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To cite this version:

Emrah Akin Sisbot, Luis F Marin, Rachid Alami, Thierry Simeon. A mobile robot that performs human acceptable motions. 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Oct 2006, Beijing, China. pp.1811-1816. hal-01987513

HAL Id: hal-01987513
https://hal.laas.fr/hal-01987513
Submitted on 21 Jan 2019

A mobile robot that performs human acceptable motions

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Abstract— **The presence of humans should be explicitly taken into account in all steps of robot's design and particularly for robot motion. The robot should reason about human partner's accessibility, his vision field and potential shared motions and behave as a social being by respecting social rules and protocols.**

This paper describes the algorithms and results of a navigation planner that takes into account the human presence explicitly. This planner is part of a human-aware motion and manipulation planning and control system that we aim to develop in order to achieve motion and manipulation tasks in presence and?or in synergy with human.

I. INTRODUCTION

The introduction of robots in our daily life raises a key issue that is "added" to the "standard challenge" of autonomous robots: the presence of humans in its environment and the necessity to interact with them. In industrial robotics, although there can be operators near, a safety distance is always maintained between humans and robots by forbidding anyone to enter. Although this approach assures the safety and good working of the system, it causes a very poor social interaction between humans and robots.

To make the robots "live" among humans, one must consider all aspects of human-robot interaction and resulting behaviors that must be taken into account in all steps of the robot design. This paper addresses issues related to the close interaction between humans and robots from the standpoint of the motion decisions that must be taken by the robot in order to ensure:

- Safe motion, i.e., that does not harm the human,
- Reliable and effective motion, i.e, that achieves the task adequately considering the motion capacities of the robot,
- User friendly motion, i.e, that takes into account a motion model of the human as well as his preferences and needs.

Let's consider a simple "fetch and carry task" as illustrated in figure 1 for a socially interactive robot [3]. The robot has to perform motion and manipulation actions and should be able to determine where a given task should be achieved, how to place itself relatively to a human, how to approach him, how to hand up the object and how to move in a relatively constrained environment in presence of humans (an apartment for instance). Our goal is to develop a robot that is able to take into account "social constraints" and to synthesize plans compatible with human preferences, acceptable by humans and easily legible in terms of intention.

Fig. 1. A "fetch-and-carry" Scenario

We have introduced our approach in [1] and discussed in [2] how user studies have influenced the design of the planner. In this paper, we further discribe some algorithmic issues and present its implementation and first tests on a mobile robot. Section II discusses related work. Section III presents the main characteristics of our navigation planner. Section IV briefly explains the implementation of this planner in our robot. Finally, we present and discuss simulations and real-world results in section V.

II. RELATED WORKS

Although human-robot interaction is a very active research field, there is no extensive amount of research on motion planning in presence of humans.

In a work by Nonaka et al. [14], the concept of safety has been defined by two types: "physical" safety and "mental" safety of human. Physical safety means that the robot does not physically injure humans. Mental safety, on the other hand, means that the motions of the robot do not cause any unpleasantness like fear, shock or surprise to humans.

The physical safety is an absolute need for human-robot interaction. It must be assured at all levels of robot's design. In [11], the safety strategies are categorized into two different types: design and control strategies. Besides new designs [9][15] that ensure safety at the physical level, fault-tolerant approaches [16] tend to detect and limit the consequences of hardware and software problems. In recent work by Kulic and Croft [17][18] a danger index is used to determine and control robot's motions in a more human friendly way.

With these approaches physical safety is assured by avoiding collisions or minimizing the intensity of a possible impact. The mental safety on the other hand relies on the interpretation of the motions by humans. To achieve more human friendly behaviors, there are a number of works trying to imitate human motions and to better understand of how humans behave in social environments. Work in [8] describes a method for placing the robot like humans in a multi-partnered conversation. This behavior results good robot placements but actually limited to imitating humans self-placement rules. In a recent work by Pacchierotti et al. [5], a human-robot hallway passage scenario is studied and ”social patterns” for relative Human-robot placement are extracted from these studies. These patterns are encoded into robot behaviors and result in a human friendly motions for a very specific hallway crossing like scenario.

