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A Framework towards a Socially Aware Mobile Robot Motion in Human-Centered Dynamic Environment

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Abstract— **For a Mobile Robot to navigate in the Human-Centered environment without imposing alien like impression by its motion, it should be able to reason about various criteria ranging from clearance, environment structure, unknown objects, social conventions, proximity constraints, presence of an individual or group of peoples, etc. Also the robot should neither be over-reactive nor be simple wait and move machine. We have adapted a Voronoi diagram based approach for the analysis of local clearance and environment structure. We also propose to treat human differently from other obstacles for which the robot constructs different sets of regions around human and iteratively converges to a set of points (milestones), using social conventions, human proximity guidelines and clearance constraints to generate and modify its path smoothly. Once equipped with such capabilities, robot is able to do higher-level reasoning for dynamic and selective adaptation of social convention depending upon the environment segment. It also leads the robot to be aware about its own motion behavior.**

I. INTRODUCTION

As Robots are navigating around us for various reasons: following [2], passing [3], accompanying [6], guiding [7] a person or a group of peoples [1], it is apparent that social norms and reasoning about space around human should be reflected in the robot's motion. In the context of Human-Robot Co-existence with a better harmony, it is necessary that Human should no longer be on the compromising side. Robot should 'equally' be responsible for any compromise, whether it is to sacrifice the shortest path to respect social norms or to negotiate the social norms for physical comfort of the person.

In [5], we evaluated the long term performance of our tour guide robot, which suggests that navigating in a human centred environment by considering a person only as a mobile object is neither enough nor accepted. In this context it is also important that robot should be able to do a higher level reasoning for planning its path based on the local structure of the environment, clearance around human, intended motion of the human and obviously the social conventions of the country it is 'working' in.

In [17] the robot tries to behave human like by maintaining 'proper' orientation and distance, while approaching and joining a group of people. In [13], robot tries to adjust its velocity around the human. In [18], we take into account human's visibility and hidden areas, whereas in [19] we consider unknown dynamic objects from the hidden zones while planning the path. In [21], we have developed an approach for social robot guide, which monitors and adapts to the human's commitment on the joint task of guiding. In [8], virtual autonomous pedestrians extrapolate their trajectories in order to react to potential collisions.

However most of these approaches do not address the issues like, maintaining the correct side while passing by or overtaking a person or while in a narrow passage like corridor, maintaining an appropriate distance from another person or a group even if there is no predicted future collision. Also, the existing approaches either assume that the environment topological structures like corridor, door, hall, etc. are known to the robot or no obvious link between the robot motion behavior with the local environment structure has been shown.

Our goal is to develop a mobile robot navigation system which: (i) autonomously extracts the relevant information about the global structure and the local clearance of the environment from the path planning point of view, (ii) dynamically decides upon the selection of the social conventions and other rules, which needs to be included at the time of planning and execution in different sections of the environment, (iii) re-plans a smooth deviated path by respecting social conventions and other constraints, (iv) treats an individual, a group of peoples and a dynamic or previously unknown obstacle differently.

The framework, presented in this paper, basically plans/re-plans a smooth path by interpolating through a set of *milestones* (the points through which the robot must pass). The key of the framework is the provision of adding, deleting or modifying the milestones based on static and dynamic parts of the environment, the presence and the motion of an individual or group as well as various social conventions. It also provides the robot with the capability of higher level reasoning about its motion behaviour.

In [16] we have presented an algorithm, which uses a set of social conventions and plans a smooth path to navigate and avoid human. However, the information about environment clearance, door and corridor was already provided to the robot. In addition, it does not perform the clearance analysis around human and there was no provision to take into account previously unknown obstacles and re-plan a smooth deviated path for avoiding it.

As far as our knowledge, no significant work has been published by others to produce smooth path by addressing

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the issues of dynamic & selective adaptation of behaviours in a human-centered environment. Next sections will describe our approach to extract the path planning oriented environment information. Then the set of social conventions, proximity guidelines and the clearance constraints, within the scope of this paper, will be outlined. Subsequently the selective adaptation of rules and their encoding in a decision tree will be discussed. Then the strategies for dealing with humans and previously unknown obstacles will be followed by our algorithm to produce the smooth path.

