

Planning Safe and Legible Hand-over Motions for Human-Robot Interaction

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Abstract—Human-Robot interaction brings new challenges to motion planning. The human, who is generally considered as an obstacle for the robot, needs to be considered as a separate entity that has a position, a posture, a field of view and an activity. These properties can be represented as new constraints to the motion generation mechanisms.

In this paper we present three human related constraints to the motion planning for object hand over scenarios. We also describe a new planning method to consider these constraints. The resulting system automatically computes where the object should be transferred to the human, and the motion of the whole robot considering human’s comfort.

I. INTRODUCTION

Human safety becomes more and more crucial with robots entering in our daily lives. Robots and humans working together in cooperation can accomplish more sophisticated tasks benefiting from the combined power and precision of the robot and of the reasoning and problem solving power of the human. This symbiotic relationship will bring new problems and challenges to the robotics research.

Clearly, in an environment where robots and humans work together, robot behaviors need to take explicitly into account the presence of humans. The physical hardware as well as software components of the robot need to be designed by considering human’s safety [1][2]. Besides ensuring safety in robot hardware with compliant designs [3][4], the motions of the robot need to be “planned” in a “human-aware” way.

The need for considering the human presence in motion plans has been established through several user studies (e.g. [5][6][7]). In particular, for manipulation tasks such as object fetch-and-carry, studies have shown the importance of approach directions [8], human-robot distances [9] and the simultaneous motion of robot parts [9]. Koay et al. [10] conducted a detailed user study investigating the spatial relation between a human and a robot in an object hand-over task. This study has provided a number of metrics and has underlined the importance of coordinating robot lower and upper body motions.

In previous work [11][12], we have presented a motion planner that explicitly takes into account human-robot constraints (e.g. their relative distance, the human’s field of view and posture) to synthesize navigation and manipulation motions. This planner was based on human-robot user studies [10][13], as well as on existing human-human space sharing theories [14]. The proposed method was the first one to investigate a “planning” approach to the problem of

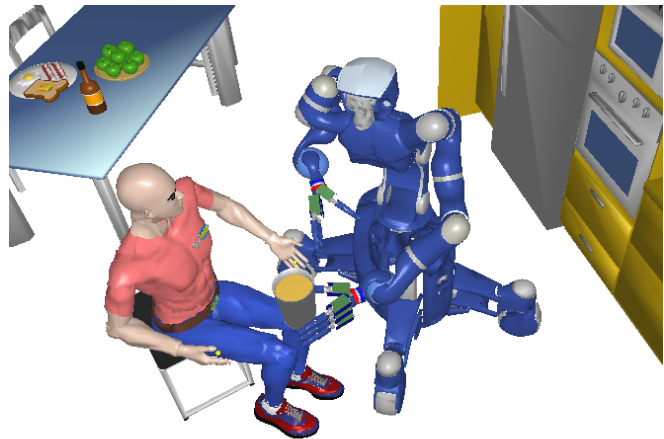


Fig. 1. An example scenario of a Human-Robot object hand-over task

human-robot intelligent space sharing. HRI constraints were represented through cost functions depending respectively on the human kinematic model, field of view and accessibility. This representation of the problem led to costmaps defined over the workspace. Motion planning was solved using grid search techniques for planning object motions, and inverse kinematics to adapt the robot to follow the object path. While this approach is sufficient in an uncluttered environment where strong workspace constraints are absent, it may fail in a highly constraint scenario.

In this paper we present refinements of the previous costmap representations and their use by more sophisticated sampling-based planning methods.

The paper is organized as follows. Section II presents the motivation that led to model the HRI constraints as costmaps. Each criterion is detailed and its impact on the output trajectory is sketched in an object hand-over scenario. Section III describes a planning method and an optimization method adapted to costmaps. Section IV presents the results of the complete planner by combining the elementary costmaps in a unified framework. Finally, Section V concludes the paper by discussing the results and giving perspectives.

II. MOTION IN HUMAN PRESENCE

The presence of humans in the robot workspace brings new constraints to navigation and manipulation planning because of the close physical interaction with the human.

In our previous work [11][12], we have presented a navigation and manipulation planner that considers a number of HRI constraints. Planning with these constraints results in a safe, legible and socially acceptable robot behavior. In this

work, three of these constraints, namely safety, visibility and arm comfort, have been taken into account and refined. These constraints can be considered as examples of a broad variety of Human-Robot Interaction properties that can be taken be considered in the design of robot's reasoning capabilities.

