Making the Case for Human-aware Navigation in Warehouses*

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Abstract. This work addresses the performance of several local planners for navigation of autonomous pallet trucks in the presence of humans in a simulated warehouse as well as a complementary approach developed within the ILIAD project. Our focus is to stress the open problem of a safe manoeuvrability of pallet trucks in the presence of moving humans. We propose a variation of ROS navigation stack that includes in the planning process a model of the human robot interaction.

Keywords: logistics; human-aware navigation

1 Introduction

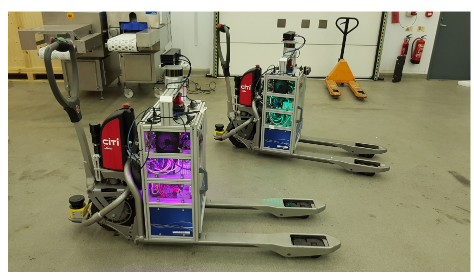

Fig. 1. The ILIAD robot, a Linde CitiTruck modified for autonomous operation

Autonomous Guided Vehicles (AGV) operating on virtual rails are evolving towards true Autonomous Mobile Robots (AMR) moving freely without any specific infrastructure or extra safety guards in warehouses. This trend raises concerns about the safety and comfort of sharing the space with humans as co-workers. Of course, obstacle-aware navigation itself has been in the focus of research for several decades already and has matured ever since, also dealing with dynamic obstacles safely. But it has been confirmed by many previous works that the aspect of *human*-aware navigation [5] demands often distinct approaches that consider also the implicit intention communicated by motion itself [4,6] and the negotiation of space for navigation.

In this paper, we focus at the case of an autonomous pallet truck (see Fig. 1), developed to operate in infrastructure-free (no beacons, magnetic strips or other

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infrastructure to facilitate navigation and localisation) in the context of the H2020 ILIAD project[1].

Specifically, the objectives of this paper are to appraise the suitability of two classical variants of the general `move_base`[2] navigation frameworks for navigation of pallet trucks in the presence of humans in a simulated warehouse setting as well as a complementary approach developed within the ILIAD project; and to suggest an extension to these frameworks to address challenges of human-aware navigation.

2 Problem statement and analysis

Classical Robot Navigation in Warehouses Safety is one of the highest priorities in any working environment. However, even though safety itself may be guaranteed by safety lasers, human *perceived* safety is a completely different matter [6]. Sudden stops or abrupt changes on speeds are usually perceived as threads by humans and have also detrimental effects on robot performance.

Aim for our work is therefore to minimise safety stops induced by a safety device itself, and maximise comfort of humans in vicinity of the robot (perceived safety), while maintaining effective and efficient operational characteristics. We will perform tests using three planning algorithms to illustrate how "classical" approaches (that do not treat humans different from other obstalces) handle human presence: *Dynamic Window Approach (DWA)*, a local planner based on an online collision avoidance strategy developed originally by Dieter Fox et al. in [3]. *Timed Elastic Bands (TEB)*, first proposed in [9], it dynamically optimizes running time and guarantees kinodynamic compliance in global trajectories. *ILIAD planner*: a real-time, lattice-based planner for non holonomic vehicles developed by Henrik Andreasson *et al* in [1].

Analysis In order to test the performance of these three classical navigation approaches, we defined five different simulation scenarios in the Gazebo simulator[3]:

- *Base Scenario*: Robot travels towards a goal 6.5 straight ahead, undisturbed.
- *Cross L-R*: Human crosses the robot's path from its left side.
- *Cross R-L*: Human crosses the robot' path from its right side.
- *Overtake*: Robot is overtaken by a human.
- *Pass-by*: Human is walking towards the robot and passes it.

Results in *Base* scenario are presented in Table 1, to be compared with results in the other scenarios. Each combination of scenarios and navigation algorithms was tested 6 times (3× *slow* moving human, 3× fast moving human, timed to collide with robot if not actively avoided). Table 2 highlight how in case of the fast human motion collisions cannot be avoided.

[1] `http://iliad-project.eu`
[2] `http://wiki.ros.org/move_base`
[3] `http://gazebosim.org`

Discussion The simulation experiments give an indication of the problems of human presence in robot navigation (as also discussed in details in [5]). In alignment with expectations, presence of humans has an immediate impact on the trajectory length, and, consequently, on the completion times.

