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A Simple And Modular Approach To Path Planning For Tractor-Trailer Robots Based On Modification Of Pre-Existing Trajectories

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Abstract

Tractor-trailer Mobile Robot systems consist of a nonholonomic mobile robot regarded as a tractor and several passive trailers linked to the tractor via a hinge. As these systems are in many cases more economical compared to multi mobile robot systems, they are nowadays used for the transport of various objects in the field of logistics. Hence an exact and efficient path planning algorithm is required. Due to the highly non-linear characteristics of such a system, path planning is always a challenging problem. Many path planning algorithms have already been proposed for mobile robots. While some of these approaches can solve the path planning problem for robots with multiple trailers, the solutions are usually complex, limited to a specific hardware configuration, or very computationally expensive. In this work, we present an algorithm that, although still computationally expensive in its current form, provides a very simple, extensible, and flexible solution for path planning of tractor-trailer robots. Based on a conventional global planner for mobile robots (like A* or Dijkstra), our algorithm adjusts the global path according to the dimension of the carried object so that the whole system traverses a collision-free path. We take advantage of the fact that the global planner has already planned a collision-free path for the mobile robot (tractor), which the trailer follows almost exactly on straight paths. Accordingly, collisions occur predominantly in or shortly after curves. We designed our algorithm to detect these particular curves and adjust the curve radius so that no collision occurs. This way, we do not need to re-plan the whole trajectory. Also, we can upgrade almost any planning algorithm for mobile robots to work with tractor-trailer systems. We validate our method based on a series of simulations. First real-world experiments are also very promising.

Keywords

Tractor-Trailer mobile robots; Path Planning; Object Transport

1. Introduction

Large and heavy robots are often needed to transport large or heavy components. These robots not only cost more than smaller robots, but they also consume more power and occupy additional hall space. Besides, the oversizing of robots leads to a waste of raw materials and energy. In this context, it becomes necessary to consider how to increase the capabilities of smaller robots. One way to achieve this is the cooperation of a formation of smaller robots. Robot formations are often used to extend the capabilities of a single robot or to break down complex tasks into simpler subtasks [1]. In this way, formations consisting of multiple mobile platforms equipped with manipulators can transport or assemble objects that would otherwise be too heavy, big or delicate for a singular mobile manipulator. In these formations, the mobile manipulators generally consist of a nonholonomic mobile platform equipped with an industrial robot. While multi-robot formations increase a robotic system's total carrying capacity, they still require additional expensive hardware to scale to a new task. The control of these formations also increases the complexity of the transport process.

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Consequently, in this work, we present an approach to replacing a robot formation member with a passive auxiliary device. The passive auxiliary device supports the transport object on one or more sides, thus reducing the robot's load. As shown in Figure 1, only a part of the object has to be held by the robot, which halves the effective gravity force.

Figure 1: Top view of a mobile manipulator (MuR 205) transporting an aluminium construction profile in combination with a roller board

In this work, we use a conventional roller board (RB) as an example of a cheap passive auxiliary device. The robot carries the RB on its loading platform and then places it at one of the object's ends before loading the transport object (see Figure 2). The object is detected using Canny Edge Detection from the Open Source Computer Vision (OpenCV) library. In our tests, the transport object was a 3 m long aluminium construction profile. One end of this profile is laid on the RB (see Figure 1). The profile can be loaded by the robot itself (see our previous work in [2]) or by a second mobile robot (when a second robot has to be used for loading, it can still perform another task during the object transport). After the robot has loaded the first end and grasped the other, it pulls the passive RB behind it as a trailer. The resulting system resembles a tractor-trailer robot (TTR), where the mobile manipulator acts as the tractor.

