

Spatial Reasoning for Human Robot Interaction

Emrah Akin Sisbot, Luis F. Marin and Rachid Alami

Abstract—Robots’ interaction with humans raises new issues for geometrical reasoning where the humans must be taken explicitly into account. We claim that a human-aware motion system must not only elaborate safe robot motions, but also synthesize good, socially acceptable and legible movement.

This paper focuses on a manipulation planner and a placement mechanism that take explicitly into account its human partners by reasoning about their accessibility, their vision field and their preferences. 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 or in synergy with humans.

I. INTRODUCTION

One key ability for robots that have to interact or to collaborate in close vicinity is spatial reasoning.

Indeed, besides "standard" needs for obstacle-free motion planning and object manipulation (grasping, placement...), there is a need to take explicitly into account the human.

We have previously reported on the development of a so-called human-aware navigation planner [4]. The planner was able to take into account human preferences not only in terms of human-robot relative distance but also in terms of relative placement and acceptable approach motion.

We extend here our framework by considering a number of spatial reasoning issues that we consider necessary to perform collaborative human-robot manipulation and more generally to allow the robot to interact in a human-friendly manner.

Let’s take for instance a simple task where a robot has to approach and to hand an object to a person. We would like the robot to plan where it has to place itself and how it has to perform its motion by taking into account the human posture (sitting, standing), the local environment (furniture, obstacles to motion and visibility) in order not only to reach the hand of the person but to do it in a legible way while monitoring the attention of the person to its behaviour.

More generally there is a need to develop reasoning skills on the human (and the robot) perception and manipulation abilities in order to answer a number of questions such as:

- Can the human see that object ? Can the human see the a given part of the robot ? (perspective) Can human reach an object ? (grasp)
- Where to place the robot in order to be able to see simultaneously an object, the hand and the face of a human partner ?

We present here below a set of ingredients that we have devised in order to build incrementally computation models

for human-robot spatial interaction. The application context is fetch-an-carry tasks in order to serve humans in their presence in coherence with a general robot architecture for human-robot interaction[5].

In Section II, we briefly discuss related work. Sections III and IV, we will explain the innerworkings of the planner and placement solver. Finally in section V, we will illustrate these two systems in a simple scenario.

II. RELATED WORK

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

The biggest concern in environments where robots and humans cohabit is the safety. In industrial environment safety concerns are reduced to minimum by isolating the robots and avoiding people to get near them. This isolation prevents most of the risks and minimises the possibility of an accident that can hurt the material and most importantly that can hurt humans. The major fallback of this safety precaution is that it avoids the close interaction between the machine and the human which it is the major interest of HRI field. As we cannot isolate the robot, the notion of safety gains a very critical role and must be studied in detail with all of its aspects [6].

In order to maintain safety and comfort of the human, the robot must not only reason for itself but also reason on other perspectives. Reasoning about how the robot has to place itself in the environment according to different perspectives introduces a notion called "mental rotation". Akerman [23] explains mental rotation as a concept of estimation of human’s relative position in the world by 3D mental tracking of transformation of an object or place.

Mental rotation is also applied (in a certain way) in robotics, like simulators for mobile robots [24], where the simulation environment provides a fake sensing in order have the robot program interact with. Next best view problems are also applications where a type of mental rotation is calculated to obtain a position to make 3D models of objects [26] or to obtain an automatic surface acquisition [27].

From psychological studies [21] [22] of human to human interaction, we learn the fact of being in other person point of view and taking his perspective eases communication and it helps to get rich interactions. Perspective taking has began to be used recently in HRI research field. Richarz et al.[25] use an area in front of human in order to obtain pointing places so that the robot can interact with him. Trafton et al. show in [28] and [29] a robot system that uses geometrical reasoning in perspective taking to take

decisions about human reasoning, they probe how human-human interaction helps if it is applied to human-robot interaction. [31] and [30] also work in perspective taking in a 3D simulated environment in order to help robot with the learning process.

Although the correct placement of the robot relative to human is very important, it is not enough to maintain safety and comfort for manipulation scenarios where the robot should move its structures very close to the human.

Besides new designs [3][9] that will ensure safety at the physical level, in software level most of the approaches are based on the minimization of an index related to various safety metrics. As an example of these methods, we can cite Kulic[7] and Ikuta[8] where the level of danger is estimated and minimized based on factors influencing the impact force during a human-robot collision, such as the effective robot inertia, the relative velocity and the distance between the robot and the human.

With these approaches physical safety is assured by avoiding collisions with human and by minimizing the intensity of a possible impact in case of a collision.