II. METHODOLOGY

A. Extracting Environment Structure

One of our interests is to know the local clearance in the environment like door, narrow passage corridor, etc. In our current implementation, we are using Voronoi diagram, which has been shown to be useful by us [22] and by others [15], [4], for capturing the skeleton of the environment. Since we are constructing the Voronoi diagram at discrete level of grid cells, we define it as the set of cells in the free space that have at least two different equidistant cells in the occupied space. Fig. 1 shows different Voronoi cells (green circles) and the red lines connecting them to the corresponding nearest occupied cells. We define the term *'Interesting Cell'* (*IC*) as the Voronoi Cell: (a) which is equidistant from exactly two cells in the occupied space and, (b) both the equidistant points are on the opposite sides on the diameter of the circle centered at that Voronoi cell. In fig. 1, the Voronoi cell *C* is such as $\angle P_1CP_2$ is 180 degrees, hence it is an *IC*. We name the line joining both the equidistant points of *IC* as the *'Interesting Boundary Lines'* (*IBL*), P_1P_2. The length of the *IBL* will be the '*clearance*' of that local region. By setting a threshold on this clearance, robot decides whether it is a narrow passage or wide region. Fig. 10 shows the local clearance of a part of the map of our lab, captured by this approach. Note that, as shown in fig. 10, in case of corridor or long but narrow passage, we will have a set of approximately parallel *IBLs*.

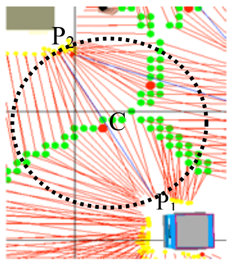


Fig. 1. Interesting cell (IC) C and Interesting Boundary Line (IBL) P_1P_2

B. Set of Different Rules

In current implementation we use following set of rules:

1) General Social Conventions (S-rules)

(S.1) Maintain right-half portion in a narrow passage like hallway, door or pedestrian path. *(S.2)* Pass by a person from his left side. *(S.3)* Overtake a person, from his left side. *(S.4)* Avoid very close sudden appearance from behind a wall.

2) General Proximity Guidelines (P-rules)

Based on proxemics literatures, such as [9], which divide space around human based on *Intimate*, *Personal, Social and Public distances,* and the results of various user studies, in [16] we have hypothesized a set of parameterized semi-elliptical regions around human as shown in the fig 2(a). Although these regions will serve as reference in our current implementation for the speed range of 0.5 m/s to 1 m/s for human and robot, separate investigation is necessary as the values of its parameters vary depending upon speed, size, children or adult, task [10] and personality [11].

The set of *proximity rules,* which we are presently using, are: *(P.1)* Do not enter into intimate space until physical interaction is needed. *(P.2)* Avoid entering into personal space if no interaction with human is required. *(P.3)* Avoid crossing over the person if the robot is already within the outer boundary of side-social regions numbered as *3* and *4* in fig 2(a). In this case pass by the human from his nearest side. One can notice that in some situations rule *(P.3)* can cause conflict with the social rule *(S.2)*, but we choose *(P.3)* to dominate because the robot will be in close proximity of human. Rules *(P.1)* and *(P.2)* also serve another purpose of ensuring physical safety of the human.

3) General Clearance Constraints (C-rules)

The clearance analysis takes care of spacious sufficiency. The set of clearance rules used are: *(C.1)* Avoid passing through a region around human if it has a clearance less than *d1*. *(C.2)* Maintain a minimum distance *d2* from the walls and obstacles. *(C.3)* Do not pass through an *Interesting Boundary Line (IBL)*, if its length is less than *d3*. Currently the values of *d1, d2, d3* depend upon the robot's size only.

We will use the term *milestone*, as a point through which the path of the robot must pass. Our algorithm performs one of the following actions for each of the rules mentioned above: (i). Inserts a new set of milestones in the list of existing milestones. (ii). Modifies the positions of a subset of existing milestones. (iii). Verifies whether a particular rule is being satisfied on the existing set of milestones or not.