Another approach that not only deals with safety but also implicitly considers comfort issues is the work by Alami et al. [7] on velocity profiles along a planned trajectory where a robot adapts its trajectory and its speed to optimize the execution time while guaranteeing that no collision will occur. Although the human is not considered explicitly, this method guarantees collision free motions by taking into account the sensor capabilities of the robot. Since the sensors have a certain range, it is likely necessary to slow down at places along the robot's trajectory where the sensors are blocked by narrow passages or corners. Finally a velocity profile is found by optimizing the execution time.

Although several authors propose motion planning or reactive schemes considering humans, there is no contribution, to our knowledge, that tackles globally the problem in such a generic way as the one proposed in this paper.

III. HUMAN AWARE NAVIGATION PLANNER

User studies with humans and robots [13][6][2] provide a number of properties and non written rules/protocols [10] of human-robot or human-human interactions. Only very limited works consider such properties and often in an ad hoc manner. We describe below a new technique that allows to integrate such additional constraints in a more generic way. First, we introduce two criteria to the motion planning stage in order to ensure human safety and comfort. These two criteria, namely “safety criterion” and “visibility criterion” present two important aspects of robot navigation in a human-robot interaction scenario.

Each criterion is represented by a set of numerical value stored in a 2D grid combining various costs depending robot's position in the environment. One can consider these grids as a set of cells containing various costs derived from the relative position to the human. These costs are highly related to the humans' state, capabilities and preferences. The grid G can be defined as:

$$G = (M_{n,p}, H_1 \ldots H_n)$$

where $M_{n,p}$ is a matrix containing $n * p$ cells represented by $a_{x,y}$, the cost of the coordinate (i, j) in the grid and $H_1 \ldots H_n$ is a list of humans in the environment. A human H_i is modeled by $H_i = (St, State_1 \ldots State_n)$ where St is the structure and kinematics of the human and $State_i$ is a human state defined by a number of cost parameters and state description:

$$State_i = (Name, Conf, Param)$$

where $Name$ is the name of the state (for ex. $Name = SITTING, STANDING$), $Conf$ is the humans configuration in that state and $Param$ represents the data needed to compute costs according to that state.

We now explain the structure of the “safety” and the “visibility” criteria and the underlying properties.

A. Safety Criterion

The first criterion, called “safety criterion”, mainly focuses on ensuring the safety by controlling the distance between robot and humans. This property aims to keep a distance between the robot and the humans in the environment. However in some cases, as the necessity of their interaction, the robot has to approach to a person whom it wants to interact with. Hence, this distance between the robot and the human is neither uniform nor fixed and depends on the interaction. The feeling of safety highly depends on humans personality, his physical capabilities and his actual state; for example, safety differs highly when the human is sitting than when he is standing. When the human is sitting, as his mobility is reduced, he tends to have a low tolerance to the robot getting close. On the contrary when standing up he gets a higher mobility, therefore allowing the robot to come closer.

These properties are presented in the current system by a “safety grid”. This grid contains a human centered Gaussian form of cost distribution. Each coordinate (x, y) in this grid contains a cost inversely proportional to the distance to the human. Then, when the distance between the human and a point in the environment (in the grid) $D((x_i, y_j))$ is greater than the distance of another point $D((x_k, y_l))$, we have $Cost(x_k, y_l) > Cost(x_i, y_j)$. Since the safety concerns loose their importance when the robot is far away from the human, the cost also decreases when getting farther from the human, until some maximal distance at which it becomes null.

Figure 2 shows a computed safety grid attached to a human who is sitting/standing on a chair. The height of vertical lines represents the value of the cost associated to each cell. As shown in the figure, humans current state (sitting, standing, etc) plays an important role in the construction of the grid. This approach allows us to maintain a level of flexibility to add other types of human state.

Once this grid is computed, searching for a minimum cost path will result a motion avoiding to move too close to the human from the fact that approaching the human is more costly than staying far away. However, if the environment is constrained and if the task requires so, the robot is allowed to approach to the human.