Although several authors propose motion planning or reactive schemes considering humans, there is no contribution that tackles globally the problem as we propose to do.

III. HUMAN AWARE MANIPULATION PLANNER

User studies with humans and robots [16][1][20] provide a number of properties and non written rules/protocols [15] 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.

Our approach is based on separating the whole problem of manipulation, e.g a robot giving an object to the human, into 3 stages. Each of these stages will produce the corresponding result and pass it to the next stage:

- Spatial coordinates of the point where the object will be handled to the human,
- The path that the object will follow from its resting position to human hand as it was a free flying object,
- The path of the whole body of the robot along with its posture for manipulation.

All these items must be calculated by taking explicitly into account the human partner to maintain his safety and his comfort. Not only the kinematic structure of the human, but also his vision field, his accessibility, his preferences and his state must be reasoned in the planning loop in order to have a safe and comfortable interaction.

In each steps of the items stated above, the planner ensures human's safety by avoiding any possible collision between the robot and the human.

A. Finding Object Exchange Coordinates

One of the key points in the manipulation planning is to decide where robot, human and the object meet. In classical motion planners, this decision is made implicitly

by only reasoning about robot's and the object's structure. The absence of human is compensated by letting him adapt himself to the robot's motion, thus making the duty of the human more important and the motions of the robot less predictable.

We present 3 properties of the interaction that will help us to find safe and comfortable coordinates of the object where the robot will handle it to the human. Each property is represented by a cost function $f(x, y, z, C_H, Pref_H)$ for spatial coordinates (x, y, z) , a given human configuration C_H and his preferences $Pref_H$ when handling an object (e.g left/right handiness, sitting/standing, etc.). This function calculates the cost of a given point around the human by taking into account his preferences, his accessibility his vision field and his state.

We will now explain the structure of the "Safety" , "Visibility" and "Arm comfort" properties ,their attached functions and how we use them to find the object exchange coordinate.

Safety: The first of the 3 properties is the "safety". The notion of safety is the absolute need of any human-robot interaction scenario. It gains a higher importance in manipulation scenario where the robot places itself close proximity of the human.

As farther the robot is from human, safer the interaction is, the safety cost function $f_{safety}(x, y, z, C_H, Pref_H)$ is a decreasing function according to the distance between the human H and object coordinates (x, y, z) . The $Pref_H$ contains preferences of the function behavior according to human states like sitting,standing, etc.

The cost of each coordinate (x, y, z) around the human is inversely proportional to the distance to the human. When the distance between the human and a point $D(H, (x_i, y_j, z_k))$ is greater than the distance of another point $D(H, (x_l, y_m, z_n))$, we have $f(x_i, y_j, z_k) > f(x_l, y_m, z_n)$. Since the safety concerns loose their importance when the object exchange point is far away from the human, once it is farther from some maximal distance, it becomes null.

The values of the Safety function is illustrated in figure 1 with 0.05m between neighboring points. It's clear that from a safety point of view, the farther the object is placed, the farther the robot will be placed, so the more safe will the interaction become.

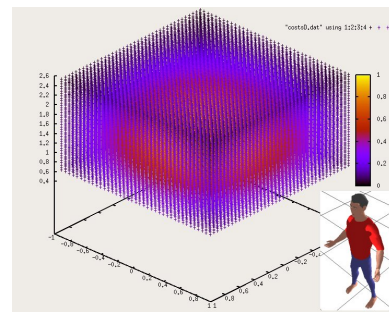


Fig. 1. The costs of Safety function mapped around the human at 0.05m resolution. This function returns decreasing costs

Visibility: The visibility of the object is an important property of HR manipulation scenarios. The robot have to choose a place for the object where it will be as visible as possible to the human. We represent this property with a visibility cost function $f_{visibility}(x, y, z, C_H, Pref_H)$. Alone this function represents the effort required by the human head and body to get the object in his field of view. With a given eye motion tolerance, a point (x, y, z) that has a minimum cost is situated in the cone situated directly in front of human's gaze direction. For this property, the $Pref_H$ can contain the eye tolerance for human as well as any preferences or disabilities that he can have.

The values of the Visibility function is shown in figure 2 with 0.05m between neighboring points. We can see that points at direction of human's gaze have lower costs. The more the human has to turn his head to see a point, the higher is the cost.

