Towards Legible Robot Navigation - How to Increase the Intend Expressiveness of Robot Navigation Behavior

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Abstract. The work at hand addresses the question: How can we achieve legible robot navigation? To this end, we investigate current state-of-the-art assumptions and methods regarding legible robot navigation in order to propose key factors for the development of a legible robot navigation. We reviewed 18 articles regarding legible robot behavior and present the conclusions from our own research. We found three important factors for legible robot navigation: straight lines, stereotypical motions and the use of additional gestures.

Keywords: human-aware navigation, legibility, intend expressive navigation

1 Introduction

Robots will increasingly become part of the habitats and work spaces of humans. Wherever they are located, in the factories as co-workers, in nursing homes or hospitals as care assistants, as guides in supermarkets, or as household-robots in our homes, one crucial behavior, which they all have in common, is navigation. A robot has to move through spaces where humans live and as Althaus et al. [2] already stated *"The quality of the movements influences strongly the perceived intelligence of the robotic system."*. The way a robot moves affects not only the perceived intelligence, but also the perceived safety, comfort and predictability [7, 18]. One important finding of a study Dautenhahn et al. [8] conducted to explore peoples' perception towards the future use of robot companions was that the behavior of a robot has to be predictable.

From all this we can conclude that (1) navigation is a crucial behavior, (2) a motion is not only an instrument to reach a goal position, it is also a way to communicate, and (3) predictability is important for robot behavior. The question now is how to generate predictable motions. Before going into details we want to point out our definition of predictable robot behavior. We use the term **legibility** to describe robot behavior that is (1) intent expressive, meaning that a human is able to infer the next actions, goals and intentions of a robot and (2) the robot behavior fulfills the expectations of a human interaction partner [17, 16]. This definition of legible robot behavior is in line with determinations of legibility in [1, 3, 5, 14, 15, 28, 29, 24, 30].

Research Question With the work at hand we want to answer the question how to generate legible robot navigation. What are the key factors for a legible robot navigation? To this end, we reviewed current literature regarding legibility in robot behavior and combined the thus collected insights with our own findings in order to propose factors that have to be considered in order to generate legible robot navigation.

2 Results of Literature Research

We will start with a literature survey regarding legibility of robot behavior. We systematically reviewed 18 articles [1, 3, 5–7, 9, 11–14, 22–27, 29, 30] published in the primary HRI publication venues from 2005 - 2013. In order to find all relevant papers we used the search terms: legibility/legible, readability/readable, and predictability/predictable in combination with motion/behavior and robot. For the work at hand we considered only 18 articles from the initial set of papers (32) claiming assumptions and/or approaches to generate legible robot behavior.

One very obvious assumption regarding legible robot behavior is that **human-like** behavior would be perceived as legible [5, 14, 11], because human behavior is well-known for humans. Therefore, the development of methods imitating human motions is very common in the HRI community.

Furthermore, Beetz et al. [5] claimed that a **stereotypical motion** is predictable, and thus legible. This assumption is supported by results from Bortot et al. [6].

In [23] the authors claim that the use of **complementary gestures** made by the robot could achieve legibility. Therefore, using their proposed gesture classification can improve the legibility of the robot. Similarly, Sisbot et al. [24] integrated complementary gestures in order to make the motion more intend expressive. This *complementary gesture assumption* is also supported by results from Basili et al. [3]. They were able to show that gaze behavior increases the ability to predict where someone is heading to.

Takayama et al. [30] claim that the **use of animation principles** makes the robot behavior more legible. They implemented additional gestures in order to let the robot show forethought and the results of their conducted study supported their assumption.

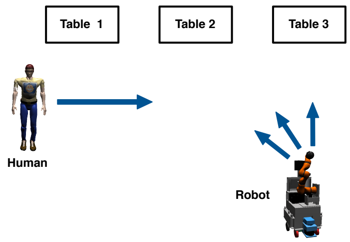
Another assumption is to **take into account social constraints, human preferences and abilities** [13, 1]. Following this Kirsch et al. [12, 13] proposed an approach to achieve legible task execution behavior. They suggest to learn human preferences and abilities in order to integrate this knowledge into a high level task planner.

Several authors like Takayama et al. [30], Guzzi et al. [11] and Kruse et al. [14] claim that **efficiency** is also one factor of legibility. Humans expect a robot to interact in an effective manner. If the robot behavior is non-legible, the human is not able to predict goals and intentions resulting in less efficient interactions.