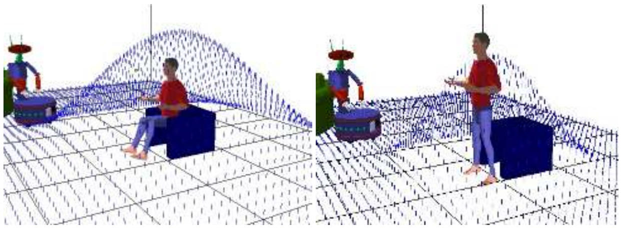

Fig. 2. A Safety grid is built around every human in the environment. It depends highly on the humans' posture. The person feels less "threatened" when standing.

B. Visibility Criterion

The second criterion, called "visibility criterion", aims to improve humans' comfort. Particularly humans generally feel more comfortable when the robot is in their field of view. This criterion allows the robot to stay and move in the field of view of the human during its motions.

The resulting grid, namely "visibility grid", is constructed according to costs reflecting the effort required by the human to get the robot in his field of view. Grid points located in a direction which the human only has to move his eyes have a lower cost than positions requiring to move the head in order to get the robot in the field of view. Also, when the robot is far away from the human, the effect of the visibility must decrease. The computed visibility costs are shown on figure 3. The zone situated in front of the human has very low costs. On the contrary, the zone situated behind the human has higher costs. Since the grid is attached to the head of the human, the computed costs are actualized when the human changes his field of view (turn his head or his direction) in planning and/or execution stage.

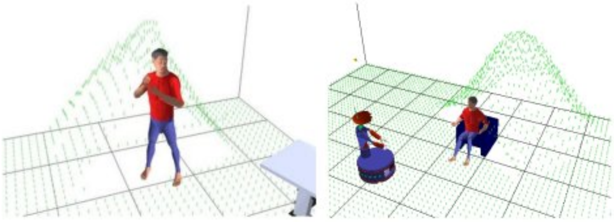

Fig. 3. Visibility grid is computed by taking into account humans field of view. Places that are far away from the person have higher costs.

C. An extension: Hidden Zones

In the grids illustrated above, the costs are calculated without taking into account the obstacles in the environment. However, obstacles in the close vicinity of the human can have various effects on the safety and comfort. If the robot is behind an obstacle, the human would feel much comfortable because the obstacle would block the direct way between human and the robot. So the safety criterion must be canceled in the zones located behind the obstacles.

On the other hand, when the robot becomes hidden by an obstacle the visibility costs lose their importance. To handle this issue, we introduce an extension to visibility and safety, called "hidden zones" criterion. This criterion helps to determine better costs for positions hidden by the obstacles.

An important effect of obstacles to the comfort of the human is the surprise factor. When the robot is hidden by an obstacle and loom in the human field of view, it can cause surprise and fear especially if it is close to the human. To avoid this effect, we must discourage the robot to pass behind an obstacle too closely, and must allow it to get into the humans field of view when sufficiently far away. This is done by putting costs to the zones hidden from the view because of the obstacles.

The costs in the hidden zone grid is inversely proportional to the distance between the human and the robot. The range of the effect of the surprise factor is approximately 3m, so the costs decrease to zero in the 3m perimeter and remains null for the other grid points (Fig. 4).

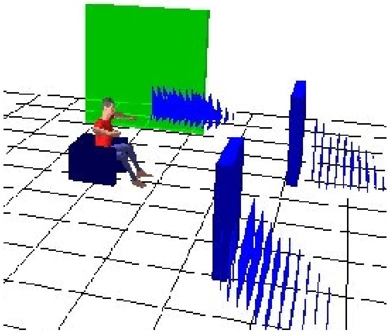

Fig. 4. Decreasing costs attributed to the zones hidden by obstacles. This supplementary costs discourage the robot getting too close to the obstacles and thus avoiding the robot to loom from hidden places

D. Path planner

Once the safety, visibility and hidden zones grids have been computed, they are merged to one single grid that the robot will search for a minimum cost path. These four grids (3 criteria + 1 final) are not constructed explicitly, the values of the cells are calculated according to the search algorithm's request. Different ways can be used to merge the grid costs. A first way can be to compute the overall cost from the weighted sum of the elementary costs:

$$Cost_{merged}(x,y) = w_1 Cost_{safety}(x,y) + w_2 Cost_{visibility}(x,y)$$

where (x, y) is a grid point, w_1 is the weight of the safety grid and w_2 is the weight of the visibility grid.