C. Selective Adaptation of Rules

From the path planning point of view we will globally divide the rules into two categories: Those which need to be included at the time of initial planning, taking into account the static obstacles only and those which will be included at the time of path execution as human or unknown obstacles will be encountered. *S-rules (S.1)* & *(S.4)* and *C-rules (C.2)* & *(C.3)* falls into first category. Rules *(S.1)* & *(S.4)* are due to the obvious reasons of avoiding conflicting situation in a narrow passages as well as to avoid collision and the feelings of surprise or fear in human. Similarly *(C.2)* & *(C.3)* are to avoid moving very close to obstacle or being stuck in a too narrow passage. Other rules fall into second category.

This selective adaptation of rules is an attempt to balance the tradeoffs between the path which minimizes the time of flight and the path which avoids conflicting, reactive and confusing situations in a human-centered environment.

D. Construction of Decision Tree

We have constructed a rule based decision tree based on different possible cases for the relative positions of the human, next milestone in the current path and the clearance of different regions around the human. In case of conflicts, the clearance constraints and the proximity guidelines have been given preference over the social conventions. Robot uses this decision tree to perform higher-level reasoning, for dealing with the dynamic human. The robot, based on user studies, which is not the focus of this paper, could also learn or enhance such decision trees. We define following two functions to query the decision tree:

*(side, valid_regions)=**get_side_regions**(R_pos, H[i]_pos, M_next, left_min_clearance, right_min_clearance)* ...*(i)*

*(milestones)=**get_milestones**(R_pos, H[i]_pos, M_next, side, valid_regions)* ...*(ii)*

Where *R_pos* is the current position of the robot, *H[i]_pos* is the predicted position and orientation of the human *i*, *M_next* is the immediate next milestone in the robot's current path, *left_min_clearance* and *right_min_clearance* are the minimum lengths of *Interesting Boundary Lines (IBLs)* on left and right sides of human predicted position. Function (i) returns, the side of the human (left/ right), through which the robot should ideally pass and the set of acceptable regions (among *1-10*, marked in fig 2(a)) around the human, though which the robot may pass.

In fig. 2(b), a subset of the decision tree, in form of different combinations of robot positions (gray) and positions of the next milestone (blue), has been shown. Function (ii) returns subset of points as the intermediate milestones, from the fixed set of points (*P1, P2, P3, P4, P5*) of fig. 2(b), in the order of their passing position. For example, if the robot is at *R1*, the next milestone to pass through is *M1*, then the function (i) will return (*left, (1, 2, 3)*) as the preferred side and acceptable regions in which robot could navigate around human while satisfying various rules. By taking the output of function (i), function (ii) will return (*P2, P5*) as an ordered set of intermediate milestones through which, the path of robot should preferably pass. But if there are some obstacles on the left side of the human such that *left_min_clearance* is not sufficient, functions (i) and (ii) will return *(right, 2, 4)* and *(P3, P4)* respectively.

E. *Dealing with Dynamic Human*

As soon as a human becomes visible to the robot and falls within some distance range, robot has to decide whether or not to initiate the human avoidance process. For this robot finds the minimum clearance around the human's predicted future position by constructing a separate set of *Interesting Boundary Lines (IBLs)*, as explained in the section IIA. Robot also predicts a series of future positions for every visible human, by just by extrapolating their previous positions and speeds (studies and works on human walking pattern like [12], [8], could help in better prediction). Then robot checks, whether any segment of its current path is falling inside any of the regions from *1-9* of fig. 2(a) or not. If not, then the robot will not show any reactive behaviour assuming it will be far from the human and its motion behaviour will not influence human. Otherwise, there will be two cases: the path segment falls inside the personal space (*5-8*) or only inside the social space around the human (*1-4*). In the first case robot decides to smoothly deviate from its path by re-planning, even if there may not be any point-to-point collision with the human. This will serve the purpose of maintaining a comfortable social distance from human as well as to signal the human about its awareness and intention well in advance. In the second case robot first queries the decision tree through function (i), *get_side_regions()*, and checks whether the passing by side returned by the function is same as the passing by side while following the current path or not. If not, only then the robot will decide to re-plan.