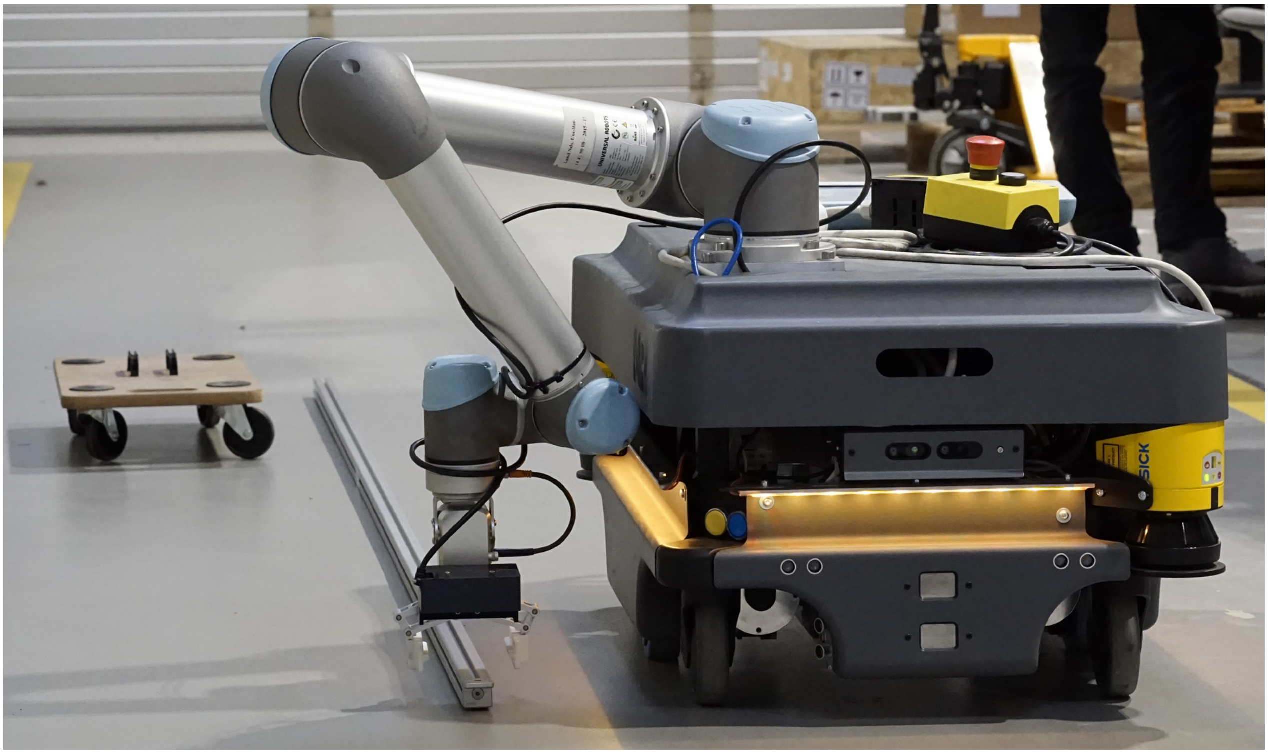

Figure 2: Top view of the TTR (MuR 205) transporting an aluminium construction profile

The main advantage of a TTR is that pulling the object on a trailer requires less energy than carrying the same object. Also, the resulting force load is much lower. Therefore, we can achieve nearly the same payload as a multi-robot system with a lower number of robots. A major disadvantage of this approach is that the RB and, thus, the object's position can no longer be actively controlled. Instead, the RB's trajectory is a consequence of the robot's trajectory, which means the RB is likely to collide with an obstacle. Conversely, the tractor's path planning must be modified to take the trailer into account.

After giving a short overview of related work, we present our modified path planning algorithm and our simulation model in section 3. In section 4, we present our simulation results and provide a conclusion and outlook on future work in section 5.

2. Related work

The problem of path planning for TTRs has been in the focus of many researchers over the last decades [3]. The various researchers have created many planners to solve path planning in different ways with different advantages and disadvantages. Although the research focuses on various aspects of the aforementioned problem, the most basic task is always to find a trajectory on which the tractor and trailer arrive at the target position in the correct orientation. This task is then made more difficult by including obstacles [4],[5], driving in reverse [6],[7] or adding more trailers [8],[9]. The first step in planning a trajectory is usually model design. A kinematic or dynamic model of the entire system is established, and subsequently, the parameters of this model are identified [10]. Researchers may choose a kinematic model over a dynamic model because it has fewer parameters and is easier to identify and compute [10]. But even for a kinematic model, the nonholonomic constraints and relatively large dimensional state-space can make modelling and identification very challenging [11].