We model these interaction constraints as costmaps attached to the human partner and which evaluate the surrounding space. A cost function represents each constraint by evaluating the quality of 3D points in the workspace of the human. These costmaps are then used in the planning method to generate complete robot motion plans.

A. Distance Constraint

The first constraint, called distance constraint, mainly focuses on ensuring the safety of the interaction by controlling the distance between the hand of the robot and the human. This property is represented by a costmap evaluating the risk to place over the hand of the robot at a given position.

The goal of this costmap is to push the robot sufficiently far to avoid any collision risks. However in situations requiring close interaction (e.g. handing over an object), the robot has to approach the person whom it wants to interact with. Therefore, the distance between the robot and the human is neither uniform nor fixed and depends on the interaction. The feeling of safety is highly dependent on the humans personality, his physical capabilities and his actual states; for example, safety differs highly in a sitting position compared to standing. When the human is sitting, his mobility is reduced and he tends to have a low tolerance to the robot getting close. On the contrary, when standing up he has a higher mobility, thus allowing the robot to come closer.

The distance costmap is a human centered Gaussian in which each point of the workspace has a cost inversely proportional to the distance to the human. Therefore the farther a point is situated from the human, the lesser its cost will be until some maximal distance at which it becomes null. Figure 2 illustrates the Distance costmap around the human's torso. As seen in this figure, costs become less important when going farther from the human.

As distance costs grow when approaching to the human, planning a motion according to this function will result on a motion where the robot tries to stay as far as possible to the human. Figure 3 illustrates the effect of this property on the robot motions. Given an initial position (Fig.3(a)) and a final position (Fig.3(c)), the figure compares a path computed using a standard planner not considering HRI constraints (Fig.3(b)) with a path generated by our planner (see section III) taking into account the distance costs (Fig.3(d)). From a pure safety point of view, the resulting new path pushes the robot farther from the human and causes a safer behavior.

B. Visibility constraint

The second constraint aims to maintain the robot as visible as possible to the human. Humans, who have the robot in their field of view, generally feel more comfortable. This property is represented by costs, called Visibility costmap,

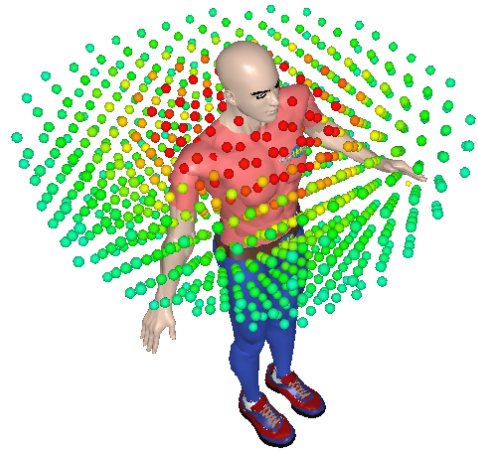


Fig. 2. The Distance constraint is modeled by a spherical costmap. For a better illustration the sphere is cut horizontally. Red points having the highest costs and green points the lowest, this function evaluates a position around the human according to the distance between the robot and the human's torso.