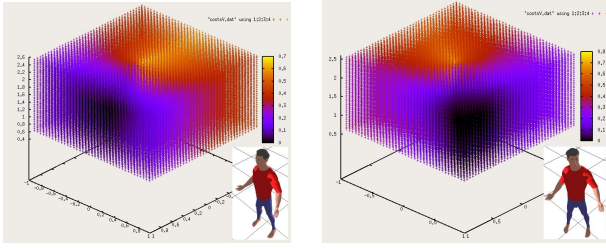


Fig. 2. The costs of Visibility function distributed around the human with 0.05m resolution. Points that are difficult to see have higher costs. The visibility function depends also to the direction of human's gaze.

Arm Comfort: The last property of the placement of the object is human's arm configuration when he tries to reach to the object. The human arm should be in a comfortable configuration when reaching the object. This property also is reflected by a cost function $f_{armComfort}(x, y, z, C_H, Pref_H)$ which returns costs representing how comfortable for human arm to reach at a given point (x, y, z) . At this case $Pref_H$ value can contain left/right handiness as well as an other preference of which arm the human prefers.

The inverse kinematics of human arm is solved by IKAN[12] algorithm which return a comfortable configuration among other possible ones because of the redundancy of the arm structure.

For a given arm configuration, the costs of Arm Comfort property is calculated by

$$f_{armComfort}(x, y, z, C_H, Pref_H) = \min(f_{LeftArmComfort}(x, y, z, C_H) + P_{left}, f_{RightArmComfort}(x, y, z, C_H) + P_{right})$$

$$f_{Left/Right ArmComfort} = \beta_1 f_{displacement} + \beta_2 f_{potential}$$

$$f_{displacement} = \sum_{j=1}^n (\theta_{rest,j} - \theta_j)^2$$

where θ_j is a joint angle of the j th joint, n is the number of arm joints, θ_{rest} is angle of the joint in the rest position

and P_{left}, P_{right} are the penalties coming from left/right handiness.

$$f_{potential} = \sum_{j=1}^m m_j g r_j$$

where m_j is the mass of the j th mass, m is the number of arm masses and r_j is the coordinates of the center of gravity of j th mass in environment frame.

As a result minimization of this function will find point where the combination of the joint displacement and arm's potential energy is minimum which is an important property for arm comfort[13][14][19].

The Arm Comfort functions for left and right arms are illustrated in figure 3-a and b. Note that only the accessible and more comfortable point are shown in these figures. All other points are evaluated as not comfortable and their costs are highest.

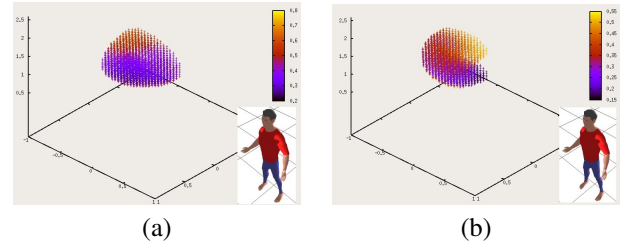


Fig. 3. Arm Comfort function for a left handed person. Eventough the shape of left (a) and right (b) arm functions is the same, a penalty is applied to the right arm thus increasing its costs. Note that only the accessible and more comfortable point are shown. Other points around the human have highest cost.

To find the object exchange point, we can search for a point that has the lowest costs for all these 3 properties. Such a point will be safe, visible and comfortable to reach.

To find this ideal point, $ObjectCoord$, we combine these 3 cost functions to obtain one single function $f_{ObjectCoord}$ that we minimize

$$f_{ObjectCoord}(x, y, z, C_H, Pref_H) = w_1 f_{safety}(x, y, z, C_H, Pref_H) + w_2 f_{visibility}(x, y, z, C_H, Pref_H) + w_3 f_{armComfort}(x, y, z, C_H, Pref_H)$$

and find

$$ObjectCoord = \min_{x,y,z} (f_{ObjectCoord}(x, y, z, C_H, Pref_H))$$

which is the point that satisfies the most these properties. This point will be goal point of the robot to carry the object. Figure-4 shows coordinates of a found point for a bottle that is calculated by taking into account 3 properties stated above.

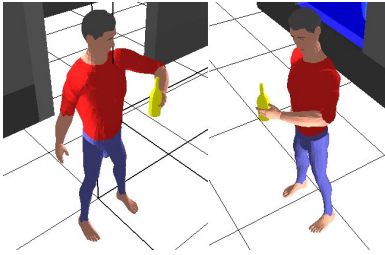


Fig. 4. Object's placement is found according to the minimization of safety, visibility and arm comfort functions.

B. Finding Object Path

As we found where the robot must place the object in the previous stage, we now have to find the path that the object will take from its initial position to this final position. To find this path we use a 3D grid based approach which we build around the human.