Consequently, many approaches have been developed to deal with model design and model identification [3] [11]. These works have in common that the model is used to generate a motion plan after the modelling phase. The motion plan is then given to a controller, which tries to keep the trailer on this target by controlling the tractor [12]. This classic approach has certain advantages. For example, the position of several trailers can be controlled very precisely [9] so that the trailer(s) can be placed in the correct position for loading and unloading. This is important when, as in the case of a truck, the trailer does the actual transport, and the towing vehicle cannot unload the cargo. As we have proved in another publication [2], our system, on the other hand, is able to monitor the position of the trailer and to load and unload the transported objects itself. This means that in our case, it is not necessary to control the exact path and final position of the trailer as long as there is no collision with obstacles.

We intend to use this advantage to develop a novel approach to the path planning of tractor-trailer systems. As described, the goal of this approach is not to maximize the tracking performance or to enable complicated manoeuvring or turning procedures. Instead, we are creating an approach that is as simple as possible and can be added modularly to an existing path planner.

Other distinctive characteristics

Typical areas of application for TTRs are logistics [13],[14] and agriculture [15]. In such cases, there is a fixed coupling point for further trailers at each tractor and trailer. This coupling point is usually designed to define the coupling position precisely while the orientation is unrestricted. This allows effortless and inexpensive attachment of trailers as well as their exact control. However, this design is also very limiting. The manoeuvring behaviour of the TTR depends very strongly on the position of the coupling point [16]. Furthermore, the rigid coupling leads to a reciprocal influence of both system's error dynamics. Disturbances acting on the tractor are transferred to the tailer and vice versa. Using a manipulator to couple the object to the tractor, we can shift the coupling point's position as desired. This means we can influence the kinematic behaviour to adapt the TTR to changes in the environment. Also, the manipulator can be operated in impedance control mode, which partially dampens external disturbances.

Another difference from most existing work is that there is no persistent link between tractor and trailer. The object is only coupled to the tractor by gripping it using a robot. The connection between the RB and the object is only caused by friction. This makes the entire system very flexible in terms of the transport objects' size and shape, but the additional degrees of freedom also make it very difficult to describe the system behaviour analytically. Therefore, in the following, we present an approach that largely avoids analytical modelling and identification for path planning and instead intuitively adapts the tractor's path similar to a human truck driver.

3. Path planning algorithm

As described, the main task in literature is usually to plan the optimal trajectory for a given set of constraints. Setting up these constraints and then optimizing the path can make this process very cumbersome. Otherwise accessible objectives, such as energy or time optimized path planning or the coordination of several TTR systems to avoid collisions between robots, become very complex. This increase in complexity is caused by the coupling of kinematic constraints in a TTR. Therefore, our approach is based on a multi-step procedure (see Figure 3), which reduces the effects of coupling and enables the use of any global path planner made for a single mobile robot.