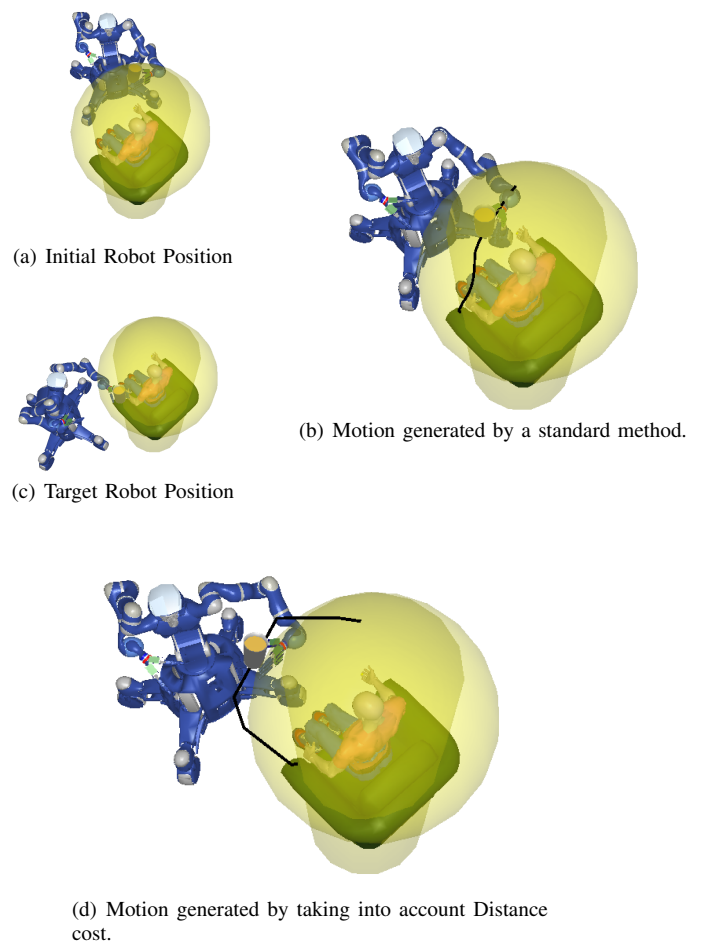


Fig. 3. A comparison between a motion generated by a standard planner and another one generated by considering the Distance constraint. With the help of this costmap the robot moves the object sufficiently far from the human while going to the desired position.

evaluating a 3D point around the human according to its place in human's field of view. This function generates a

costmap around the human representing the effort required by the human to get the robot in his field of view. Figure 4 shows an example of visibility costmap. The greater the effort of the human is required to see a point, the greater the cost of that point will be.

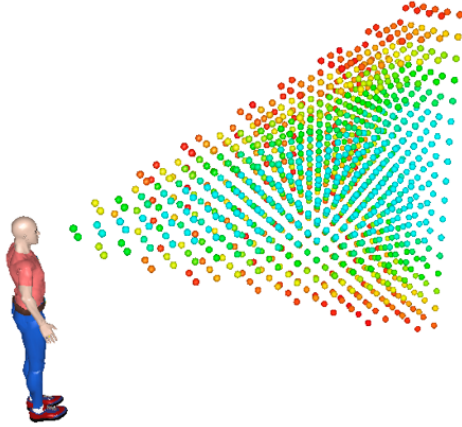


Fig. 4. The Visibility property and its representation as a costmap. The greater the effort of the human is required to see a point, the greater the cost of that point will be.

If we generate a path for the hand of the robot considering the visibility costs, the resulting path will be as visible as possible to the human. Such a path is illustrated in figure 5 along with a comparison to a path planned with RRT method.

C. Comfort constraint

The third constraint represents the comfort of the human. An important property to consider for evaluating a point in the environment is its level of accessibility. Depending on the position of the human hand, the position of the object can be hard, or impossible to reach. For a robot that interacts with a person this property is crucial to take into account, especially in object hand over scenarios, since the interaction should be comfortable and not physically challenging for the human.

We represent this property with a costmap modeling how much effort the human does to reach a certain point in the environment. A point around the range of human arm is reached by Generalized Inverse Kinematics algorithm [15], [16] by moving the arm and the torso of the human. The resulting posture is then evaluated by its comfort [17]. The comfort is estimated with two functions. The first function computes a joint angle distance from a resting posture to the actual posture and the second one considers the potential energy of the arm by measuring the height of the arm and forearm. A weighted sum is applied to merge both cost functions and to compute the final comfort cost of the posture. These cost functions favor comfortable and natural posture.

Figure 6 illustrates examples of reaching postures ordered by their comfort levels from left to right. The difference of