This grid contains a set of cells with various costs derived from the relative configuration of the human, his state, his capabilities and preferences. A grid G is defined as:

$$G = (M_{n,p,r}, H_i, f_{path})$$

where $M_{n,p,r}$ is a 3D matrix containing $n \times p \times r$ cells represented by $a_{i,j,k}$, the cost of the coordinate (i, j, k) in the grid, H_i is the human to which the grid is attached. The function f_{path} calculates the value of each cell according to its coordinate and the type of the criterion that the grid represents.

A human H_i is modeled by $H_i = (St, State_1 \dots State_n)$ where St is the structure and kinematics of the human and $State_i$ is a human state defined by a number of cost parameters. A state is defined by:

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

where $Name$ is the name of a posture state (e.g. $Name = SITTING, STANDING$), $Conf$ is the human's configuration in that state (if applicable) and $Param$ represents the data and preferences needed to compute cost according to that state.

We use a combination of safety and visibility functions for the f_{path} cell cost function. With the use of these two, a path that minimizes cell costs will be safe and visible to the human:

$$f_{path}(x, y, z) = \alpha_1 f_{safety}(x, y, z) + \alpha_2 f_{visibility}(x, y, z)$$

After the construction of this 3D grid, an A* search is conducted from the initial object position to the $ExchangeCoord$ that minimizes the sum of f_{path} of cells all along the path.

This path, illustrated in figure 5, will be the path that the object and the robot's hand will follow.

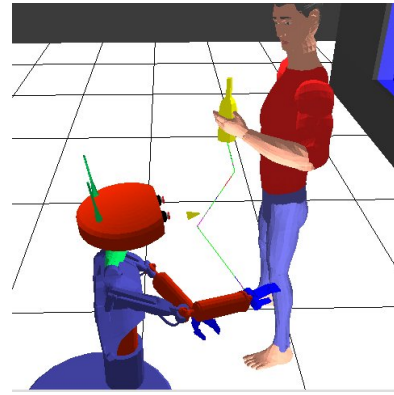


Fig. 5. Object's motion is planned as it is a freeflying object. This path is the result of a A* search that minimizes safety and visibility properties' functions all along object's motion.

C. Finding Robot Path

Eventhough we found a path for the object (and robot's hand) to follow, it is not enough to produce a acceptable robot motion in HRI context where the motion should be safe, comfortable and predictable. With this motion the robot must make clear of its intention.

The third and final stage of planning consists of finding a path for the robot that will follow object's motion. The object's motion is computed as it was a freeflying object. But in reality it is the robot who holds the object and who will make the object follow it's path.

To adapt the robot structure to the object's motion, we use Generalized Inverse Kinematics [18][17] algorithm. Although this method is computationally expensive, it has certain advantages:

- **Not dependent to the robot structure:** The Generalized Inverse kinematics method only needs a Jacobian matrix easily obtainable from robot's structure. This property make this method easily portable from one robot to an other.
- **Multiple tasks with priorities:** This method allows us to define additional tasks next to the main task. Therefore the robot not only accomplish its task but also can take into account additional tasks during its motion.
- **Customizable according to various criteria:** Various costs, potentials or postures can be used as an additional criterion to the main task.

We use two tasks with different priorities to find an acceptable posture. The first task with higher priority contains the joints that affects the hand of the robot. This task aims to reach to a given point in object's path. The second task controls robot's gaze direction (camera joints) containing all the joints that affects to robot's head.

The general formulation[17] of Generalized Inverse Kinematics with two tasks can be expressed as:

$$\Delta\theta = J_1^{+\lambda_1} \Delta x_1 + [J_2 P_{N(J_1)}]^{+\lambda_2} (\Delta x_2 - J_2 (J_1^{+\lambda_1} \Delta x_1))$$

where J_1 and J_2 are the Jacobian matrixes of two tasks, $+\lambda_1$ is the singularity robust pseudoinverse operator, Δx_1 and

Δx_2 are goal points for two tasks, and finally $\Delta\theta$ represents the resulting configuration of the robot.

With this method, the robot's posture is adapted to object's motion. Eventough the first task (motion of robot's arm) is enough for the manipulation scenario, the supplementry task of moving the head helps the robot express its intention clearly, thus makes the interaction more comfortable.

At the end of this stage we obtain a path, shown in figure 6 for the robot which is safe, visible and comfortable to the human as we took into account his accessibility, field of view and his preferences.