Once robot has decided to deviate, it needs to find a set of intermediate points (milestones) around human through which the deformed path should pass. Fig. 2(c) shows a situation in which the current path of the robot (red line) enters into the personal space of the human predicted position at *P1* and exits at *P2*. Robot first finds the mid point of the line *P1P2* and projects it to the outer ellipse of social space, at *M2*, from the viewpoint of human predicted future position. If side of *M2* complies with the values returned by function (i), *get_side_regions()*, robot accepts it as the milestone to pass through. Otherwise the robot uses function (ii), *get_milestones()*, to get the milestones, for deviation, from the fixed set of points around the human.

F. *Dealing with Previously Unknown Obstacles*

The obstacles, which were previously unknown or are at changed positions; need to be dealt dynamically by the robot. For this, robot first updates the Voronoi diagram in a window of width *w* around that obstacle. Then for avoiding such obstacles, the rules, which have been discussed in subsection II-C, for planning using static environment, will be used to add or modify milestones for re-planning the smooth deviated path.

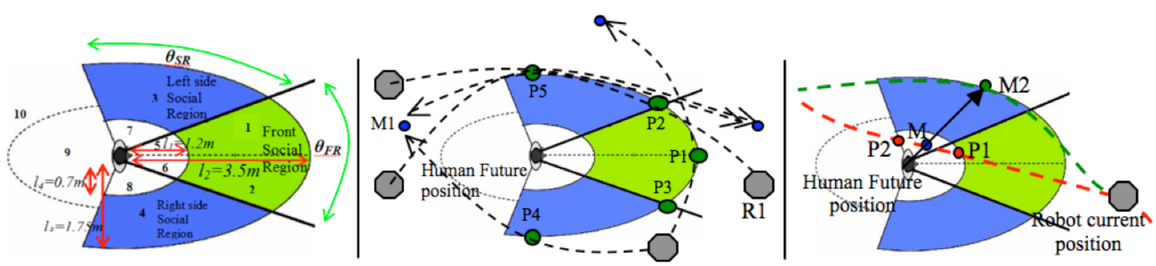


Fig. 2. (a) Construction of parametric region around human. (b) Avoiding a person by using decision tree for getting milestones. Different combination of robot's position (gray polygon) and next milestone of robot's path (blue circle) relative to human predicted position result into different set of points around human (green circles) treated as new milestones for modified path, through which the robot should pass (c) Another way of avoiding a person by calculating new milestone. Initial path (red), modified path (green). The segment *P1P2* of the initial path, which intersects the personal space of predicted human future position, is found and its mid point *M* is projected to point *M2* (treated as new milestone) till the social boundary of human.

G. Generating Smooth Path

For the current discussion, the task of the robot is to reach to a goal place from its current location. The algorithm to generate the smooth path is as follows:

1 START; Set *FIRST_ITERATION=TRUE*
2 Insert the start and goal points in set of fixed milestones FM.
3 Set *FM_D=NULL*; It is set of milestones due to dynamic environment, will be populated at step 17.
4 Merge the set *FM_D*, in *FM*. Let *tmp_FM=FM*.
5 Passing through all the milestones of *tmp_FM*, in the order, plan a shortest path by cost grid based A* algorithm by taking into account static obstacles only.
6 Extract the set of crossing boundaries $CB \subseteq IBL$ and the corresponding crossing points *CP*, through which the shortest path *SP* is passing.
7 If(FIRST_ITERATION==TRUE) {
7.1 Extract the information about passing through a narrow passage, door or corridor.
7.2 If narrow passage or door, mark the corresponding crossing boundary as *D*, where ($D \in CB$).
7.3 If corridor, find the entry and exit boundaries $C\_Enter \in CB$ and $C\_Exit \in CB$. Note if robot is already inside a corridor, the *C_Enter* will be that *IBL* of the corridor, which is just next to the robot along the shortest path to the goal.
7.4 Mark all the *CB*s and *CP*s between *C_Enter*' and '*C_Exit*' from the list of *CB* and *CP as 'dead'*, which will be not used for finding *CB* in next iteration.
7.5 *FIRST_ITERATION=FALSE }*
8 Apply the rule set *SR_P,* which has been selected to be used in planning stage itself, on *CP*. This will shift some of the crossing points marked as '*C_Enter*', '*C_Exit*' and '*D*' along either side of the corresponding boundary lines.
9 Store the set of modified crossing points in *CP_M*. Note that $CP\_M \subseteq CP$ .If *CP_M=NULL,* jump to *12*.
10 Set *tmp_FM=NULL;* Merge *FM* and *CP_M* into *tmp_FM*.
11 *Repeat from step 5.*
12 Merge the set *CP* into the *FM*.
13 Generate Hermite polynomial based smooth spline path by interpolation through *FM*
14 Update the list of visible human, *H*. Find human groups *HG* and individual human *HI*.
15 For any visible *HG*, *if* Test for Human Group Avoidance is passed, modify the parameters of elliptical region according to the spread of the group, *then goto step 17 else goto 18*.
16 For any visible *HI*, *if* Test for Individual Human Avoidance is passed, *goto step 17 else goto step 18*.
17 Extract milestones for human or group avoidance and merge in *FM_D*.
18 *Repeat from step 4*.
19 End