Visibility is not only a prerequisite for legibility, because a human is not able to anticipate anything from a hidden motion, it is also a very important factor for generating legible motions. Sisbot et al. and Dehais et al. claim that a legible robot motion must be as visible as possible [9, 26]. This assumption is implemented in the Human Aware Motion Planner [22, 24, 27, 29] as well as in the Human Aware Navigation Planner [28, 25]. The visibility assumption is based on results from Dautenhahn et al. [7].

To conclude, in order to generate legible robot behavior, the following assumptions were proposed in the reviewed articles:

- model human-like behavior [5, 14, 11]
- generate stereotypical motions [5, 6]
- generate efficient motions [11, 14, 30]
- add complementary motions (gestures) in order to clarify intentions (e.g. gaze, pointing, use animation principles) [23, 24, 3, 30]
- take into account social constraints, human abilities, and preferences [13, 12, 1]
- robot motion must be as visible as possible [9, 26].



(a) Experimental Setup

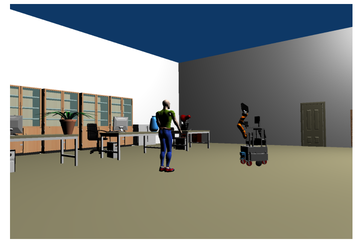

(b) Simulator view

Fig. 1. In the experiment we showed the participants simulated videos (b) of a robot and a human crossing the robots path. The robot is heading towards one of the tables (a).

3 Lessons Learned from Our Research

In the following we present our own findings regarding legible robot navigation. In our work we concentrate on human-robot path crossing scenarios.

3.1 Investigate Legibility of Existing Navigation Methods

In our first experiments we evaluated the legibility of existing navigation methods [16]. In a simulator-based experiment we showed the participants different videos of a robot and a human crossing the robot's path in an office environment (see Fig. 1). We measured legibility by asking the participants to (1) predict the goal after seeing a part of the video and after seeing the complete video (2) to rate how much the actual robot behavior matched their expectations and (3) how surprisingly the behavior was perceived.

From our results we concluded that existing state-of-the-art navigation algorithms fail in the presence of humans regarding legibility. In situations were a human was crossing the robots path the tested algorithms produced strange movements like small curves, or the robot was spinning around, or in the worst case the robot crashed into the human. All these strange movements were rated as non-legible although straight movements towards the goal and decreasing the velocity when approaching the human revealed higher legibility ratings. This fact is also confirmed by results from our second experiment [19] were we showed the participants first-person perspective videos of a similar setup.

3.2 Measuring Human Expectations

For further investigations towards a legible robot navigation we designed and conducted a study in order to find how a human would expect a robot to move when a human is crossing its way [21, 20]. To this end, we let participants steer a robot in a real-world scenario in which an instructed confederate was crossing the robot's path (see Fig. 2). We captured the movements of the robot and the confederate in order to find (1) the expected behavior in a path-crossing scenario and (2) to find the spatial coherence between robot, confederate and the behavioral reaction of the robot. We found out that a good strategy is to drive straight towards the goal and only react (stop) to a crossing human when the spatial relationship predicts to stop, otherwise drive on towards the goal.

(a) Steering BIRON (b) Laboratory (c) Study Setup

Fig. 2. In the study we let participants steer the robot (a) in our Laboratory (b). An instructed confederate crosses the robots path by chance as depicted in (c).

4 Conclusion

In the following we conclude the aforementioned findings regarding legible robot behavior and draw the key factors for generating legible robot navigation behavior.

Straight Towards the Goal The first, and from our opinion the main factor for a legible robot navigation is that a robot should always move as far as is possible straight towards its goal and react as smoothly as possible to a human. Bortot et al. [6] showed in their experiment that a straight and stereotypical motion leads to higher human performance and well-being. Moreover, this fact was formerly stated by Beetz et al. [5]. Furthermore, in our own aforementioned study [21, 20], where we let participants steer the robot in order to find their preferred robot behavior, we also found that a straight way towards the goal is preferred. Straight lines towards the goal are also fulfilling the efficiency criteria that we mentioned earlier in our review as one factor of legible motion. In addition, our simulator based experiment [19] showed that driving curves or spinning around leads to lower legibility. Participants told us, that they were confused by the strange movements the robot was performing in some trials. In addition, straight lines are also in line with the claim for human like behavior. In a human-human path crossing experiment Basili et al. [4] found that humans do not swerve. Decreasing the velocity in order to avoid a collision was the observed behavior.

