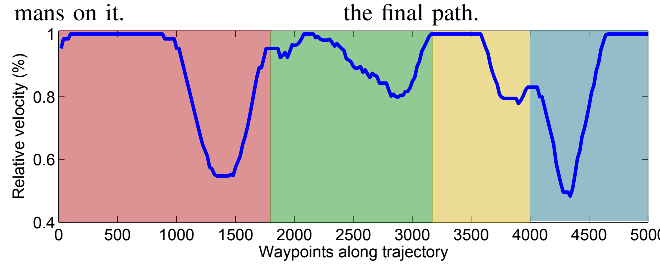
We consider that the interaction phase is out of the scope of this paper[2]. However, disengaging in a friendly-manner is as important as a proper approaching. In this case, the robot moves 0.5 meters backwards in order to get out of the personal space of the person it is interacting with. From this new point, a new path is planned and the robot navigates towards it following the rules of the subproblem 1.a. The process is shown in figure 5.

3) 1.c Follow human: In this case, the robot is intended to follow the human (walk with him/her) throughout the environment in a way that the navigation is comfortable for both human and robot. In this case, we apply the FM^2-based robot formation motion planning algorithm described in [16]. This is a leader-followers based algorithm in which the leader is navigating and the followers try to follow the leader adapting a prescribed geometry in order to keep

[2]The interaction phase motions depend on the scenario. As a first approximation, the robot can be assumed to be static during the interaction.



(a) Binary environment with humans on it. (b) **W**, saturation at 0.5m and the final path.



(c) Velocities profile along the trajectory.

Fig. 4: Result for the proposed approach. The start point is at the top of the map and the path provided avoids personal spaces except when it means to get very close to obstacles.

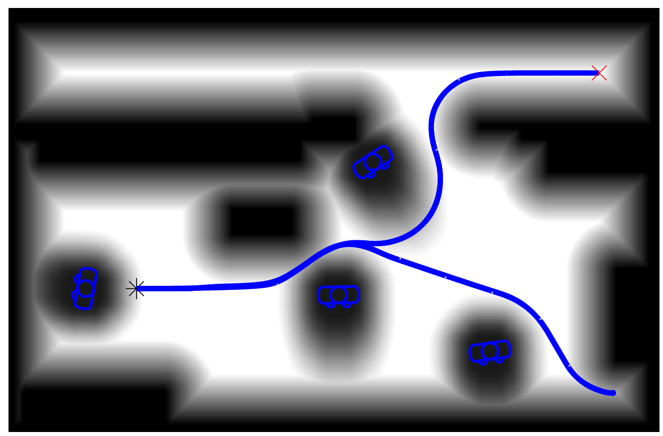


Fig. 5: Results for the approaching-disengaging proposed solution. Red point to human: approach. Human to blue point: disengage.

the formation as much as possible but adapting to the environment and adapting to the environment.

The geometry deformation is based on the value of the velocities map. The geometry is computed normally, the partial goals for every follower are set and, depending on the velocity value for that partial goal, their position are adapted. Figure 6 depicts the basics of this algorithm.

Therefore, in this subproblem the human can be treated as the leader of the formation and the robot follows him/her according to the robot formation motion planning algorithm described. Note that the prescribed relative position has to be determined by a higher-level layer. The algorithm tries to keep this situation as much as possible. The way the algorithm is designed will give preference always to the human in case of narrow corridors or cluttered environments. A sequence of this algorithm is shown in figure 7.

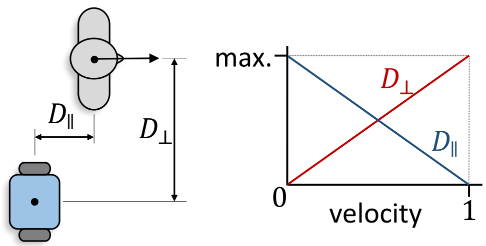


Fig. 6: How the robot's goal positions are set when it is following an human.