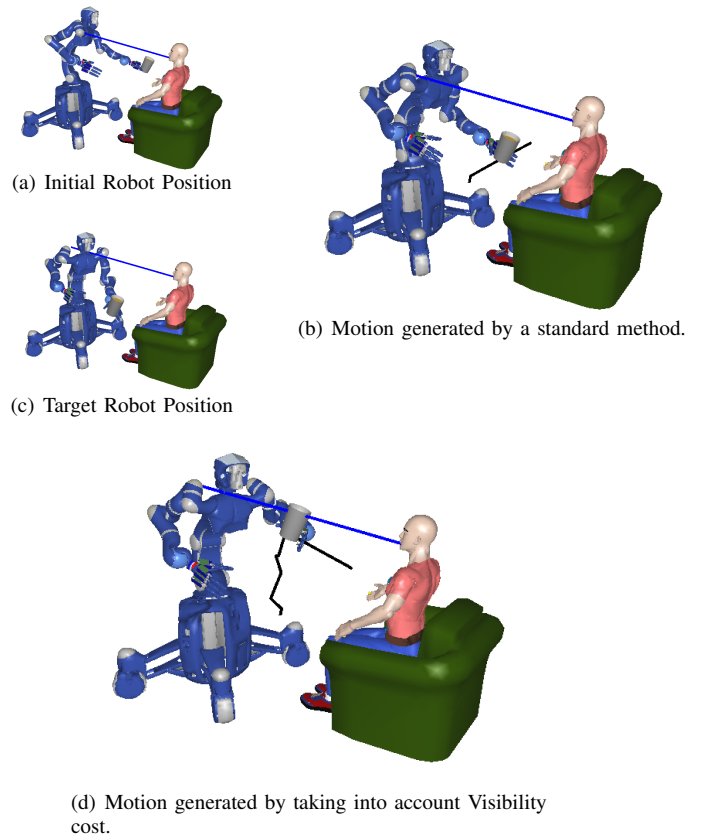


Fig. 5. A comparison between a motion generated by a standard planner and another one generated by considering the Visibility cost. The center of human's field of view is illustrated with the blue line. With the help of this cost function the robot moves the object in a way that it stays as visible as possible to the human. Meanwhile the standard planning method generates a direct yet "risky" motion without considering where the human is looking at.

comfort is clearly visible between the leftmost image where the human reaches a point around his hand, and the rightmost image where the human forces his kinematic structure to reach a point near his back.

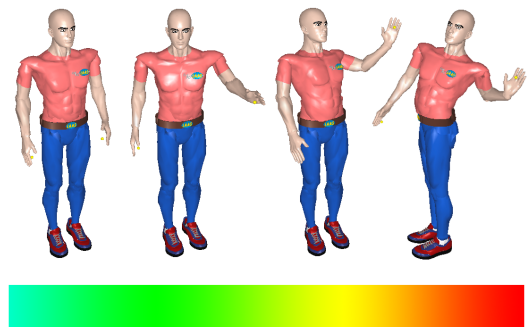


Fig. 6. Reaching postures for the human ordered from a comfortable (left) to a less comfortable (right) position.

Figure 7 illustrates a costmap built around the human representing the comfort of human's left arm. As the energy increases, the effort also increases to reach higher positions. The positions requiring a minimal effort are evaluated as

most comfortable.

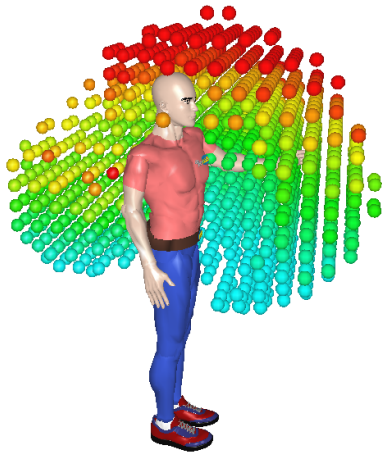


Fig. 7. The arm comfort costmap for the left arm of the human.

The comfort constraint is used to generate robot motions where the end effector maintains the object at positions as comfortable as possible for human grasp. Figure 8 illustrates the effect of this constraint in the motions of the robot. Given an initial (Fig. 8(a)) and a goal (Fig. 8(c)) configuration, a comparison is given between a motion planned by a standard planner (Fig. 8(b)) and a motion planned by taking into account the comfort constraint (Fig. 8(d)). In the latter case, the robot moves the object in a way that the human has always the possibility to reach the object in a comfortable way.