Another way is to consider the maximum cost values when merging the grids

$$Cost_{merged}(x,y) = max(Cost_{safety}(x,y), Cost_{visibility}(x,y))$$

Note that we do not merge hidden zones grid with the other two grids. That is mainly because hidden zones grids serves as a replacement of these two grids for positions where the robot could be seen if it wasn't blocked by an obstacle. The final grid is computed by:

```
  if ($R$ is on $(x,y)$ AND
$R$ is in field of view of $H_i$ AND
$H_i$ cannot see $R$ because of obstacle $O$)
then $Cost_{final}(x,y)$ <- $w_3 Cost_{hiddenzones}(x,y)$
else $Cost_{final}(x,y)$ <- $Cost_{merged}(x,y)$
```

Our planner can use both merging ways depending on the task and on the balance between criteria and also the weights of the grids can be tuned according to the properties of the task.

Once the final grid is computed, the cells corresponding to the obstacles in the environment are labeled as forbidden and an A* search is performed to find minimum-cost path between given two positions of the robot. The computed path is collision-free and also respects the safety and the visibility.

IV. IMPLEMENTATION

The "Human-aware navigation planner" is implemented within the Move3D [12] software platform developed at LAAS. The whole system has been ported to our robot Rackham(Figure 5), equipped with SICK laser scanner, a tilt & pan camera, infrared proximity sensors and sonars with three Pentium III processors.

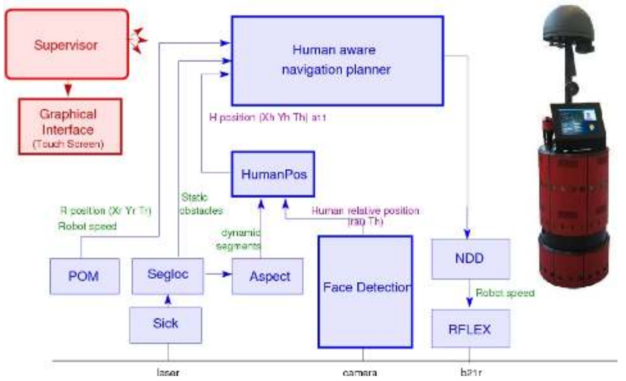

Fig. 5. General architecture of the robot composed of various modules

The navigation planner is developed in OpenGenom [20] as a module of the LAAS architecture [19]. As the whole system (composed of modules as illustrated in figure 5) is very sensitive to the humans' position and states, we built a "Human Position" module (HumPos) to detect humans in the environment. This module mainly relies on the laser data and visual detection by the camera.

The planner module works with a static internal 3D map along with each humans model, his grid construction parameters and the robot model. The humans' positions are updated by the HumPos module and the robot's current position is updated by Position Manager module. A constant data flow from HumPos to the planner is necessary to maintain the states of humans.With these inputs (figure 6), the navigation planner module calculates a path that takes into account social constraints explained in previous section.

Knowing human positions is necessary for our system to work. We can find a number of works aiming to detect humans with the use of laser, like [21] that detects cylinders and lines to find legs by analyzing their geometric characteristics, in [22] that combines camera and laser to track people and in [23] where a particle filter for tracking moving objects with a laser scan is successfully applied. We have created a simple module that uses visual and laser based recognition to detect and localize humans in the environment.

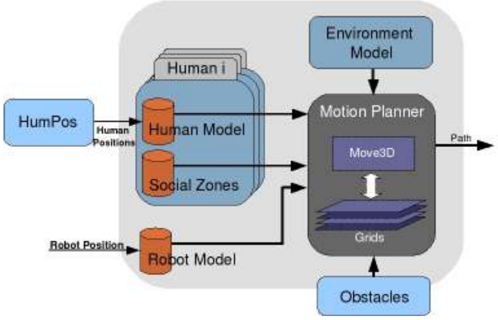

Fig. 6. Architecture of the human aware navigation planner module

The module HumPos is in charge of human detection and tracking and feeds the planner with a list of humans in the environment. This list contains positions and orientations of the detected humans with a detection probability attached to them. The main input of the HumPos module is the laser data. It is divided in three phases. The first phase detects legs, based on segments built from laser data that are not in the environment's map. The second phase detects legs from lectures provided by raw laser data that works as a filter of the first phase by matching the items found in the two phases. Finally the last one is in charge of the human detection and tracking based on visual data. Figure 7 illustrates the data flow and components of Human Detection and Tracking module.

