Being safe around the robot

Benjamin Vadant, Mamoun Gharbi, Rachid Alami, Thierry Simeon

Being safe around the robot

Benjamin Vadant, Mamoun Gharbi, Rachid Alami, Thierry Siméon– surname.name@laas.fr
CNRS, LAAS, 7 avenue du Colonel Roche, F-31400 Toulouse, France
Université de Toulouse, LAAS, F-31400 Toulouse, France

***Abstract*—This paper is about cost based approaches for motion planning in HRI setups. A general approach (TRRT) developed at LAAS is presented as well as some previous cost based work on human aware motion generation.**

We also introduce a way to handle dangerous object using this approach: sharp edges and other dangerous object parts should never be directly exposed to the human. A cost function is computed to tackle this issue. Finally we are presenting first results about a new extension of TRRT which is used in HRI motion generation.

I. Introduction

Robots are coming into our houses. They appeared in factories where safety was satisfied by physically separating them from humans (fig. 1). In the near future, in our day to day environment, robots are going to interact with us, thus being in close proximity of humans. This raises concerns about the safety and the comfort of humans around robots. Indeed, the difficulty is not just being able to move safely around humans but also to generate legible behaviors complying with social rules.

In order to facilitate the introduction of robots into our homes, robots have to be safe to be around and they should induce a safety feeling to humans around them. This feeling, often assimilated with the expression of comfort, is the key for a good human-robot interaction. Plus, the novelty is always bad for humans. So, the randomness of the trajectories generated by probabilistic methods while allowing to generate safe trajectories quickly, makes them unacceptable in numerous cases. This unpredictable motion may surprise the humans and making him feel uncomfortable. In addition to that, a surprise may induce the human to have an unpredictable reaction that can be dangerous for himself (e.g. stepping back and colliding with a furniture).

Multiple approaches to the social motion generation exist but here, we focus on a generic approach based on cost methods.
Although creating robots that co-exist with us requires working on navigation and manipulation, this paper will focus on the issue of handling objects around and with the human. Section II clearly states the limit of the problem we chose to address here. Section III discusses related work. Section IV is a reminder on how the TRRT algorithm is working. Finally, we present our ongoing work on the matter in Section V.

II. Problem Statement

The problem we address in this paper is how to make a human feel comfortable around a manipulation robot.

Fig. 1. Factory robots working in a secluded areas

Even though this field is linked to subjects such as navigation in human vicinity(see the survey of Kruse & al. [11] for recent results), or human safety near a robot, we are not addressing those two fields here, our interest is mainly the manipulation part and the comfort that it should bring.

As said in the previous section, one of the keys to a good Human-Robot Interaction (HRI) is the psychological safety and the comfort of the humans. In this view, a robot needs to follow a set of unwritten rules called ”the social rules”. Those rules differ from one place to another, but there are still some common bases that we try to approach in our work. Here are some examples:

- **Motion speed:** The trajectory execution speed should be neither too fast nor too slow, both would induce unwanted side effects.
- **Motion Smoothness:** Blows and discontinuities on trajectories should be avoided.
- **Human motion awareness:** The robot should not put the human in an uncomfortable physical position as much as possible (e.g. weird handovers).
- **Distances:** The robot should respect the proxemics theory [7], by not getting too close to the human with any part of the robot.
- **Human gaze:** The human gaze and field of view should be taken into account, hidden motions can be disturbing.
- **Possible objects hazard:** sharp objects can be dangerous, and should be handled with extra care around the human.

Our approach consists in using cost functions to evaluate a set of observable constraints linked to these rules, and to choose the solution with the smallest cost. In the next section, different approaches are presented including our previous work concerning the costs.

III. Related Work

The problem being stated, different approaches have been used in the literature. First we detail control approaches. In order to have smooth motions around the human the actuator must be controlled with precision and flexibility. In their work, Broquere & al. [2] show a jerk limited controller that communicates with the motion planner to create human aware trajectories. In [4], they bounded both velocity and jerk by a filter at the controller level. Others [3], use a depth sensor and force detectors to slow and/or stop the robot motion if the human gets too close or touches it.

A second approach is the generation of legible trajectories and motions for the robot in a human environment. In [1], the robot learns how the humans are navigating in order to limit its interference in their path. [18] chooses to use the human path: the behavior of the robot seems then more logic to the humans. When the robot is interacting with humans while navigating, it has to maintain a certain distance with the humans defined in the concept of proxemics [6]. For instance, [22] uses this approach with a robot following a person.
For the manipulation tasks, [8] presents a danger index evaluating the trajectory used by the robot. In [16] this index is minimised in order to obtain a safe path. [21] uses a danger index based on the position of the human's head thus integrating the perception of the human to generate safe and "seemingly" safe paths.