III. PLANNING HAND OVER MOTIONS

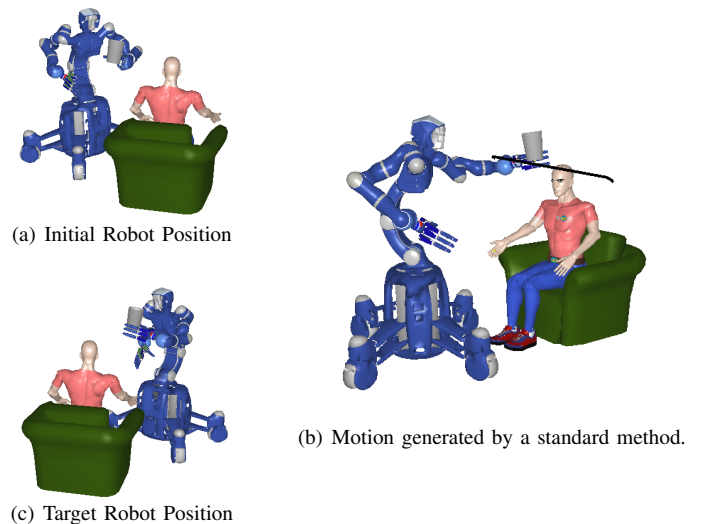
A. Computing a transfer point

For object hand over tasks, an important property to consider is the place where the object will be passed from the robot to the human. This point needs to be chosen by considering all the properties presented above in order to be safe, visible and comfortable.

In order to compute the most suitable place for the object transfer, namely Object Transfer Point, a weighted sum of all three costmaps is calculated. This new costmap evaluates the points around the human according to their distance, visibility and reachability to the human. A search to find the less costly point in this costmap, considering feasibility with respect to obstacles and robot kinematics, is used to generate the Object Transfer Point, the place where the robot will carry the object.

B. Planning on configuration space

1) *Path planning*: Several approaches have been proposed to extend sampling-based algorithms for computing good-quality paths with respect to cost functions. In particular, RRT variants [18], [19], [20] have been introduced in the context of field robotics. In this work, we apply a more general algorithm, called T-RRT [21], briefly explained below. This section also presents a new method for local optimization of the solution through a post-processing phase



(d) Motion generated by taking into account Comfort cost.

Fig. 8. A comparison between motion generated by a standard planner and another one generated by taking into account Comfort cost. In the latter case, the robot moves the object in a way that the human has always the possibility to reach the object in a comfortable way.

that can handle a general cost function defined over the configuration space [22].

As the constraints described in section II are represented by costmaps, they are perfectly suitable for the T-RRT planning algorithm. Distance, visibility and comfort costmaps are merged together with a weighted sum as follows:

$$c(h, q) = \sum_{i=1}^N w_i c_i(h, FK(q)),$$

where q is a configuration and FK the robot's forward kinematics function.

The T-RRT algorithm [21] takes advantage of the performance of two methods. First, it benefits from the exploratory strength of RRT-like planners resulting from their expansion bias toward large Voronoi regions of the space. Additionally, it integrates features of stochastic optimization methods, which apply transition tests to accept or reject potential states. It makes the search follow valleys and saddle points of the cost-space in order to compute low-cost solution paths (see Figure 9). This planning process leads to solution paths with low value of the integral of cost regarding the input costmap landscape.

Similarly to the Extend version of the basic RRT algorithm [23], a configuration is randomly sampled. It yields both the nearest tree node to be extended, and the extension direction. This stage also integrates collision detections in the presence of binary obstacles. Thus, if the new portion of the path leads to a collision, a null configuration is returned and the extension fails independently of the associated costs. This extension process ensures the bias toward unexplored free regions of the space. In the second stage irrelevant configurations regarding the search of low cost paths are filtered using a transition test similar to the one used in stochastic optimization methods before inserting a new configuration in the tree.

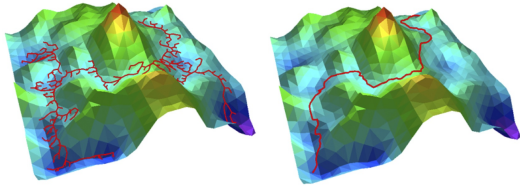


Fig. 9. T-RRT constructed on a 2D costmap (left). The transition test favors the exploration of low-cost regions, resulting in good-quality paths (right).

2) *Local optimization*: In order to optimize paths generated by the motion planner, we employ an extension of the shortcut method. This extension is similar to the original approach, but the cost of the path is tested together with collisions and kinematic constraints.

This method reduces the length of the input path while improving its quality, and usually converges rapidly to a local minimum (Figure 10).