The first iteration flag is to ensure that the robot will pass through the regions and boundaries through which the shortest path is passing, by taking into account the static environment. This will ensure that, just to avoid dynamic objects and humans, robot should not take a longer path through entirely different regions. Wherever merging has been mentioned, it is done by the analysis: between which two successive boundaries of *CP* a particular point is falling and in the case of conflict the nearer one to the robot is put first in the merged list.

Fig. 3 illustrates different steps of the algorithms. The dotted blue line shows the shortest path from start point *S* to the goal point *G*, generated by cost grid based A* approach. The initial Voronoi Diagram of the environment generated by taking into account the static obstacles only, has been shown as skeleton of green points. The thin red lines are the *Interesting Boundary Lines (IBLs)*. Reader should not be confused with the rectangular tiles on the floor with *IBLs*. The blue circles show the set of initial milestones *CP*, extracted at the first iteration of *steps 1-7.5*. Now to realize the social rule and clearance constraints selected to be used at the initial planning state as discussed in section II(C), a process of refinement on the milestone along the line of minimum clearance i.e. *IBL* will be performed. *Step 8* performs these refinements on the milestones. For the realization of rule *(S.1)*, the refinement process is to shift the milestones, which are of a corridor, a door or a narrow opening, towards the middle of the right half portion, based on the expected orientation at crossing points. The green milestones at boundaries 1, 5, 6 and 7 are obtained by such shifting of the blue milestones. The refinement associated with other rules are, if the distance of the crossing point is less than a required minimum distances from the nearest end of the corresponding *IBL*, then shift away the crossing points along the *IBL* until middle of the *IBL* is reached or the desired distance is achieved. These rules resulted into the green milestones at boundary 3 & 4 by shifting away the corresponding blue milestones. All the milestones, which will be refined by the initial social rules, will be treated as the fixed milestones for the next iterations. *Steps 9-11* assure

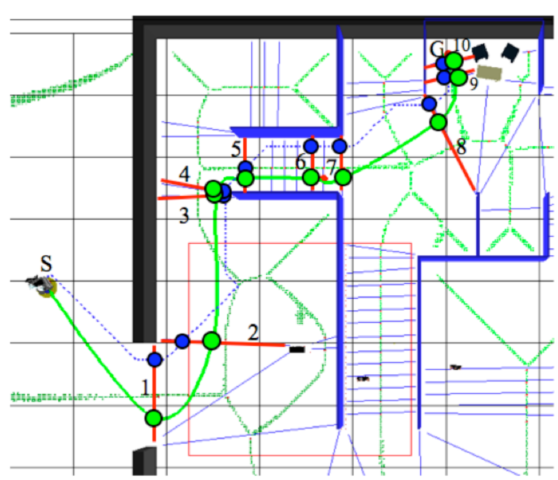


Fig. 3. Steps of iterative refinements on the path to incorporate social conventions and clearance constraints at planning stage.

the shortest path between two fixed milestones, because as few milestones have been shifted, the other milestones may no longer fall on the probable shorter path. For example the blue milestones of boundaries 2 & 8 have been shifted to the green milestones in the second iteration of the algorithm.

After getting a set of milestones through which the robot should pass, robot solves Hermite cubic polynomial for continuity constraint on velocity and acceleration at boundaries to piecewise connect the milestones. The green curve in fig. 3 shows the final smooth path generated by using the final set of milestones for planning the initial path.