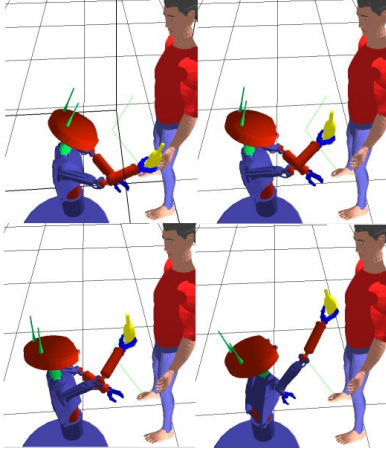


Fig. 6. Calculated path for this manipulation scenario. The robots looks to the object during this motion, with this behavior it shows its intention to its human partner.

IV. PERSPECTIVE PLACEMENT

In order to interact with human, the robot has to find how to place itself in a configuration where it can have an “eye contact” with the human. This constraint helps to restrain search space to find a destination point and it can be divided in two phases; finding positions that belongs to human attentional field of view and validating these positions in order to have a visual contact and prevent big visual obstructions from blocking robot perception.

The area in human attentional field of view, called “Interaction Area”, is defined as the zone in front of the person limited by an angle $\alpha_{view} \mid 0^\circ \geq \alpha_{view} \leq 180^\circ$ and by a radius $Rad_{min} < Rad < Rad_{max}$ depending on the characteristics of the interaction, robot sensor capabilities and human preferences.

In figure 7-a, the Interaction Area is represented by a green arc and human's field of view out of the Interaction Area is shown red color. Once interaction area is defined, random points are generated and selected based on following properties:

- **Collision Free:** robot in this position must not have collision with objects in the environment.
- **Sensor Oriented:** one or more sensors must be in direction to the objective element (a human in this case) in order to perceive it.

- **Without Visual Obstructions:** in sensor's acquisition, human has to be present in a user demanded proportion.

To determine what is perceived by a camera, we use 2D perspective projection of the 3D environment. This is acquired from sensor's relative position in the space to the robot global desired position.

The obtained projection is a 2D vector $MatP$ where the value of a position (x, y) represents one point in the projection image of objects in camera's field of view. In the figure 7 2D projection is illustrated.

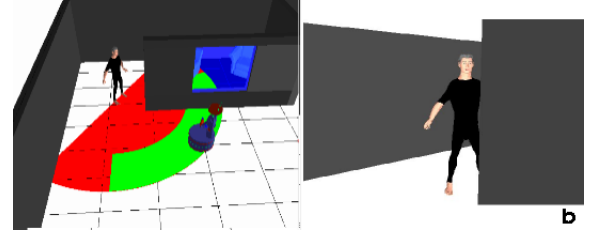


Fig. 7. a) Robot positioned in the interaction area (Green). b) Robot's computed perception (2D projection)

We define “relative projection” Pr as the quantity of an element of the environment represented in $MatP$, obtained by:

$$Pr(Ob) = \sum MatP(x, y) \mid (x, y) \in Ob$$

The relative projection of an element that is not projected Pr_{hidden} can be obtained as:

$$Pr_{hidden}(Ob) = Pr_{desired}(Ob) - Pr_{visible}(Ob)$$

where $Pr_{visible}$ is the relative projection that considers visual obstructions (only visible projection). On the other hand, $Pr_{desired}$ is relative projection obtained without considering objects in the environment (as it should look without visual obstacles). In figure 8, we can observe the difference between desired and visible relative projections.

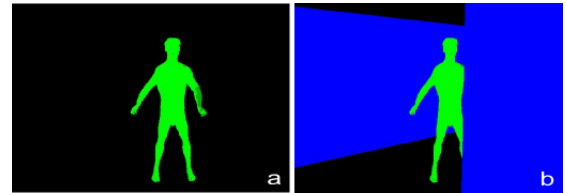


Fig. 8. Relative projections in green the objective, in blue and black elements and/or environment. a) Desired relative projection b) Visible relative projection (what actually the robot perceives)

Objective's Ob visibility percentage, $Watch$ is determined by:

$$Watch(Ob) = Pr_{visible}(Ob) / Pr_{desired}(Ob)$$

Finally, as a method of selection for a perspective placement:

$$Watch(Ob) \geq \mu$$

where μ is a threshold that corresponds to a desired percentage.

V. AN EXAMPLE

In this section we will illustrate the Human Aware Manipulation Planner and Perspective Placement mechanism in a simple scenario.

Let's take the environment illustrated in figure 9 containing a human and a robot. The human is in a room waiting for the robot to carry his bottle. The robot has the bottle at its hand and all it has to do is to carry and give it to human.