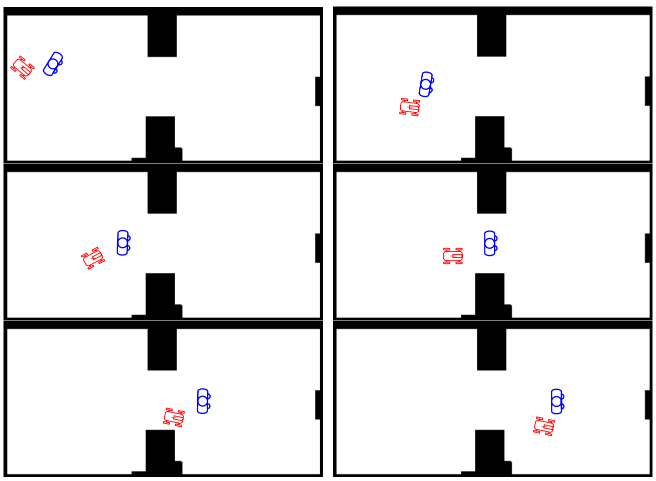


Fig. 7: From top-left to bottom-right: sequence of a robot following a human with the FM^2-based robot formation motion planning algorithm.

B. *Group of Humans Cases*

Now, humans are not treated individually but every group is modelled as a unique agent. A Gaussian-based O-space model for F-formations is given in [17]. However, it is only for groups of 2 people. Recently, this O-space model was expanded in order to take into account more than 2 people in the group. This later model consists on the application of the initial model to every pair of adjacent humans and later all the models are averaged.

The way this model is applied to the velocities map of the FM^2 is exactly the same as the addition of the personal spaces Φ_i for the single human cases.

1) 2.a Robot to point: This case is parallel to the subproblem 1.c but the humans in the interaction are taken as a single agent. The result is shown in figure 8.

2) 2.b Observe group, ask for permission to enter: This subproblem refers to the task of approaching the group in a friendly way and ready for trying to start an interaction with the group. Again, this problem is analogous to the subproblem 1.b explained in section IV-A, but only the first approaching step.

In this case, the goal point of the robot is the centroid of the O-space. However, the path is trimmed in order to properly set the goal point in an acceptable zone. Therefore, the path ends when one of the following conditions are satisfied:

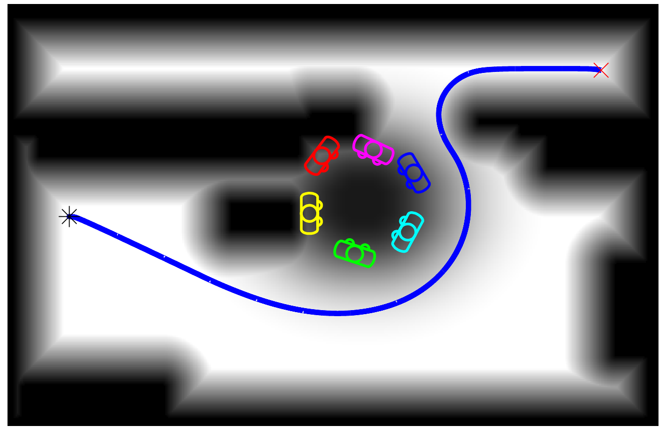


Fig. 8: Results for the solution of a group of humans as obstacle. $\mathbf{W}$ with the O-space model, saturation at 0.5m and the final path.

- When the distance to any of the humans of the group is less than 0.5 meters.
- When there is a risk of O-space invasion. If the O-space value for the robot position is lower than twice the maximum O-space value for all the humans within the group it is considered as an O-space invasion. Also a threshold is set we set a threshold (0.8) in our case to consider a point as an invasion of the O-space.

This way, the robot will approach towards the group and will stop at a point in which the robot shows its intention to become a part of the group but without invading it. An example is given in figure 9.

3) 2.c Full interaction: enter, interact, disengage: This phase can be considered as the continuation of the previous subproblem 2.b. Once the robot has approached and shown its intention to enter the group, and the group has accepted the robot, it should enter the group. For this, we compute the path from the current position to the centroid of the O-space of the group. The points of the path are evaluated so the new goal point is set at that point of the path in which the O-space value is equal to the average value of the O-space values of all the members of the group. This way, the robot takes an average position within the group. This behavior can be easily set to be more aggresive (or more discreet).