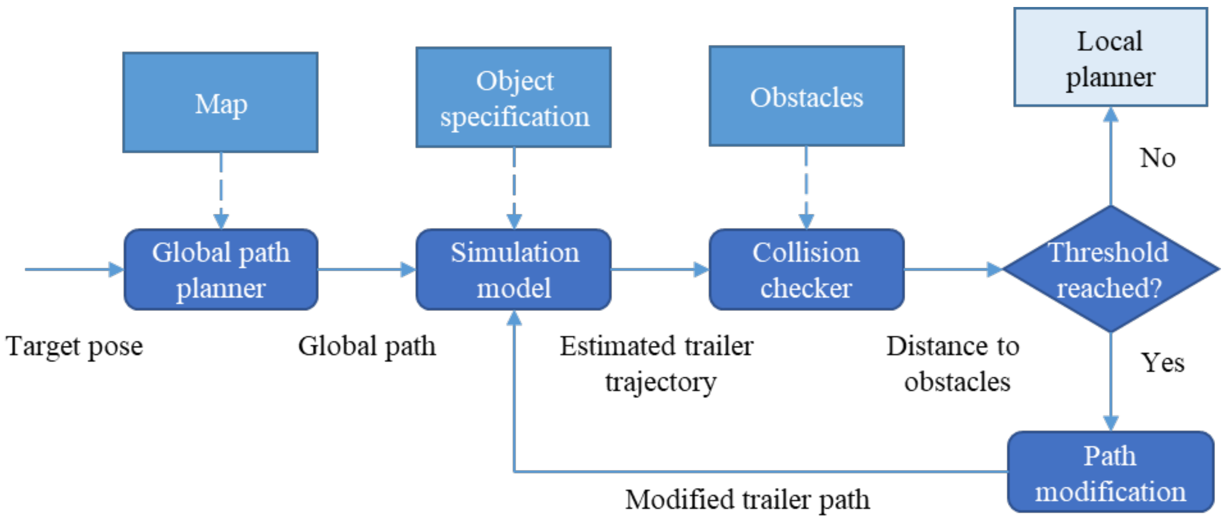

Figure 3: Flow chart of our proposed algorithm for path modification

First, we use the global path planning algorithm to generate the path target for the tractor. As we only consider the tractor in this first planning step, we can use any arbitrary planner from literature. This also means that our modification algorithm can be modularly “attached” to any existing navigation stack . To obtain an approximation for the trailer's path, we use a robot model in the Gazebo simulation environment (see section 3.1). If the simulation shows that the trailer maintains a safe distance from obstacles, we do not make any changes to the path and pass it directly to the local planner. Alternatively, we perform the procedure shown in Figure 3 to adjust the tractor's trajectory online, which we will describe in the following.

3.1 Simulation model

The simulation model is used to estimate how the trailer moves given the tractor's path. It consists of a mobile platform model, a manipulator model, an object model, and a trailer model. The models were created in the simulation environment Gazebo and are shown in Figure 4. Gazebo uses a numerical dynamics simulation to estimate the RB's motion. The advantage to an analytical model is the ease of model changes. Compared to a conventional TTR, we have to account for various additional parameters like manipulator pose, the angle of the profile, and 4 loose wheels (the typical configuration is 2 loose and 2 fixed wheels). With a numerical dynamics simulation, we can add these parameters to the model without significantly increasing complexity.