To find a correct placement for manipulation, the robot must see the state and the place of the human. So the first reasoning should be about where to place itself to see the human. In this example, there are 2 possible ways for the robot to see human: one by looking through window and one by entering to the room. So the Perspective Placement mechanism finds a collision free configuration in front of the window with human in the field of view. In figure 9, we can see this configuration with the path to reach it planned by our Human Aware Navigation Planner[4].

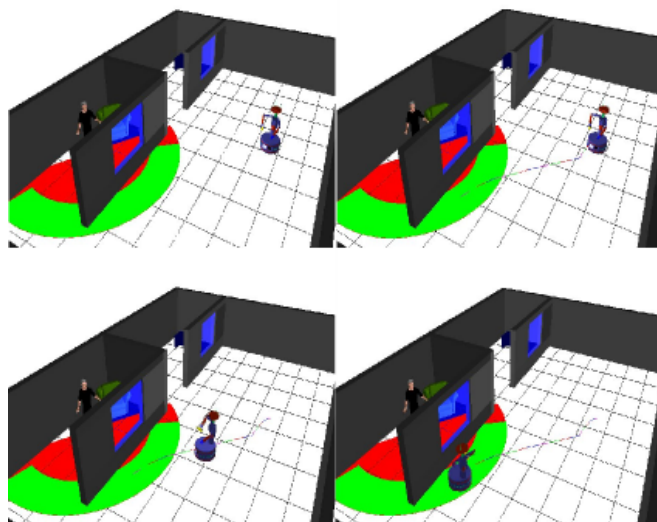


Fig. 9. Perspective Placement mechanism finds a collision free configuration by the window that allows to see the human for further manipulation. The robots then plans a path towards this target configuration.

After reaching its goal, the robot sees where the human is and finds a good start configuration for the Human Aware Manipulation Planner. Perspective Placement mechanism then redemands to the path planner to produce a collision free, human aware path to reach this new configuration (figure 10).

After reaching its destination, the robot uses Human Aware Manipulation Planner to plan its final body motion (figure 11). The produced path is collision free, but also it is comfortable for the human gaze direction, his arm comfort and his safety are taken into account in the planning loop.

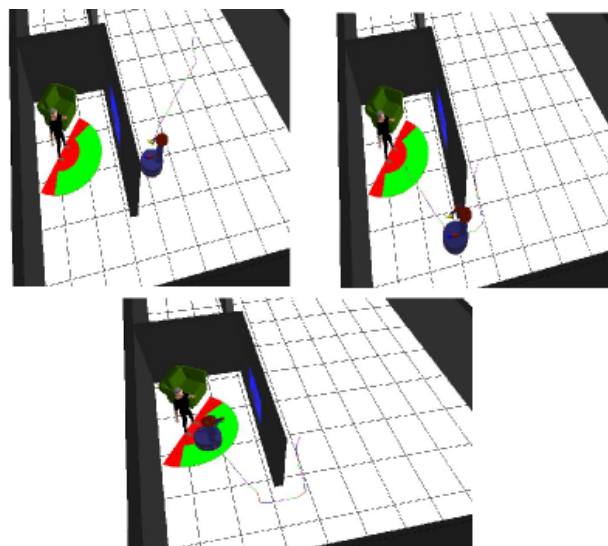


Fig. 10. After seeing where the human is, Perspective Placement mechanism finds another configuration that will be suitable for manipulation.

VI. CONCLUSION

In this paper we have presented two systems that take into account explicitly human presence for the spatial reasoning for robot activities. The first system we described, named Human Aware Manipulation Planner, synthesize not only safe but also comfortable motions to humans by reasoning on their kinematic structure, their visibility and their preferences. We then described Perspective Placement Mechanism which finds a collision free and visible configuration to link the manipulation and navigation planners.

The next step will be to integrate Human Aware Manipulation Planner in a real robot and conduct studies with subjects to evaluate the effectiveness our approach. In parallel with this integration, another step will be to take into account human motions and dynamics in the planning loop and a replanning schema to synthesize more socially acceptable robot motions.

Using spatial reasoning for deducing some possible positions of objects, like surfaces were the objects could be placed or hidden geometrical volumes formed by non visible spaces from objects and also of humans will result a better task oriented interactions.

Also we plan to integrate these systems along with the Human Aware Navigation Planner to obtain a general solver of Human Aware Motion planning problems which will produce friendly and socially acceptable paths with fluid passages between navigation and manipulation.

VII. ACKNOWLEDGMENTS

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.