Here at LAAS: The main approach developed at LAAS is the use of cost functions that enable the robot to have behaviors that are socially acceptable by the human. In [20], we use the costs to find places where the robot should avoid to navigate: behind obstacles for example. In addition to that, as seen in the proxemics theory [7], the robot should avoid entering the personal space of a human (which size varies depending on posture). In the particular case of an interaction meant with a human, the robot should be visible as much as possible while approaching the human given his field of view and obstacles. This approach has been tested in [10] where Koay et al. show, in addition to confirm the cost based approach, that humans prefer the robot to approach them from the sides when sitting.

Concerning manipulation planning, we also use costmaps integrating human field of view and robot-human distances in order to compute comfortable motions. This approach is presented in [19]. A part of this paper addresses another problem which is choosing target position by considering the human comfort. As in [15], this choice results on a cost computation of the human comfort, based on human displacement from initial position and members potential energy. The same costs, and others, concerning the human's will to move, have been used in [14] to predict human navigation motions and a good handover position.

On a more algorithmic level, Jaillet & al. [9] presents a probabilistic method using RRT applied to costmaps named TRRT. In [13], they propose an application of this TRRT method to HRI problems like handing over objects in human vicinity, using field of view and distances to compute the needed costmap. The next section will detail the TRRT algorithm which can be considered as a general approach to HRI problems.

IV. The TRRT algorithm

The TRRT method [9] uses the exploratory strength of RRT algorithms to allow a fast search of the environment and a cost function in order to implement stochastic optimisation methods : thanks to transition tests, potential configurations are selected according to their quality.

In Algorithm 1, we present the pseudocode of this planner. It is quite similar to a RRT-Extend method [12]. The main difference is the presence of the $TransitionTest$ and $MinExpandControl$ functions.

Algorithm 2 shows the pseudocode of the $TransitionTest$ function. This part of the TRRT method has 2 roles : on one hand, accepting and rejecting configurations depending on their cost (lines 2 to 5), and, on the other hand, making sure the algorithm doesn't fall in a local minima by accepting certain increasing values. Plus, it integrates some adaptive tuning of a temperature parameter to control the strength of the filtering. The $TransitionTest$ is the key feature that makes the TRRT method a generic approach to a large number of problems, including the HRI domain.

The $MinExpandControl$ function makes sure that the planner explores correctly the search space. In order to achieve this goal, it tests the distance between q_{near} and q_{rand} against an increment step δ. If the distance is bigger then we accept q_{rand} as it explores the search space far from the current tree. Else, it tests the refinement of the tree. If it has reached the maximum value, q_{rand} is rejected. Else it is accepted.

As a result, by defining adapted cost functions, we can use the same algorithm to navigation, manipulation and mobile-manipulation in the presence of humans.

V. Ongoing work

Our recent work concerns an update of the TRRT algorithm in order to handle a more specific problem: how to handle dangerous objects, with cutting edges for example. We developed a new extension to the TRRT that exposed in this section.

A. Dangerous object handling

This subsection is in-between industrial and HRI settings. Indeed, robots equipped with grippers can handle dangerous objects such as knives, screwdrivers, hatchets... And when the robot is moving such objects, it becomes a real hazard for its surroundings (living people or furnitures). As a result, it is important to minimize the risk of collision and if the collision is unavoidable, to make it as *painless* and *harmless* as possible.

In order to know how to avoid this dangerous situation, it is important to consider what is making those objects dangerous. We used the work of Haddaddin in [5]. This paper shows the consequences of impact on flesh depending on