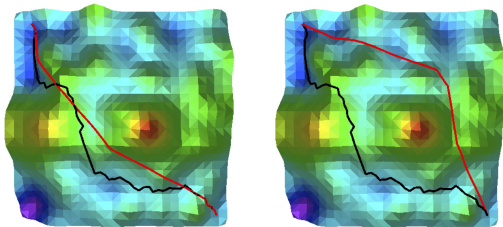


Fig. 10. A medium-quality path in black is improved red path by the two local path-optimization methods resulting in the red path. The *Shortcut* method (left) converges more quickly to a local minimum, while the *Perturbation* method (right) is less local and tends to further improve the path.

IV. EXAMPLE & RESULTS

By taking into account the three constraints, the overall system is able to generate comfortable object transfer positions, and to compute a visible, safe and comfortable robot paths to move the object to this hand over position. Figure 11 shows a kitchen scenario as a complete illustration by using all above mentioned models and methods.

In this example, the robot is holding a glass in its hand while the human is sitting and looking at his left (human gaze direction is illustrated with a blue line in figure 11(a)). The goal of the robot is to hand over the object. The final

position of the object (Object transfer point) is automatically computed by the planner. As the three constraints are considered during this computation, the resulting position is already safe, visible and comfortable to reach by the human, and will be used as the target configuration (Fig. 11(b)).

Figure 11(b) illustrates a path generated by a classical motion planner. The robot follows a direct path without considering any constraints on human. On the other hand, the solution obtained by our human-aware planner has interesting properties (Fig. 11(c)): all along the path, the robot stays sufficiently far from the human and avoids penetrating his safety bubble; the path deviates towards human's gaze direction to ensure the visibility of the object; and for the last part of the path the object is comfortably reachable to the human.

V. CONCLUSION

In this paper we have presented three constraints that increase the quality of the human-robot interaction in motion planning level. Each one of these constraints, namely Distance, Visibility and Comfort, represents an important property related to the position, kinematics and field of view of the human. A planning method and a transfer point generation method is also presented and the results of the overall system is illustrated by an example.

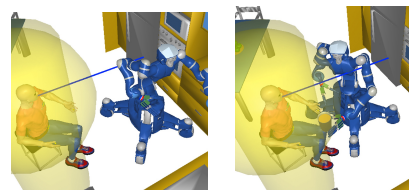
An important aspect of the interaction to take into account in our perspectives is the motions of the human partner. While planning for itself, the robot can also plan for the human in order to find cooperative solutions involving the robot and the human moving together. This will allow us to generate plans where the human contributes, thus opening the door to a wider solution set.

VI. ACKNOWLEDGMENTS

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REFERENCES

- [1] R. Alami, A. Albu-Schaeffer, A. Bicchi, R. Bischoff, R. Chatila, A. D. Luca, A. D. Santis, G. Giralt, J. Guiochet, G. Hirzinger, F. Ingrand, V. Lippiello, R. Mattone, D. Powell, S. Sen, B. Siciliano, G. Tonietti, and L. Villani, "Safe and dependable physical human-robot interaction in anthropic domains: State of the art and challenges," in *Proceedings IROS Workshop on pHRI - Physical Human-Robot Interaction in Anthropic Domains*, A. Bicchi and A. D. Luca, Eds., Beijing, China, October 2006.
- [2] S. Nonaka, K. Inoue, T. Arai, and Y. Mae, "Evaluation of human sense of security for coexisting robots using virtual reality. 1st report: evaluation of pick and place motion of humanoid robots," in *IEEE International Conference on Robotics and Automation, ICRA*, vol. 3, New Orleans, USA, April 2004, pp. 2770–2775.
- [3] M. Zinn, O. Khatib, B. Roth, and J. K. Salisbury, "Playing it safe [human-friendly robots]," *IEEE Robotics & Automation Magazine*, vol. 11, no. 2, pp. 12–21, 2004. [Online]. Available: <http://dx.doi.org/10.1109/MRA.2004.1310938>
- [4] A. Bicchi and G. Tonietti, "Fast and soft arm tactics: Dealing with the safety-performance trade-off in robot arms design and control," *Robotics and Automation Magazine*, vol. 11, no. 2, pp. 22–33, 2004.



(a) Initial Robot Position (b) Target Robot Position



(c) Motion generated by a standard method.



(d) Motion generated by taking into all three cost functions.

Fig. 11. A complete object hand over example scenario. The robot has the object in its hand. The human is sitting on a chair looking at his left. While the motion planned with a standard planner does not consider the presence of the human, the one planned by taking into account the three constraints generates a comfortable motion. By following this path the robot stays as visible as possible, as sufficiently far as possible and the object is comfortable to reach by the human.