Once the robot enters, the interaction continues. We consider this phase as a matter of future work. Once the robot wants to disengage from the group, the same behavior as for problem 1.c is given. The robot moves backwards 0.5 meters in order to get out of the O-space and then a new goal point is set. The group is the considered as an obstacle.

The summary of this solution can be found in figure 10.

V. CONCLUSION

The proposed solution for the social path planning problem satisfies the points shown in the literature about how a robot should navigate in an environment shared with humans. With the FM^2 as a basis, all the proposed scenarios where successfully solved while partially accomplishing the rules exposed in [10]. Actually, those rules are not taken as strict

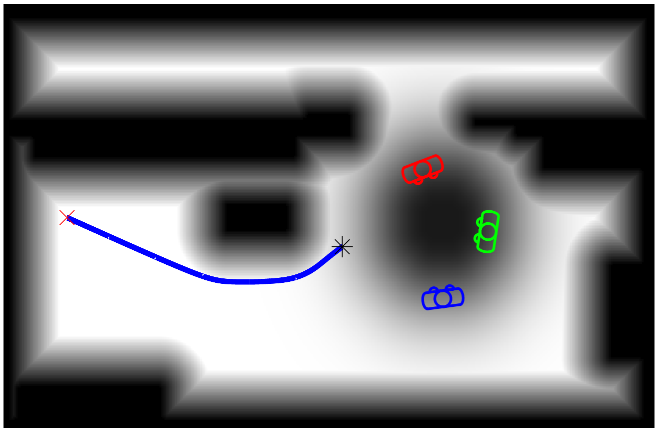


Fig. 9: Results for the solution of observing, approaching a group of humans. $\mathbf{W}$ with the O-space model, saturation at 0.5m and the final path.

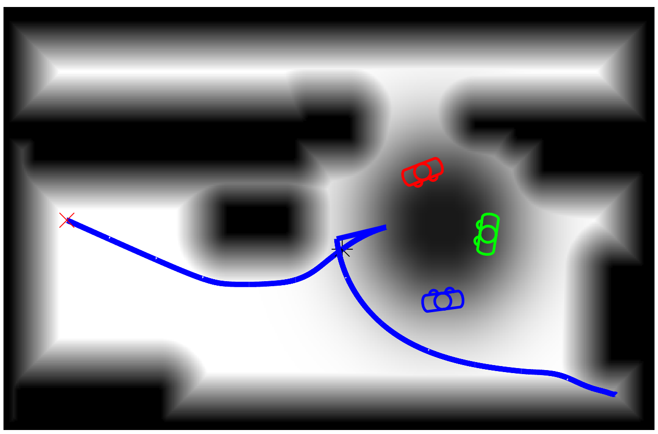


Fig. 10: $\mathbf{W}$ with the O-space model, saturation at 0.5m and the final path.

as Lam states in his work. However, the paths are collision free and the humans have always the highest priority. On the other hand, the interference rule is violated only in those cases in which it is dangerous to the robot to avoid invading the personal space of the humans. Also, the waiting rule is not taking into account, since we consider that this creates a very clumsy social navigation for the robot. In our case, the robot decreases its velocity when a personal space is invaded, so the actions are scaled according to the surroundings.

Although there is a lack of experimental validation of the proposed solution with humans, the contribution of this paper is quite important: a global solution to the novel social path planning formulation based on the FM^2 path planning algorithm. This solution is able to deal with both individuals and group of humans. In this last case, very few work can be found in the literature and a novel point of view has been detailed. Also, the use of the O-space values as indicators for the social behavior of the robot is a novel idea which is worthy to keep exploring.

The interaction phases have been omitted in this work since they are a whole research field by its own. The interaction highly depends on the objective of the robot and the human.

Finally, work in progress and in the near future is focused on expanding the solution to dynamic environments with all humans mobile, on experimental validation on the basis of fused data captured from multiple lasers, and on further generalization of the model to human-human, human-robot and robot-robot interaction, etc.