We know that this approach is contrary to the results Dragan et al. [10] observed in their experiment. They could show that a sweeping arm motion towards a goal is more legible in terms of goal predictiveness. Nonetheless, we think there is an important difference between legible arm motions without any human interaction and a navigation where a human might cross a robot's path. This is one point that has to be further investigated in the future.

Stereotypical Behavior As suggested by Beetz et al. [5] and validated by Bortot et al. [6] a robot that behaves the same way in similar situations is way more legible than a somehow optimized motion with permanently varying trajectories. Therefore, another very important key factor for a legible navigation algorithm is to produce consistent trajectories.

Additional Gestures Another factor to increase the legibility of robot navigation is the use of additional gestures or motions like gaze, pointing, or torso direction in order to communicate goals and intentions. In navigation especially the direction the robot is heading to could be communicated with gaze cues. This is in line with results of an experiment conducted by Basili et al. [3]. Also Sisbot et al. [24] used additional gaze and head motions in order to increase the legibility of a motion. Furthermore, Takayama et al. [30] suggested to use animation principles in order to make robot behavior more legible. Some participants suggested in a debriefing of a study that one can use winkers at a robot to indicate directional changes. To conclude, every motion or gesture that indicates the robot's direction or goal increases legibility.

The aforementioned key factors are a first step towards a legible robot navigation. This list is not intended to be exhaustive. Further research is necessary to investigate the factors for a legible navigation and a more important issue is the implementation of these factors into a navigation method.

References

1. Rachid Alami, Aurélie Clodic, Vincent Montreuil, Emrah Akin Sisbot, and Raja Chatila. Toward Human-Aware Robot Task Planning. In *AAAI Spring Symposium*, 2006.
2. Philipp Althaus, H. Ishiguro, T. Kanda, T. Miyashita, and H.I. Christensen. Navigation for Human-Robot Interaction Tasks. In *IEEE ICRA*, 2004.
3. Patrizia Basili, Markus Huber, Omiros Kourakos, Tamara Lorenz, Thomas Brandt, Sandra Hirche, and Stefan Glasauer. Inferring the Goal of an Approaching Agent: a Human-Robot Study. In *IEEE RO-MAN*, 2012.
4. Patrizia Basili, Murat Sag, Thibault Kruse, Markus Huber, Alexandra Kirsch, and Stefan Glasauer. Strategies of Locomotor Collision Avoidance. *Gait & Posture*, 2012.
5. Michael Beetz, Freek Stulp, Piotr Esden-Tempski, Andreas Fedrizzi, Ulrich Klank, Ingo Kresse, Alexis Maldonado, and Federico Ruiz. Generality and Legibility in Mobile Manipulation. *Autonomous Robots*, 28(1), 2010.
6. Dino Bortot, Maximilian Born, and Klaus Bengler. Directly or on detours? How should industrial robots approximate humans? In *ACM/IEEE HRI*, 2013.
7. K. Dautenhahn, M. Walters, S. Woods, K.L. Koay, C.L. Nehaniv, 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 Conference on Human-Robot Interaction*, 2006.
8. Kerstin Dautenhahn, Sarah Woods, Christina Kaouri, Michael L Walters, Kheng Lee Koay, and Iain Werry. What is a Robot Companion-Friend, Assistant or Butler? In *IEEE/RSJ IROS*, 2005.
9. Frédéric Dehais, Emrah Akin Sisbot, Rachid Alami, and Mickaël Causse. Physiological and Subjective Evaluation of a Human-Robot Object Hand-Over Task. *Applied Ergonomics*, 2011.
10. Anca D Dragan, Kenton CT Lee, and Siddhartha S Srinivasa. Legibility and Predictability of Robot Motion. In *ACM/IEEE HRI*, 2013.
11. Jérôme Guzzi, Alessandro Giusti, Luca M Gambardella, Guy Theraulaz, and Gianni A. Di Caro. Human-friendly Robot Navigation in Dynamic Environments.
12. Alexandra Kirsch, Thibault Kruse, and Lorenz Mösenlechner. An Integrated Planning and Learning Framework for Human-Robot Interaction. In *Workshop on Planning and Plan Execution for Real-World Systems*, 2009.