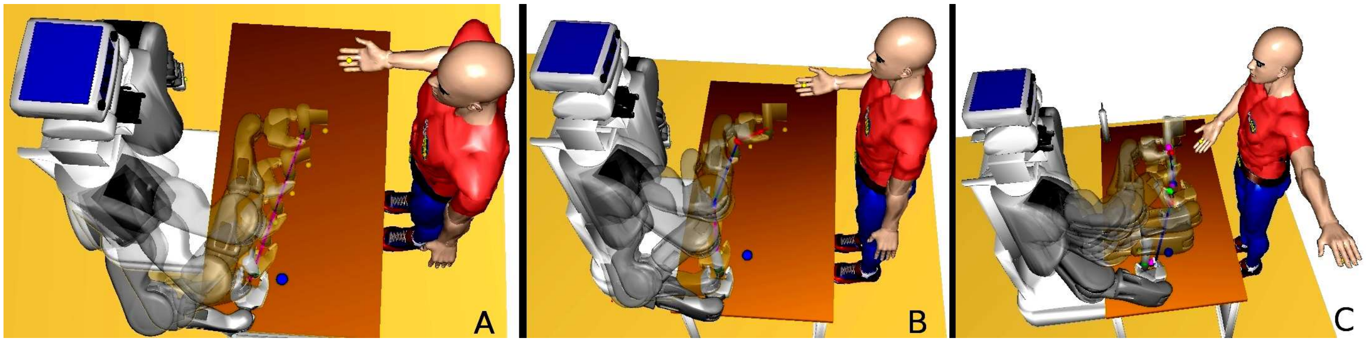

Fig. 2. (A) represents a trajectory generated with only a RRT, the trajectory is straight without any consideration for human safety. (B) is a trajectory generated using TRRT with the cost function in VI.a.1, the trajectory takes into account the proximity of the human and try to approach it at the very end. (C) shows a trajectory generated using TERRT, the object is oriented along the path in such a manner that the dangerous direction is presented toward the human at the end of the motion.

Algorithm 1: Transition-based RRT

Input: the configuration space CS
the cost function $c : CS \rightarrow \mathbb{R}_*^+$
the root q_{init} and the goal q_{goal}
Output: the tree T
begin
  $T \leftarrow InitTree(q_{init})$;
  while ***not*** $StopCondition(T, q_{goal})$ **do**
    $q_{rand} \leftarrow SampleConf(CS)$;
    $q_{near} \leftarrow BestNeighbor(q_{rand}, T)$;
    if ***not*** $Extend(T, q_{rand}, q_{near}, q_{new})$ **then**
      Continue;
      if $TransitionTest(c(q_{near}), c(q_{new}), d_{near-new})$ ***and*** $MinExpandControl(T, q_{near}, q_{rand})$ **then**
        $AddNewNode(T, q_{new})$;
        $AddNewEdge(T, q_{near}, q_{new})$;
end

Algorithm 2: TransitionTest(c_i, c_j, d_{ij})

begin
  if $c_j > c_{max}$ **then**
    return False;
  if $c_j < c_i$ **then**
    return True;
  $p = exp(\frac{-(c_j - c_i)/d_{ij}}{K * T})$;
  if $Rand(0, 1) < p$ **then**
    $T = T/\alpha$;
    $nFail = 0$;
    return True;
  else
    if $nFail > nFail_{max}$ **then**
      $T = T * \alpha$;
      $nFail = 0$;
    else
      $nFail = nFail + 1$;
    return False;
end

the shape, the mass, the velocity and the orientation of the effector. Following the result of this study, we divided the cost function design into the next two parts.

1) The position of the object: In order to avoid collision, one could simply pass by as far as possible from the obstacles. Unfortunately, this distance is not sufficient enough in certain cases. Thus, it is important to focus on the dangerous object the robot is handling. The shape of this object defines dangerous direction(s): if the object has a sharp edge, the dangerous direction will be the normal to this edge. If it has a tip, the dangerous direction will be in the same direction as this tip etc.

We are currently working on a cost function which allows us to minimize the dangerousness of the generated path. It is composed by two parts depending on :

- the distance to collision : humans directly feels it as a ”time to collision” thus it is important that if collision is possible, it should be as far as possible.
- the orientation toward the human : in such case where avoiding the collision is not possible at all, the orientation of the dangerous object is important to increase the comfort of the humans around the robot.

Our current implementation of this cost function is the following :

$$C_q = e^{w_\alpha . \alpha . (1 + \frac{w_d}{d})}$$

With w_α the weight applied to the orientation of the object, w_d the weight applied to the distance to collision. d is the closest distance between the human and the dangerous object and α is the angle between the dangerous direction and the vector between the pair of closest points between the dangerous tip and the human.

In the future, the idea would be to put the same function for obstacles as well and find the right tuning in order to achieve safe motion for the human AND his environment.

This first function can be directly implemented in a TRRT algorithm as it tests configuration.