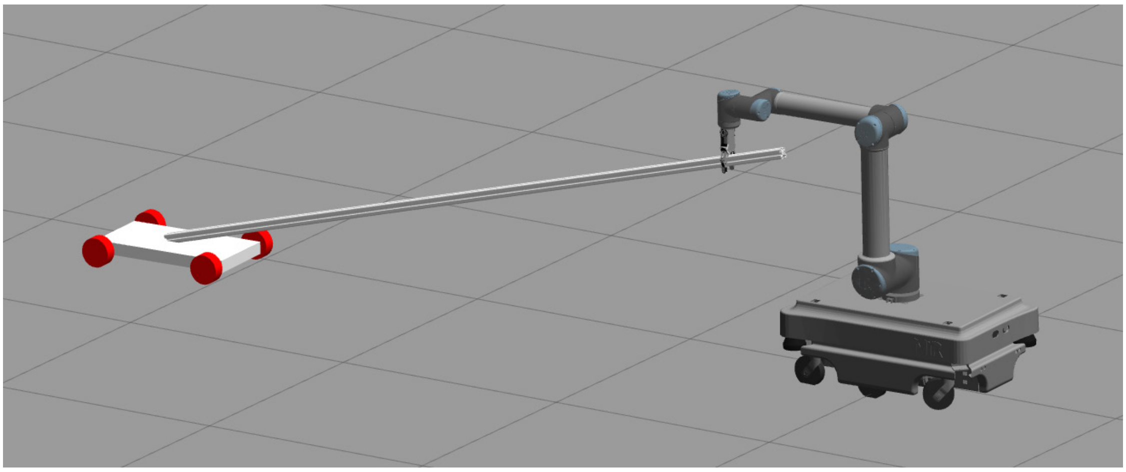

Figure 4: Model of the TTR in the simulation environment Gazebo

To build our entire system model, we used the manufacturer's existing models for the manipulator and the mobile platform. In this way, we achieve behaviour that is as realistic as possible. We calculate the object's mass, inertia, and center of gravity based on the manufacturer's CAD data and specifications. We assume that the object and its coupling to the manipulator are rigid. The coupling to the RB is made by static friction. We assume a friction coefficient μ_H of 0.5 for aluminium on wood according to [17]. The RB is modelled as a rigid plate with a length of 59 cm and a width of 29 cm. The four wheels are mounted on bearings along their vertical and rotational axes[1]. The bearings are assumed to have a friction coefficient of $c_{R,b} = 0.01$. The wheels' dimensions and distance are taken from the real roller board used to verify our simulations. The rolling resistance of the plastic wheels $c_{R,w}$ is assumed to be 0.01.

3.2 Path modification

While moving in a straight line, the trailer is always located exactly behind the tractor, eliminating the possibility of collisions with the surrounding area. Conversely, this means that all collisions with the environment occur in or shortly after curves. To minimize the computational effort, we only adjust the global trajectory segments in which the tractor takes a curve. The identification of these segments is described in section 3.2.1. Section 3.2.2 describes the modification process we have developed to adapt the existing path to a tractor-trailer system.

3.2.1 Curve detection

A curve is characterized by the presence of both linear v_x and angular velocities ω at the same time. Therefore, the first step is to derive the global path and exclude all segments, where one of the two velocities is zero. All segments where $|v_x| \gg |\omega_z|$ are also excluded, as curves with a very low curvature do not lead to any significant displacement of the trailer. Next, the start- and endpoints of the individual curve segments are determined. The start point is always the first point of the segment, and the endpoint the last point. Figure 5 shows the segmented path. The start- and endpoints of the respective curve are marked in step 3 and 4. By comparing the start orientation ϑ_S and end orientation ϑ_E, the direction of the curve can be determined in the last step. If $\vartheta_S > \vartheta_E$ it is a left curve, otherwise a right curve.

[1] For visual reasons, the wheels in our model are attached on the side instead of underneath. The kinematic behaviour is still equal.