Scenario	base		
Planner	DWA	TEB	ILIAD
∅ time to compl.	37.38	32.62	**31.98**
∅ path length	6.55	**6.5**	6.67
∅ robot speed	0.17	0.2	**0.21**

Table 1. Performance results of three classical navigation approaches in base scenario.

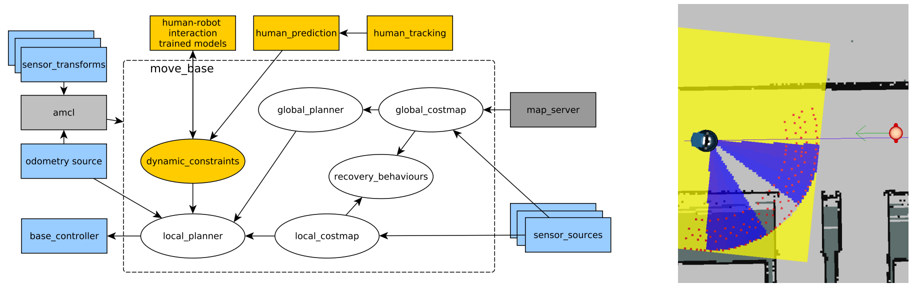
The TEB planner outperforms DWA in all our test cases, likely due to its ability to better plan with the Ackermann constraints of the robot's kinematics. Both motion controllers (TEB & DWA) are liable to failure due to collision, and inefficiency (time, paths) due to constant replanning of trajectories due to the dynamic motion. On the other hand, *ILIAD* planner is always capable of handling crossings by just stopping (implementing the preferred model of [6]). Although it is a very accurate planner, it does not change its trajectory in presence of obstacles/humans, but instead slows down and even stops if an obstacle happens to be too close. In crossing scenarios, this crossing is so narrow that fully stops the robot, notifying an early finish of the plan, but safe after all. This policy is clearly insufficient in the event of an obstacle that is heading towards the robot, like in scenario *pass-by*. As a conclusion, strong commitment to a robot's original path (and slowing the execution of the trajectory in the presence of humans), like offered by the ILIAD planner, can indeed show better performance than continuous replanning (TEB & DWA), in specific scenarios. More generally, a motion planner must actively avoid humans, but a certain level of commitment to its global reference path is expected to provide a good trade-off.

3 Proposed Approach and Conclusion

As the experiments have indicated, an operational "sweet spot" may exist between the full commitment to a global trajectory (current ILIAD planner) and the continuous replanning approach of the classical motion controllers. Hence, we propose an extension to the classical ROS `move_base` stack, depicted in Fig. 2(a), to incorporate additional constrains into the local planning. This concept shall allow the robot to flexibly switch between very strong commitment to a (global) reference trajectory provided by narrow constraints, and to give freedom to flexibly avoid humans in other situations.

Scenario	cross L-R			cross R-L			overtake			pass-by		
Planner	DWA	TEB	ILIAD	DWA	TEB	ILIAD	DWA	TEB	ILIAD	DWA	TEB	ILIAD
∅ time to compl.	40.07	35.14	**28.22**	38.99	35.5	**27.61**	37.95	34.88	**31.26**	48.86	**41.75**	-
∅ path length	6.59	6.54	**4.54**	6.56	6.52	**5.41**	6.55	**6.53**	6.66	**6.85**	7.20	-
∅ robot speed	0.16	**0.18**	0.17	0.17	0.18	**0.19**	0.17	0.18	**0.21**	0.13	**0.16**	-
∅ min. h-r dist.	1.43	1.47	**1.85**	**2.0**	1.96	1.65	0.78	0.78	0.78	0.44	**0.53**	-
#Collisions	3	3	**-**	3	3	**-**	-	-	-	3	3	6

Table 2. Performance results in 3 scenarios (∅ of 6 runs at 2 different human speeds, ∅ computed on successful runs only).



(a) Classical navigation architecture with proposed additional modules (yellow).

(b) QTC-generated constraints for DWA.