13. Alexandra Kirsch, Thibault Kruse, E.Akin Sisbot, Rachid Alami, Martin Lawitzky, Dražen Bršćič, Sandra Hirche, Patrizia Basili, and Stefan Glasauer. Plan-Based Control of Joint Human-Robot Activities. *KI - Künstliche Intelligenz*, 24(3), 2010.
14. Thibault Kruse, Patrizia Basili, Stefan Glasauer, and Alexandra Kirsch. Legible Robot Navigation in the Proximity of Moving Humans. In *IEEE ARSO*, 2012.
15. Thibault Kruse, Alexandra Kirsch, Emrah Akin Sisbot, and Rachid Alami. Exploiting Human Cooperation in Human-Centered Robot Navigation. In *IEEE RO-MAN*, 2010.
16. Christina Lichtenthäler, Tamara Lorenz, Michael Karg, and Alexandra Kirsch. Increasing Perceived Value Between Human and Robots—Measuring Legibility in Human Aware Navigation. In *IEEE ARSO*, 2012.
17. Christina Lichtenthäler, Tamara Lorenz, and Alexandra Kirsch. Towards a Legibility Metric: How to Measure the Perceived Value of a Robot. *ICSR*, 2011.
18. Christina Lichtenthäler, Tamara Lorenz, and Alexandra Kirsch. Influence of Legibility on Perceived Safety in a Virtual Human-Robot Path Crossing Task. In *IEEE International Symposium on Robot and Human Interactive Communication*, 2012.
19. Christina Lichtenthäler, Tamara Lorenz, and Alexandra Kirsch. Influence of Legibility on Perceived Safety in a Virtual Human-Robot Path Crossing Task. In *IEEE RO-MAN*, 2012.
20. Christina Lichtenthäler, Annika Peters, Sascha Griffiths, and Alexandra Kirsch. Social Navigation - Identifying Robot Navigation Patterns in a Path Crossing Scenario. In *ICSR*. Springer, 2013.
21. Christina Lichtenthäler, Annika Peters, Sascha Griffiths, and Alexandra Kirsch. Be a Robot! Robot Navigation Patterns in a Path Crossing Scenario. In *ACM/IEEE HRI*, 2013.
22. 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 *IEEE ICRA*, pages 5012–5017, 2011.
23. Chrystopher L Nehaniv, Kerstin Dautenhahn, Jens Kubacki, Martin Haegele, Christopher Parlitz, and Rachid Alami. A Methodological Approach Relating the Classification of Gesture to Identification of Human Intent in the Context of Human-Robot Interaction. In *IEEE RO-MAN*, 2005.
24. Emrah Akin Sisbot and Rachid Alami. A Human-Aware Manipulation Planner. *IEEE Transactions onRobotics*, 28(5), 2012.
25. Emrah Akin Sisbot, Rachid Alami, Thierry Siméon, Kerstin Dautenhahn, M Walters, and S Woods. Navigation in the Presence of Humans. In *IEEE-RAS International Conference on Humanoid Robots*, 2005.
26. Emrah Akin Sisbot, Aurélie Clodic, Rachid Alami, and Maxime Ransan. Supervision and Motion Planning for a Mobile Manipulator Interacting with Humans. In *ACM/IEEE HRI*, pages 327–334, 2008.
27. Emrah Akin Sisbot, Luis F Marin, and Rachid Alami. Spatial Reasoning for Human Robot Interaction. In *IEEE/RSJ IROS*, 2007.
28. Emrah Akin Sisbot, Luis F Marin-Urias, Rachid Alami, and Thierry Simeon. A Human Aware Mobile Robot Motion Planner. *IEEE Transactions on Robotics*, 23, 2007.
29. Emrah Akin Sisbot, Luis F Marin-Urias, Xavier Broquere, Daniel Sidobre, and Rachid Alami. Synthesizing Robot Motions Adapted to Human Presence. *International Journal of Social Robotics*, 2(3), 2010.
30. Leila Takayama, Doug Dooley, and Wendy Ju. Expressing Thought: Improving Robot Readability with Animation Principles. In *ACM/IEEE HRI*, 2011.