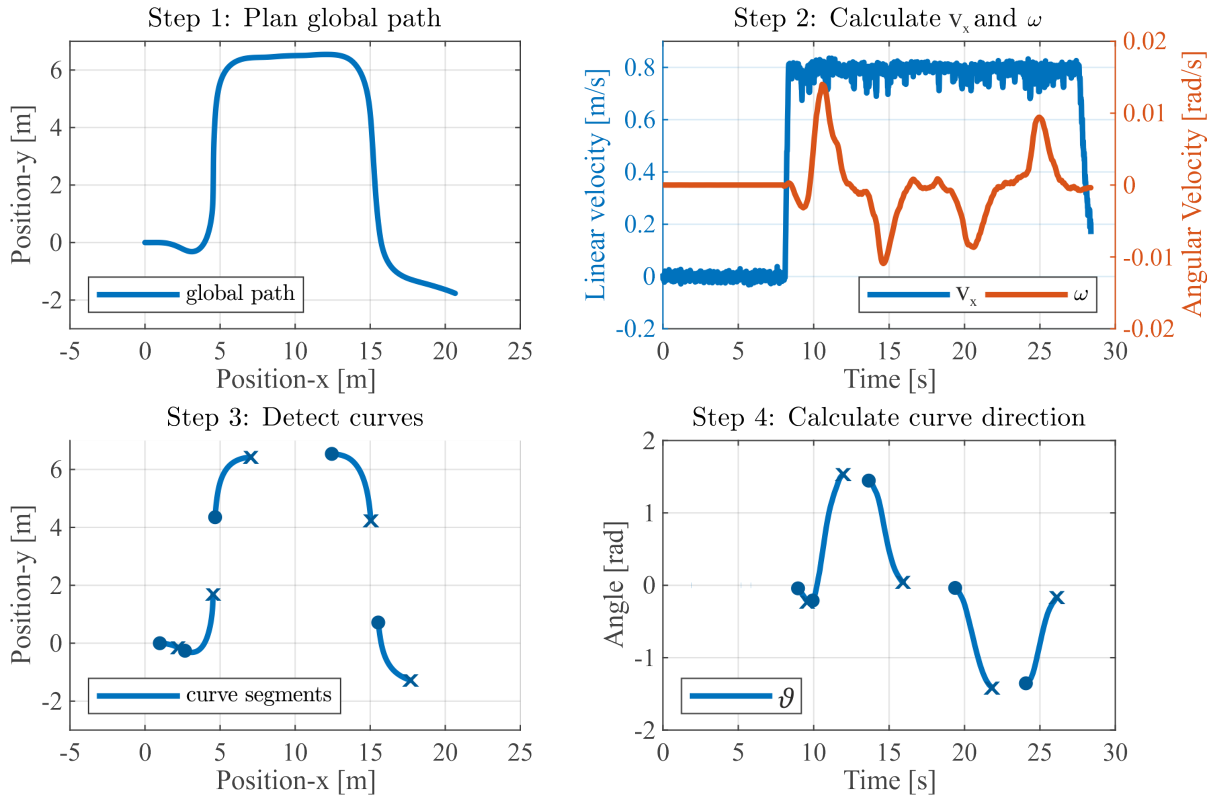

Figure 5: The four steps of curve identification. Start points are marked with a circle; endpoints with an x.

After determining all curves, which may cause a collision, the tractor's path is now modified in these segments.

3.2.2 Curve modification

In the curve modification, the simulation is used to determine the RB's minimum distance from any obstacle in every curve. If the minimum distance is below a predefined threshold, this curve is modified. We have set the threshold to 30 cm since this value is also preset as the mobile robot's safety distance. Should the RB get closer to an obstacle at the inner side of a curve, we simply increase the curve radius. This is done by defining two points $\boldsymbol{p}_1$ and $\boldsymbol{p}_2$. Given the start pose $\boldsymbol{x}_S$ and the end pose $\boldsymbol{x}_E$ as

$$\boldsymbol{x}_S = (x_S, y_S, \vartheta_S)^T \qquad\qquad \boldsymbol{x}_E = (x_E, y_E, \vartheta_E)^T \tag{1}$$

$\boldsymbol{p}_1$ and $\boldsymbol{p}_2$ are defined as:

$$\boldsymbol{p}_1 = \begin{pmatrix} \cos(\vartheta_S)\cdot d_1 - k\cdot\sin(\vartheta_S)\cdot d_2 + x_S \\ \sin(\vartheta_S)\cdot d_1 + k\cdot\cos(\vartheta_S)\cdot d_2 + y_S \end{pmatrix} \qquad \boldsymbol{p}_2 = \begin{pmatrix} -\cos(\vartheta_E)\cdot d_1 + k\cdot\sin(\vartheta_E)\cdot d_2 + x_E \\ -\sin(\vartheta_E)\cdot d_1 - k\cdot\cos(\vartheta_E)\cdot d_2 + y_E \end{pmatrix} \tag{2}$$

The length d_1 defines the distance from $\boldsymbol{p}_1$ tangential to $\boldsymbol{x}_S$ and $\boldsymbol{p}_2$ tangential $\boldsymbol{x}_E$. The length d_2 denotes the parallel distance to the tangent through $\boldsymbol{x}_S$ and $\boldsymbol{x}_E$ where k equals:

$$k = \begin{cases} -1 \; for \; \vartheta_S < \vartheta_E \\ \;\; 1 \; for \; \vartheta_S > \vartheta_E \end{cases} \tag{3}$$

In the next step, we use a 3rd order Bézier curve to compute a new trajectory between $\boldsymbol{x}_S$ and $\boldsymbol{x}_E$. The Bézier curve is described by:

$$x(t) = \sum_{i=0}^{n} \binom{n}{i} t^i \cdot (1-t)^{n-i} \cdot b_i \tag{4}$$

with $= 3$, $t_S \leq t \leq t_E$, $\boldsymbol{b}_1 = \boldsymbol{x}_S$, $\boldsymbol{b}_2 = \boldsymbol{p}_1$, $\boldsymbol{b}_3 = \boldsymbol{p}_2$ and $\mathbf{b}_4 = \boldsymbol{x}_E$. As shown in Figure 6, the curve radius is increased depending on the parameters d_1 and d_2.