H. Proof of Convergence

The convergence of the algorithm lies in the fact that, after each iteration there will be a set of fixed milestones, which will not change in next iterations, as they will already be satisfying the rules. Hence eventually the *step 9* will result into an empty set of modified milestones, *CP_M,* and will jump to *step 12* to generate the final path. In all our test runs, in 2-3 iterations the algorithm has converged hence facilitating the algorithm to run online.

III. Experimental Results and Analysis

For testing our framework, the models of environment, robot and human is fed and updated into our developed 3D representation and planning software Move3D. Fig. 4 is the part of a big simulated environment of dimension 25m x 25m; S and G are start and goal position for the robot. The blue lines are the *Interesting Boundary Lines (IBLs)* extracted by our proposed approach. The Voronoi diagram has been shown as green skeleton of points. A* shortest path has been shown as blue dotted path. The green curve is the smooth social path generated by the robot by our proposed algorithm. Note that robot autonomously inferred that it is in a corridor and shifted the path to the right side of the corridor, till the autonomously found exit of the corridor. In literature [20], [14], Voronoi diagram itself has been used as the robot's path. However, one could discover that the planned path by presented approach avoids unnecessary route of Voronoi diagram in the wider regions, e.g. the region enclosed by blue ellipse. Moreover, in the regions where all the constraints are satisfied, our algorithm provides a path segment close to the shortest path by A* planner, e.g. the region enclosed by the red ellipse. But if there is no sufficient clearance, our algorithm shifts the crossing points to the middle of the *IBLs*, hence following the Voronoi diagram in that region for assuring maximum possible clearance. Hence our algorithm inherits the characteristics of A* and Voronoi diagram based paths at the places where they perform better while globally maintaining the social conventions and smoothness of the path.

Fig. 5(a) shows robot passing by a person in the corridor without creating any conflicting situation. Fig. 5(b) and 5(c) show the detection of a group of peoples based on their relative speeds and positions, and avoiding the group from the left side. Note the initial path in fig. 4 has been smoothly

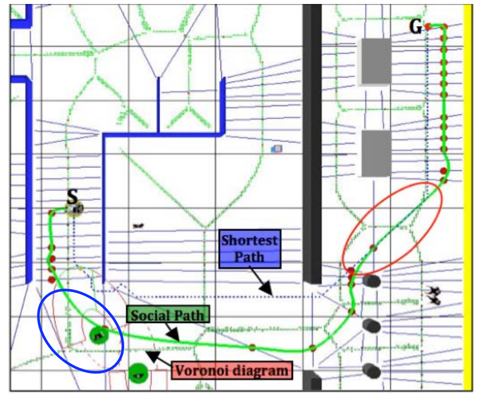
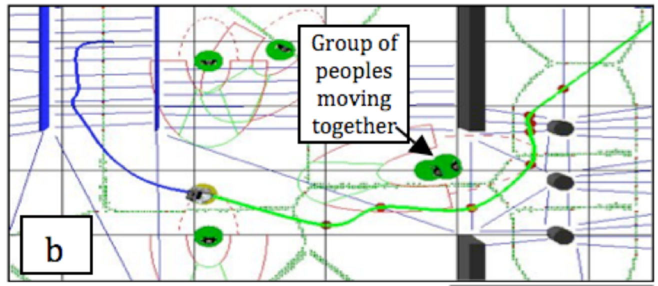


Fig. 4. S and G are start and goal positions. Thick Green path is the smooth and socially acceptable path planned by our approach. Dotted Blue path is the shortest path planned by cost grid based A* planner. Green skeleton of points is the Voronoi diagram.



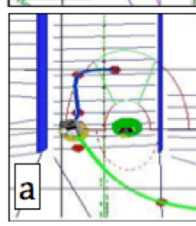
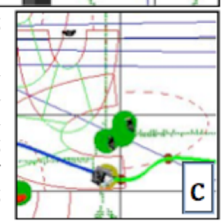


Fig. 5. (a) Robot passing a person in corridor, (b) planning a smooth deviation in path to avoid group of peoples with sufficient signaling distance (see fig. 4 for initial path), (c) Passing by the group from left.



modified in fig. 5(b) at the predicted passing by place.