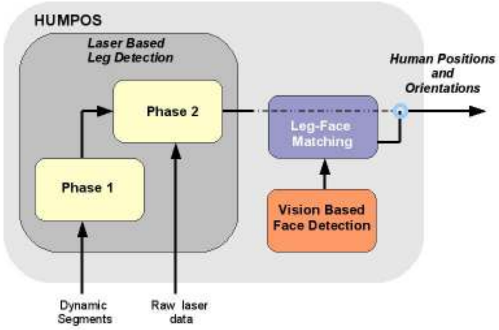

Fig. 7. Human Detection module which combines laser and visual data to detect humans in the environment. The output of this module is a list of humans described by Id's, positions and orientations.

V. Results

A. *Simulation results*

The features of our planner are illustrated on the scenario of figure 8 representing an apartment scenario with two persons: Clark (with light shirt) and Bruce (with dark shirt). We look at the synthesized trajectories between the living room and the kitchen in different situations.

In figure 8-a, we show the path generated by the navigation planner for a situation in which Clark orders the robot to bring a sandwich from the kitchen. The computed motion takes into account the safety and the comfort of both humans by trying to stay in the visibility fields. We can see in figure 8-b computed path avoids looming from behind the kitchen wall that would cause discomfort. Instead the robot chooses a path that keeps a certain distance to this wall. In figure 8-c, we can see that Bruce came to talk to Clark, so the robot calculates a different trajectory which maintains the visibility of Clark and also avoids passing too near to Bruce's back. The minimum cost approach of our navigation planner allows the robot to choose an alternative path if the path is blocked by an obstacle or a person (Figure 8-d).

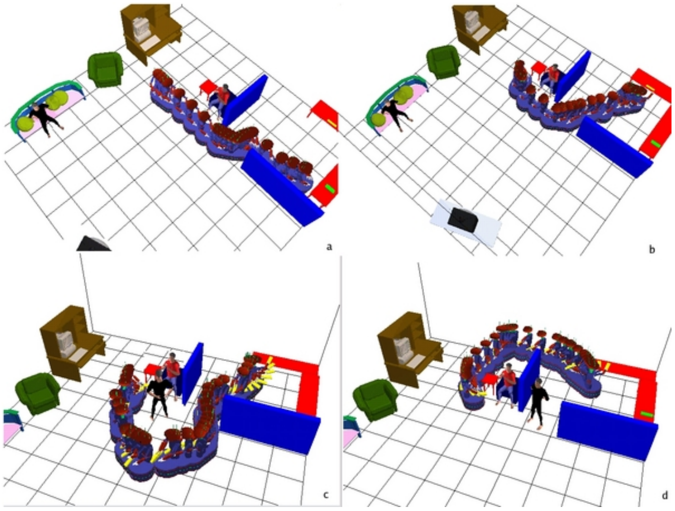

Fig. 8. A living room scenario with 2 persons, Clark (with light color shirt) and Bruce (with dark shirt) in 4 different situations. The robot paths are illustrated with traces

Our planner is fast enough to replan and adapt its path along the execution. If a grid modifying change occurs, like a change in human state or position, or appearance of a dynamic obstacle, the fast computation times allow us online replanning and a smooth switch to the new path. Table I shows the processing cpu-times of the planner for the examples above for 3 different grid resolutions.