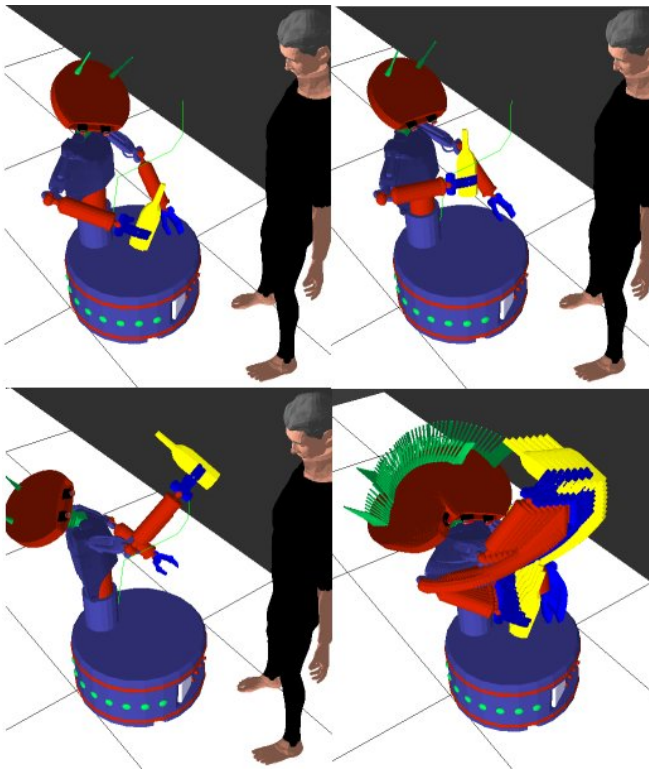


Fig. 11. Path planned by Human Aware Manipulation Planner. The object placement and robot posture are safe, comfortable and also shows clearly the robot's intention.