We have implemented our presented framework on our mobile robot Jido. It uses vision based tag identification system for detecting dynamic objects like trash bin, table, etc., and markers based motion capture system for reliable person detection. Fig. 6 shows the sequence of images where the robot has predicted that even if there is no direct collision with the human, it might enter into the personal space of the human hence modified its path to smoothly avoid the person from her left side. Fig. 7 shows the case where robot has suspended the social convention of passing by, due to insufficient clearance on the left side of the

Fig. 6. Experimental mobile robot Jido, avoiding the person by maintaining the social convention of passing by from her left side.

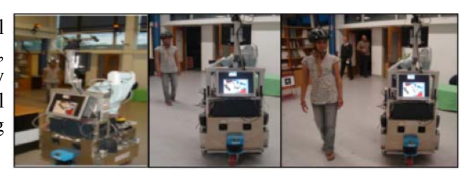
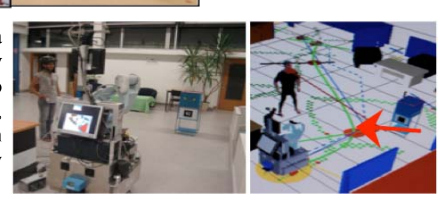


Fig. 7. Suspending the social convention of passing from left. Instead passing from right because of insufficient clearance on the left of human.

Fig. 8. Robot crosses a standing person by avoiding entering into her personal space, because no interaction is required. Red arrow shows the planned path.



person. Instead the robot has modified its path to pass by from the right side. Fig. 8 shows the case when robot has planned the path, shown as red arrow, to smoothly cross the standing person, to reach the goal, while maintaining the proximity constraints *(P.1) & (P.2)* around the person. Fig. 9 shows the results of avoiding previously unknown obstacles, for which robot updates the Voronoi diagram to extract new clearance information and our presented algorithm adds new set of milestones to re-plan the smooth deviated path as shown in fig. 9(c). Fig. 10 shows the bigger portion of our lab having corridor. The green curve is the smooth path generated by the robot using the presented approach to reach from S to G. Although not shown here, our implementation is generic to easily switch between right and left handed walking system.

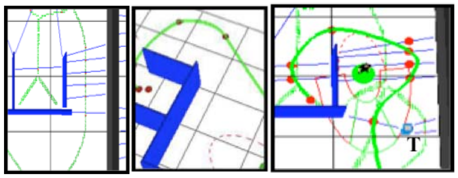


Fig. 9. (a) Initial Voronoi Diagram and clearance (IBLs), (b) initial planned path, (c) during execution the updated clearance information and deviated path due to presence of previously unknown trash bin, marked as T.

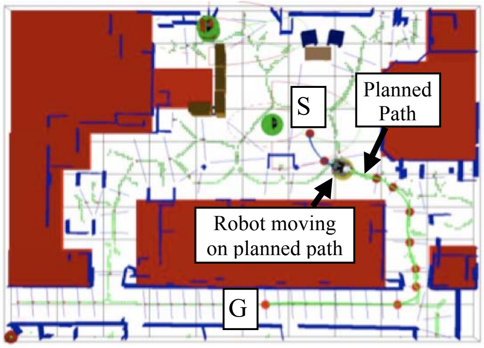


Fig. 10. Path generated in the bigger map of our lab, from S to G using our presented framework.

IV. Conclusion and Future Works

This paper is a step towards enabling the robot socially and contextually aware. The key idea of the presented framework is to get a set of milestones and plan a smooth path via them. Our framework facilitates the addition, deletion or modification in the milestone based on various rules. We have presented the concept of selective adaptation of rules and a method to practically extract the clearance information in the grid-based map of the environment. Our robot equipped with such capabilities autonomously decides, which rules need to be used in a particular part of the environment and at a particular state of planning and execution. We have also shown that apart from satisfying various constraints, the generated path inherits the characteristics of both, the cost grid based shortest path as well as Voronoi diagram based path at the regions, where they perform better. Moreover our approach treats an individual, a group and an unknown obstacle differently.

This developed robotics platform could also be used for various user studies. Such studies will not only help to refine and verify the correlation among various factors like social convention, proximity and clearance but also to identify unknown factors and missing links, which define behavior and shape of the navigation path in a dynamic environment.

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