2) The motion of the object: Sometimes, it is required to move dangerous objects closer to humans or obstacles. It is even possible to have to present to the human the dangerous direction. In that case, a simple TRRT would prefer shorter trajectories in order to diminish the whole cost of the motion. This would result in frightening motions with, for example, direct approach. To avoid this situation, we consider an extension of the TRRT algorithm : TransitionEdgeRRT. This method tests also the evolution of the cost of the edges before and after the old configuration. By adding this $TransitionTestEdge$, we hope to achieve safer transition. The test is a simple transition test but, instead of comparing the cost of the "old" and the "new" configurations we wish to connect, we compare the cost of the possible new edge to the maximum cost of the directly preceding edges.

This new extension allows to join the simplicity of TRRT and motion consideration without having to use kinodynamic planner. To demonstrate the idea, we thought of calculating the angle between the translation vector and the dangerous direction along the path. By maximizing this criterion, we prevent harmful collisions (like stabbing). We concentrated our effort on translation as it is the type of hazard the most present in object handling. We plan to investigate further to integrate rotating motions in the future.

Finally, we want to modulate speed at the controller level in order to take into consideration the importance of velocity in an impact. In figure 2, we present 3 examples in order to compare the trajectories obtained with or without TRRT and TERRT. The first figure shows a trajectory where the human was not taken into consideration. The second one shows that the robot performs a detour in order to reach the close proximity of the human as late as possible. Finally, the TERRT method generates a trajectory where the hachet is directed toward the human only by rotation : during the motion, the dangerous direction and the motion direction are not colinear so the safety of the human is improved.

B. TRRT byproduct : the cost functions

Using the TRRT algorithm forces us to create cost functions to generate eligible motions. These functions can have other applications such as the evaluation of trajectories in a database (like the one used in [17]) in order to sort them. For now, an implemented version of the TRRT is running on the PR2 robot (from Willow Garage), using a cost function based on distances computation and human field of view (FoV). The cost is low when the handled object is far from the human and in his FoV. If the object gets closer or get out from the FoV, the cost raises. Another application of a cost based algorithm is the handover where the choice of position can be handled by costs: the robot needs to be seen from the human, the handled object too, and a respectable distance should separate the human from the robot. The cost are here hand tuned. For each different example, they may need adjustment, one of the next steps is to introduce machine learning processes in order to enhance the cost usage.

VI. Conclusion

In this paper, we presented the main approach we use, here at LAAS, concerning HRI motion generation: our work is focused on cost-based methods. We talked about previous work at the origin of our current approach. In a second part, we showed some of our ongoing work on the matter : the creation of cost functions which can be used to handle safely dangerous objects around humans. Finally, we introduced first results about a new extension of the TRRT method, TransitionEdge RRT. This variant is intended to provide a simple way for considering the direction of the motion in the cost function.

In a future work, as all our methods contain weights, we will need to test the generated behaviour in real life, first with roboticists then with common people. This can only be achieved by putting in place a strict protocol taking into account physical criteria such as those we identify earlier and psychological aspects we will define with specialists.
To improve furthermore our methods, we will in the future take into considerations the incertitude of the perception of the human: current methods can give false positives. We recently began to work on a way to *slow down* the reaction of the robot which shows promising results for now.
Finally, in order to make the generated motions of our algorithms more logical for the human, we plan to investigate further the definition of the search space. By limiting the area around the human the robot can reach, we hope to obtain simpler trajectories.

Acknowledgment

This work has been supported by EU FP7 "SAPHARI" under grant agreement no. ICT-287513.

References

[1] Maren Bennewitz, Wolfram Burgard, Grzegorz Cielniak, and Sebastian Thrun. Learning motion patterns of people for compliant robot motion. *The International Journal of Robotics Research*, 24(1):31–48, 2005.

[2] Xavier Broquere, Daniel Sidobre, and Ignacio Herrera-Aguilar. Soft motion trajectory planner for service manipulator robot. In *Intelligent Robots and Systems, 2008. IROS 2008. IEEE/RSJ International Conference on*, pages 2808–2813. IEEE, 2008.

[3] A. De Luca and F. Flacco. Integrated control for phri: Collision avoidance, detection, reaction and collaboration. In *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS EMBS International Conference on*, pages 288–295, 2012.

[4] Oscar Gerelli and Corrado Guarino Lo Bianco. A discrete-time filter for the on-line generation of trajectories with bounded velocity, acceleration, and jerk. In *Robotics and Automation (ICRA), 2010 IEEE International Conference on*, pages 3989–3994. IEEE, 2010.