REFERENCES

- [1] K. Dautenhahn, M. Walters, S. Woods, K. L. Koay, C. Nehaniv, E. Sisbot, R. Alami, T. Siméon, "How may I serve you?, A Robot Companion Approaching a Seated Person in a Helping Context", Conference on Human-Robot Interaction(HRI06), Salt Lake City, Utah, USA,
- [2] K. Madhava Krishna, Rachid Alami and T. Siméon, "Safe proactive plans and their execution," Robotics and Autonomous Systems, Vol.54, N3, pp.244-255, Mars 2006
- [3] A. Bicchi and G. Tonietti, "Fast and Soft Arm Tactics: Dealing with the Safety-Performance Trade-Off in Robot Arms Design and Control", IEEE Robotics and Automation Magazine, IEEE Volume 11, Issue 2, June 2004 Page(s):22 - 33
- [4] E. A. Sisbot, L. F. Marin, R. Alami and T. Siméon, "A mobile robot that performs human acceptable motion, Proc in (IEEE/RSJ) IROS,2006.
- [5] R. Alami, R. Chatila, A. Clodic, S. Fleury, M. Herrb, V. Montreuil, E. A. Sisbot, "Towards Human-Aware Cognitive Robots", The Fifth International Cognitive Robotics Workshop (The AAAI-06 Workshop on Cognitive Robotics), 2006.
- [6] R. Alami, A. Albu-Schaeffer, A. Bicchi, R. Bischoff, R. Chatila, A. De Luca, A. De Santis, G. Giralt, J. Guiochet, G. Hirzinger, F. Ingrand, V. Lippello, R. Mattone, D. Powell, S. Sen, B. Siciliano, G. Tonietti and L. Villani, "Safe and Dependable Physical Human-Robot Interaction in Anthropomorphic Domains: State of the Art and Challenges", Proc. IROS'06 Workshop on pHRI - Physical Human-Robot Interaction in Anthropomorphic Domains, 2006.
- [7] D. Kulic and E. Croft, "Pre-collision safety strategies for human-robot interaction", Autonomous Robots, Volume 22, No 2, 2007.
- [8] K. Ikuta, H. Ishii and M. Nokata, "Safety evaluation methods of design and control for human-care robots", The International Journal of Robotics Research, Vol 22, No. 5, 2003, pp. 281-297.
- [9] M. Zinn, O. Khatib, B. Roth, J.K. Salisbury, *Playing it safe [human-friendly robots]*, Robotics & Automation Magazine, IEEE Volume 11, Issue 2, June 2004 Page(s):12 - 21.
- [10] T. Siméon, JP. Laumond, F. Lamiraux, *Move3D: a generic platform for motion planning*, 4th International Symposium on Assembly and Task Planning, Japan,2001.
- [11] S. Nonaka, K. Inoue, T. Arai and Y. Mae, *Evaluation of human sense of security for coexisting robots using virtual reality*, in. Proc IEEE ICRA, New Orleans, USA, 2004.
- [12] D. Tolani, A. Goswami and N. Badler, *Real-time inverse kinematics techniques for anthropomorphic limbs*, Graphical Models and Image Processing, Volume 62, Issue 5, Pages: 353-388,2000.
- [13] R. T. Marler, J. Yang, J. S. Arora, and K. Abdel-Malek, *Study of Bi-Criterion Upper Body Posture Prediction using Pareto Optimal Sets*, IASTED International Conference on Modeling, Simulation, and Optimization, Oranjestad, Aruba, Canada.
- [14] M. Katayama, H. Hasuura, *Optimization principle determines human arm postures and "comfort"*, SICE 2003 Annual Conference, Volume: 1, Pages: 1000-1005, 2003.
- [15] E. T. Hall, "The Hidden Dimension", Doubleday, Garden City, N.Y., 1966.
- [16] K.L. Koay, E. A. Sisbot, D. A. Syrdal, M.L. Walters, K. Dautenhahn and R. Alami, *Exploratory Study of a Robot Approaching a Person in the Context of Handling Over an Object*, AAAI 2007 Spring Symposia (AAAI 07), Palo Alto, California, USA.
- [17] P. Baerlocher and R. Boulic, *An inverse kinematics architecture enforcing an arbitrary number of strict priority levels*, The Visual Computer, Volume: 20, Pages: 402-417, 2004.
- [18] K. Yamane, Y. Nakamura, *Natural motion animation through constraining and deconstraining at will*, Visualization and Computer Graphics, IEEE Transactions, Volume 9, Issue 3, Pages: 352 - 360, 2003.
- [19] K. Abdel-Malek, Z. Mi, J. Yang., and K. Nebel, *Optimization-based layout design*, ABBI 2005, Vol. 2, No. 3-4, pp. 187-196, 2005.
- [20] K. Sakata, T. Takubo, K. Inoue, S. Nonaka, Y. Mae, T. Arai, *Psychological evaluation on shape and motions of real humanoid robot ROMAN 2004*.
- [21] B. Tversky, P. Lee, and S. Main Waring, "Why do Speakers Mix perspectives", *Spatial Cogn. Computat.*, vol. 1, 1999, pp 312-399.
- [22] P. U. Lee and B. Tversky, "Costs of Switching Perspectives in Route and Survey Description", *Proceedings of the twenty-third Annual Conference of the Cognitive Science Society*, Edinburgh, Scotland 2001.
- [23] E. K. Ackerman, "Perspective-Taking and Object Construction: Two keys to learning", *Constructionism in Practice: Designing, Thinking, and Learning in a Digital World*, Mahwah, New Jersey, 1996.
- [24] J. Faust, C. Simon, W. D. Smart, "A Video Game-based Mobile Robot Simulation Environment", *Proc. of IEEE International Conf. on Intelligent Robots and Systems (IROS'06)*, 2006, Beijing, China.
- [25] J. Richarz, C. Martin, A. Scheidig, H. M. Gross, "There You Go! - Estimating Pointing Gestures In Monocular Images For Mobile Robot Instruction", *Robot and Human Interactive Communication ROMAN 2006.*, Univ. of Hertfordshire, Hatfield, UK. .
- [26] A. Bottino and A. Laurentini, "What's NEXT? An interactive next best view approach", *Journ. of Pattern Recognition*, 2006, pages 126-132.
- [27] R. Pito, "A Solution to the Next Best View Problem for Automated Surface Acquisition", *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 1999.
- [28] J. G. Trafton, N. L. Cassimatis, M. D. Bugajska, D. P. Brock, F. Mintz, A. C. Schultz, "Enabling effective human-robot interaction using perspective-taking in robots", *IEEE Transactions on Systems, Man, and Cybernetics, Part A*, 2005, 460-470.
- [29] J.G. Trafton, A. C. Schultz, M. Bugajska, F. Mintz, "Perspective-taking with robots: experiments and models", *Robot and Human Interactive Communication ROMAN 2005*, Page(s): 580 - 584.
- [30] C. Breazeal, M. Berlin, A. Brooks, J. Gray, A. L. Thomaz, "Using perspective taking to learn from ambiguous demonstrations", *Robotics and Autonomous Systems*, 2006, pgs: 385-393.
- [31] M. Berlin, J. Gray, A. L. Thomaz, C. Breazeal, "Perspective Taking: An Organizing Principle for Learning in Human-Robot Interaction.", AAAI, 2006, Boston, Mt.