- [5] M. Yoda and Y. Shiota, "Basic study on avoidance motions for human behaviors," in *IEEE International Workshop on Robot and Human Interactive Communication, RO-MAN*, Tokyo, 1995, pp. 318–322.
- [6] E. Pacchierotti, H. Christensen, and P. Jensfelt, "Human-robot embodied interaction in hallway settings: a pilot user study," in *IEEE International Workshop on Robot and Human Interactive Communication, RO-MAN*, Nashville, USA, August 2005, pp. 164–171.
- [7] —, "Evaluation of passing distance for social robots," in *IEEE International Workshop on Robot and Human Interactive Communication, RO-MAN*, Hatfield, UK, September 2006, pp. 315–320.
- [8] K. Dautenhahn, M. Walters, S. Woods, K. L. Koay, C. L. Nehaniv, E. A. Sisbot, R. Alami, and T. Siméon, "How may i serve you?: a robot companion approaching a seated person in a helping context," in *ACM SIGCHI/SIGART International Conference on Human-Robot Interaction, HRI*, Utah, USA, March 2006, pp. 172–179.
- [9] F. Yamaoka, T. Kanda, H. Ishiguro, and N. Hagita, "How close?: model of proximity control for information-presenting robots," in *ACM/IEEE International Conference on Human-Robot Interaction, HRI*, Amsterdam, The Netherlands, March 2008, pp. 137–144.
- [10] 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," in *Association for the Advancement of Artificial Intelligence Spring Symposia, AAAI*, Palo Alto, CA, USA, March 2007.
- [11] E. A. Sisbot, L. F. M. Urias, R. Alami, and T. Siméon, "Spatial reasoning for human-robot interaction," in *IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS*, San Diego, CA, USA, November 2007.
- [12] E. A. Sisbot, L. F. Marin-Urias, R. Alami, and T. Simeon, "Human aware mobile robot motion planner," *IEEE Transactions on Robotics*, vol. 23, pp. 874–883, 2007.
- [13] Cogniron, "Cogniron project ra3 final deliverable," LAAS/CNRS, Tech. Rep., April 2008.
- [14] E. T. Hall, *The Hidden Dimension*. Doubleday, 1966.
- [15] K. Yamane and Y. Nakamura, "Natural motion animation through constraining and deconstraining at will," *IEEE Transactions on Visualization and Computer Graphics*, vol. 9, no. 3, pp. 352–360, July–September 2003.
- [16] P. Baerlocher and R. Boulic, "An inverse kinematics architecture enforcing an arbitrary number of strict priority levels," *The Visual Computer: International Journal of Computer Graphics*, vol. 20, no. 6, pp. 402–417, 2004.
- [17] M. Katayama and H. Hasuura, "Optimization principle determines human arm postures and "comfort"," *SICE 2003 Annual Conference*, vol. 1, pp. 1000–1005, August 2003.
- [18] A. Ettlín and H. Bleuler, "Randomised Rough-Terrain Robot Motion Planning," in *Proc. IEEE/RSJ Int. Conf. on Intelligent Robots and Systems*. Citeseer, 2006, pp. 5798–5803.
- [19] C. Urmson and R. Simmons, "Approaches for heuristically biasing RRT growth," *IEEE/RSJ IROS 2003*, 2003.
- [20] R. Diankov and J. Kuffner, "Randomized statistical path planning," in *Proceedings of IEEE/RSJ 2007 International Conference on Robots and Systems (IROS)*. Citeseer, 2007.
- [21] L. Jaillet, J. Cortés, and T. Siméon, "Sampling-based path planning on configuration-space costmaps," *IEEE Transactions on Robotics*, in press, 2010.
- [22] J. Mainprice, E. A. Sisbot, L. Jaillet, J. Cortes, R. Alami, and T. Simeon, "Planning human-aware motions using a sampling-based costmap planner," in *submitted to IEEE/RSJ International Conference on Intelligent Robots and Systems, IROS*, 2010.
- [23] S. LaValle and J. Kuffner, "Rapidly-exploring random trees: Progress and prospects," in *Algorithmic and computational robotics: new directions: the fourth Workshop on the Algorithmic Foundations of Robotics*. AK Peters, Ltd., 2001, p. 293.