In conclusion, in this paper we have introduced the social path planning problem, including a subdivision and generic formalization. We have also provided a personal space model for groups of humans. Most importantly, we have devised and demonstrated algorithms based on the fast marching squares method, which are able to provide a general solution to the social path planning problem. Our results prove the strengths of our approach and its generalizability, enabling robots to gracefully enter human environments, interacting and co-existing with us safely and naturally.

References

[1] S. Sehestedt, S. Kodagoda, and G. Dissanayake, "Robot Path Planning in a Social Context," in *IEEE Conf. Robotics Automation and Mechatronics*, June 2010, pp. 206–211.

[2] J. Guzzi, A. Giusti, L. Gambardella, and G. A. Di Caro, "Human-friendly robot navigation in dynamic environments," in *IEEE Intl Conf on Robotics and Automation*, Karlsruhe, Germany, May 6–10, 2013.

[3] T. Kruse, P. Basili, S. Glasauer, and A. Kirsch, "Legible Robot Navigation in the Proximity of Moving Humans," in *IEEE Workshop on Advanced Robotics and its Social Impacts*, May 2012, pp. 83–88.

[4] J. Rios-Martinez, A. Escobedo, A. Spalanzani, and C. Laugier, "Intention Driven Human Aware Navigation for Assisted Mobility," in *IEEE/RSJ Int.l Conf. Intelligent Robots and Systems*, 2012.

[5] D. Feil-Seifer and M. J. Matarić, "People-aware navigation for goal-oriented behavior involving a human partner," in *IEEE Intl. Conf. Development and Learning (ICDL)*, Aug. 2011, pp. 1–6.

[6] S. Satake, T. Kanda, D. F. Glas, M. Imai, *et al.*, "How to approach humans?: strategies for social robots to initiate interaction," in *ACM/IEEE Intl. Conf. Human Robot Interaction*, 2009, pp. 109–116.

[7] C. Pedica and H. H. Vilhjálmsson, "Spontaneous Avatar Behavior for Human Territoriality." *Applied Artificial Intelligence*, vol. 24, no. 6, pp. 575–593, 2010.

[8] A. Valero-Gómez, J. V. Gómez, S. Garrido, and L. Moreno, "Fast Marching Methods in Path Planning," *IEEE Robotics and Automation Magazine*, no. in press, 2013.

[9] J. V. Gómez, N. Mavridis, and S. Garrido, "Social Path Planning: Generic Human-Robot Interaction Framework for Robotic Navigation Tasks," in *2nd Intl. Workshop on Cognitive Robotics Systems: Replicating Human Actions and Activities*, 2013.

[10] C.-P. Lam, C.-T. Chou, K.-H. Chiang, and L.-C. Fu, "Human-Centered Robot Navigation - Towards a Harmoniously Human-Robot Coexisting Environment." *IEEE Trans. Robotics*, vol. 27, no. 1, pp. 99–112, 2011.

[11] A. Kendon, *Conducting interaction: Patterns of behavior in focused encounters*. Cambridge University Press, 1982.

[12] S. Garrido, L. Moreno, M. Abderrahim, and D. Blanco, "FM2: A Real-time Sensor-based Feedback Controller for Mobile Robots," *Intl. J. Robotics and Automation*, vol. 24, no. 1, pp. 3169–3192, 2009.

[13] J. V. Gómez, "Advanced Applications of the Fast Marching Square Planning Method," Master's thesis, Carlos III University, 2013.

[14] J. A. Sethian, *Level Set Methods and Fast Marching Methods*. Cambridge University Press, 1996.

[15] T. Amaoka, H. Laga, S. Saito, and M. Nakajima, "Personal Space Modeling for Human-Computer Interaction," in *International Conference on Entertainment Computing*, vol. 5709, 2009, pp. 60–72.

[16] J. V. Gómez, A. Lumbier, S. Garrido, and L. Moreno, "Planning robot formations with fast marching square including uncertainty conditions," *Robotics and Autonomous Systems*, vol. 61, no. 2, 2013.

[17] J. Rios-Martinez, A. Spalanzani, and C. Laugier, "Understanding human interaction for probabilistic autonomous navigation using Risk-RRT approach." in *IEEE/RSJ Intl. Conf. Intelligent Robots and Systems*, 2011, pp. 2014–2019.