[5] Sami Haddadin, Simon Haddadin, Augusto Khoury, Tim Rokahr, Sven Parusel, Rainer Burgkart, Antonio Bicchi, and Alin Albu-Schäffer. On making robots understand safety: Embedding injury knowledge into control. *The International Journal of Robotics Research*, 31(13):1578–1602, 2012.

[6] Edward T Hall, Ray L Birdwhistell, Bernhard Bock, Paul Bohannan, A Richard Diebold Jr, Marshall Durbin, Munro S Edmonson, JL Fischer, Dell Hymes, Solon T Kimball, et al. Proxemics [and comments and replies]. *Current anthropology*, pages 83–108, 1968.

[7] Edward Twitchell Hall and Edward T Hall. *The hidden dimension*. Anchor Books New York, 1969.

[8] Koji Ikuta, Hideki Ishii, and Makoto Nokata. Safety evaluation method of design and control for human-care robots. *The International Journal of Robotics Research*, 22(5):281–297, 2003.

[9] Léonard Jaillet, Juan Cortés, and Thierry Siméon. Sampling-based path planning on configuration-space costmaps. *Robotics, IEEE Transactions on*, 26(4):635–646, 2010.

[10] Kheng Lee Koay, Emrah Akin Sisbot, Dag Sverre Syrdal, Mick L Walters, Kerstin Dautenhahn, and Rachid Alami. Exploratory study of a robot approaching a person in the context of handing over an object. In *AAAI Spring Symposium: Multidisciplinary Collaboration for Socially Assistive Robotics*, pages 18–24, 2007.

[11] Thibault Kruse, Amit Kumar Pandey, Rachid Alami, and Alexandra Kirsch. Human-aware robot navigation: A survey. *Robotics and Autonomous Systems*, 2013.

[12] Steven M LaValle. Rapidly-exploring random trees a new tool for path planning. 1998.

[13] Jim Mainprice, E Akin Sisbot, Léonard Jaillet, Juan Cortés, Rachid Alami, and Thierry Siméon. Planning human-aware motions using a sampling-based costmap planner. In *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, pages 5012–5017. IEEE, 2011.

[14] Jim Mainprice, Mamoun Gharbi, Thierry Siméon, and Rachid Alami. Sharing effort in planning human-robot handover tasks. In *RO-MAN, 2012 IEEE*, pages 764–770. IEEE, 2012.

[15] Jim Mainprice, E Akin Sisbot, Thierry Siméon, and Rachid Alami. Planning safe and legible hand-over motions for human-robot interaction. In *IARP Workshop on Technical Challenges for Dependable Robots in Human Environments*, volume 2, page 7, 2010.

[16] Makoto Nokata, Koji Ikuta, and Hideki Ishii. Safety-optimizing method of human-care robot design and control. In *Robotics and Automation, 2002. Proceedings. ICRA'02. IEEE International Conference on*, volume 2, pages 1991–1996. IEEE, 2002.

[17] Mike Phillips, Benjamin Cohen, Sachin Chitta, and Maxim Likhachev. E-graphs: Bootstrapping planning with experience graphs. In *Proceedings of the Robotics: Science and Systems (RSS)*, 2012. run:/home/bvadant/Documents/Publications/SAA/Biblio/Phillips 2012.pdfFichier.

[18] Takeshi Sasaki and Hideki Hashimoto. Human observation based mobile robot navigation in intelligent space. In *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*, pages 1044–1049. IEEE, 2006.

[19] Emrah Akin Sisbot, Luis F Marin, and Rachid Alami. Spatial reasoning for human robot interaction. In *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*, pages 2281–2287. IEEE, 2007.

[20] Emrah Akin Sisbot, Luis Felipe Marin-Urias, Rachid Alami, and Thierry Simeon. A human aware mobile robot motion planner. *Robotics, IEEE Transactions on*, 23(5):874–883, 2007.

[21] VJ Traver, AP del Pobil, and M Perez-Francisco. Making service robots human-safe. In *Intelligent Robots and Systems, 2000.(IROS 2000). Proceedings. 2000 IEEE/RSJ International Conference on*, volume 1, pages 696–701. IEEE, 2000.

[22] Takashi Yoshimi, Manabu Nishiyama, Takafumi Sonoura, Hideichi Nakamoto, Seiji Tokura, Hirokazu Sato, Fumio Ozaki, Nobuto Matsuhira, and Hiroshi Mizoguchi. Development of a person following robot with vision based target detection. In *Intelligent Robots and Systems, 2006 IEEE/RSJ International Conference on*, pages 5286–5291. IEEE, 2006.