TABLE I

Computation times of the paths in figure 8

Grid Resolution	Figure 8-a	Figure 8-b	Figure 8-c	Figure 8-d
0.2m	0.07	0.09	0.06	0.15
0.1m	0.21	0.25	0.23	0.50
0.05m	0.44	0.78	0.49	0.20

Fig. 9. A comparison between a classic motion planner and the human-aware navigation planner. Clearly the last one produces more acceptable path by taking into account the safety and visibility of each human in the environment

B. *Real world experiment results*

The system has bees implemented and tested on our Rackham robot. Figure 9 shows the difference between the path calculated by a classic motion planner and the human aware navigation planner. In this scenario, there are two persons in the robot's environment. One of them has his back turned to the robot and thus does not see the robot. The robot goal is to go to the other corner of the room.

A classical motion planner would simply compute a straight line path from one corner to the other and the human collision avoidance would be obtained by obstacle avoidance during execution. In figure 9-a, we see that, as the humans are placed on the robots trajectory, the robot treats the humans as obstacles. Although it successfully avoids them, it passes too close and may cause discomfort to the person who has not seen the robot coming.

In figure 9-b, we can see the solution computed for the same situation by our human-aware navigation planner. The produced path takes into account humans' position and orientation. In case of a change in the environment or in the humans' positions/orientations the planner immediately replans a path during execution. Figure 10 shows the resulting trajectories The robot is represented by a grey circle and humans are represented by green circles with corresponding orientations. Each path is produced by replanning respect humans safety and humans field of view. We can clearly see the comfort and safety difference between a classic planner (figure 9-a) and the human-aware navigation planner (figure 9-b).

More examples and videos illustrating the navigation planner features can be found at http://www.laas.fr/∼easisbot .

VI. Conclusion

In this paper we have presented algorithms, simulation and real world experiment results of a motion planner reasoning

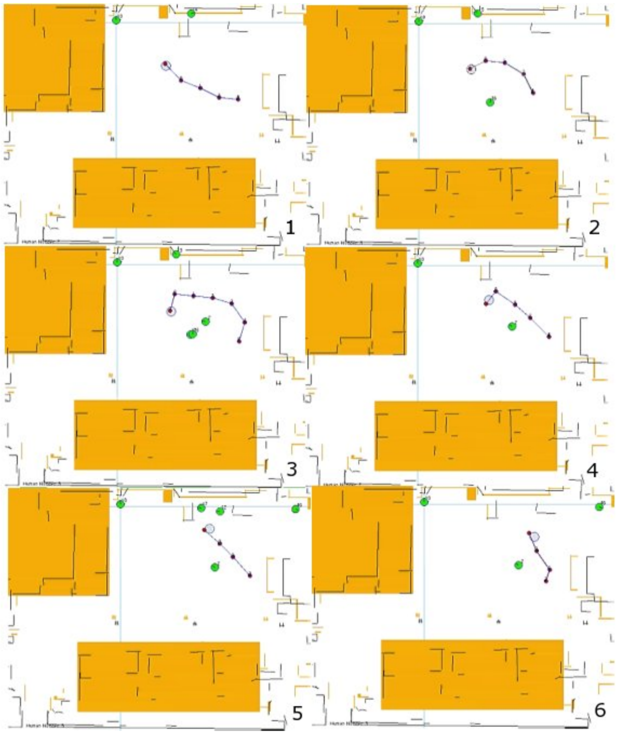

Fig. 10. Replanned path during the execution of a trajectory. The path is then recalculated in case of a change in the environment or humans' states and executed immediately

about humans position, field of view and posture. Our planner produces robot trqjectories significantly different from those produced by classical motion planners. Fast processing times have given the opportunity to replan online and assured a good reactivity.

The robot speed is also a very important aspect to be taken into account in human-robot interaction scenario. It can have a major effect to the comfort and safety of the humans. One of the next steps will be the adaptation of robot speed to produce more friendly motions. Another future work will be on validating our navigation planner. User studies have to be conducted in order to evaluate the effectiveness of the whole system.

We are also planning to extend our work to manipulation scenarios in order to allow the robot to hand objects to a human while respecting safety and social constraints.

ACKNOWLEDGMENT

The work described in this paper was partially conducted within the EU Integrated Project COGNIRON (”The Cognitive Companion”) and funded by the European Commission Division FP6-IST Future and Emerging Technologies under Contract FP6-002020.

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