Fig. 2. Architectural overview and example QTC-generated constraint [2]

Current implementation can track humans around the robot [7] and plan accurate global reference trajectories [1]. Relative motion between human and robot is represented as a sequence of Qualitative Trajectory Calculus (QTC) states, as in [2]. This way, different situations will be trained and represented in a Markov model, allowing to learn and predict suitable, situation-dependent dynamic constraints (see Fig. 2(b) for an example). This work will be extended towards a more flexible and ROS-compatible framework, allowing the dynamic incorporation of local constraints, based on trained models. Other deep learning navigation algorithms, such as [8] will be also taken into consideration as candidates for enhancement with human aware constraints.

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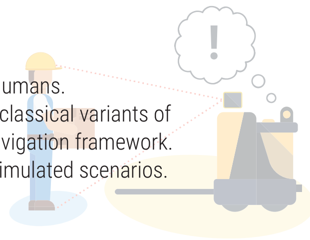
Goals

- Minimise safety stops.
- Maximise comfort of humans.
- Appraise the suitability of classical variants of the general **move_base** navigation framework.
- Study human safety in 4 simulated scenarios.



Discussion

- Clear limitations of classical approaches in presence of humans (as discussed in detail in [4]).
- **TEB** planner outperforms **DWA** in all our test cases.
- Both **TEB & DWA** are liable to failure due to collision and inefficiency (time, paths) due to constant trajectory replanning.
- ***ILIAD*** planner is always capable of handling crossings (implementing the preferred policy of [5]).
- This policy is clearly insufficient in the event of an obstacle that is heading towards the robot, like in scenario *pass-by*.

Performance results in 3 scenarios (∅ of 6 runs at 2 different human speeds,∅ computed on successful runs only).

Scenario	cross L-R			cross R-L			overtake			pass-by		
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#Collisions	3	3	-	3	3	-	-	-	-	3	3	6

Analysis

Planners:

- Dynamic Window Approach (**DWA**): a local planner based on an online collision avoidance strategy [1].
- Timed Elastic Bands (**TEB**): dynamically optimizes running time and guarantees kinodynamic compliance in trajectories [2].
- **ILIAD** planner: real-time, lattice-based planner for non holonomic vehicles [3].

Scenarios:

- Cross **L-R**: Human crosses the robot's path from its left side.
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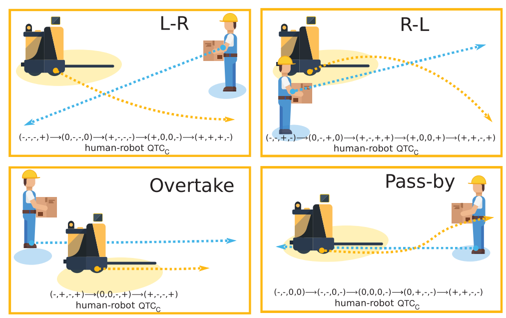
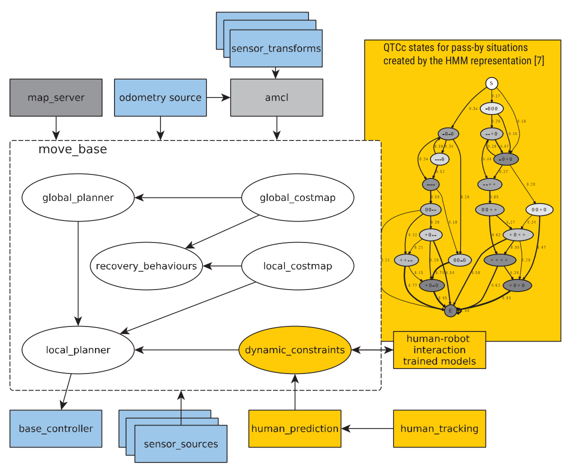


Proposed Approach and Conclusion

- A motion planner that actively ***avoids humans but has a certain level of commitment*** to its global reference path is expected to provide a good trade-off.
- Hence, we propose an ***extension*** to the classical ROS ***move_base*** stack, depicted in the graph, to ***incorporate additional constrains*** into the local planning.
- Current implementation can track humans around the robot [6] and plan accurate global reference trajectories [1].
- Relative motion between human and robot is represented as a sequence of Qualitative Trajectory Calculus (QTC) states, as in [7].
- This way, different situations will be trained and represented in a Markov model, allowing to learn and predict suitable, situation-dependent dynamic constraints.



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