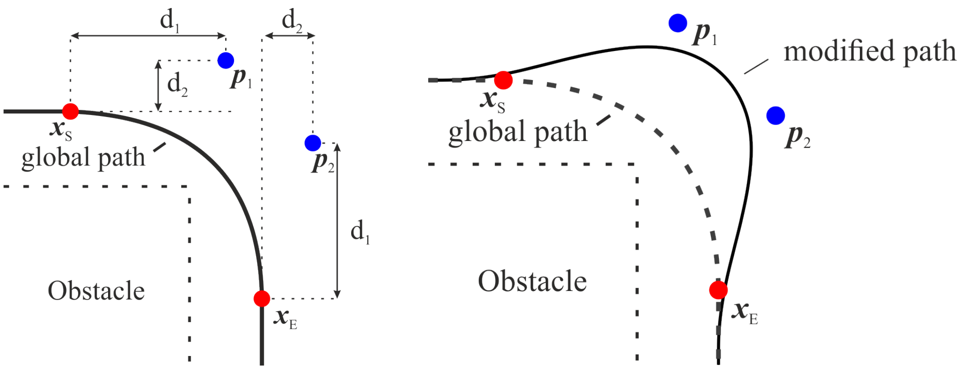

Figure 6: Bezier Curve with all control points (left: original; right: modified)

Several factors influence the selection of these parameters. On the one hand, a high value for d_1 or d_2 may result in collisions with obstacles at the outer edge of the curve. Also, the total path becomes longer, resulting in longer transport times. On the other hand, a value that is too small does not solve the original issue. Experiments show that we can achieve a good middle ground for $d_1 = l/2$, where l is the total length of the TTR. The length d_2 is determined using the local costmap. The local costmap is provided by the Robot Operating System (ROS) and represents the cost of traversing different areas of the map close to the robot. The cost map specifies, among other things, the smallest distance that the robot must maintain from an obstacle to avoid colliding with it (see Figure 8). By placing $\boldsymbol{p}_2$ at the boundary of the costmap (the next increase in cost), we can maximize the curve radius without risking a collision of the curve's outskirt. For this purpose, the smallest distance to the local costmap in the direction of $\boldsymbol{p}_2$ is determined for $d_2 = 0$. This distance is then set as d_2, whereby the maximum value is limited to $d_2 = d_1$. This process is carried out for all curves with a risk of collision. If the endpoint of a curve is closer from the start point of the next curve than d_1, both curves are combined. For this purpose, the end pose of the first curve $x_{E,1}$ and the start point of the second curve $x_{S,2}$ are deleted. The Bézier curve is then fitted with $\boldsymbol{b}_1 = \boldsymbol{x}_{S,1}$, $\boldsymbol{b}_2 = \boldsymbol{p}_{1,1}$, $\boldsymbol{b}_3 = \boldsymbol{p}_{2,1}$, $\boldsymbol{b}_4 = \boldsymbol{p}_{1,2}$, $\boldsymbol{b}_5 = \boldsymbol{p}_{2,2}$ and $\mathbf{b}_6 = \boldsymbol{x}_{E,2}$.

Lastly, the local planner uses the modified path to calculate the motion commands for the tractor. An exemplary modified global path is shown in Figure 5 on the right. This publication focuses on the global planner, so we will not describe the modifications to the local planner in detail. At this point, it is only important that the local planner uses the global trajectory, the costmap and the footprint of the robot to generate the motion commands for the tractor. We provide more detail on the estimation of the robot footprint in [16]. With this, our algorithm is complete, and we will evaluate it in the next section.

4. Evaluation

To validate our approach and as a proof of concept, we conducted simulative and physical experiments. In both cases, it was shown that collisions could be avoided even in confined environments. Nevertheless, we will focus exclusively on simulation results in this publication since they provide a much simpler and more accurate evaluation of the individual trajectories and different environments that can be tested. For the simulation, we use the model presented in section 3.1. The object is a 3-meter long aluminium construction profile with a weight of 4.5 kg. Considering the length of the profile and the gripper's additional weight, one mobile manipulator could not transport this profile alone. Three of the maps we tested are shown in Figure 7. The original global path (target path) is also marked, as created by the lattice motion planner [18].

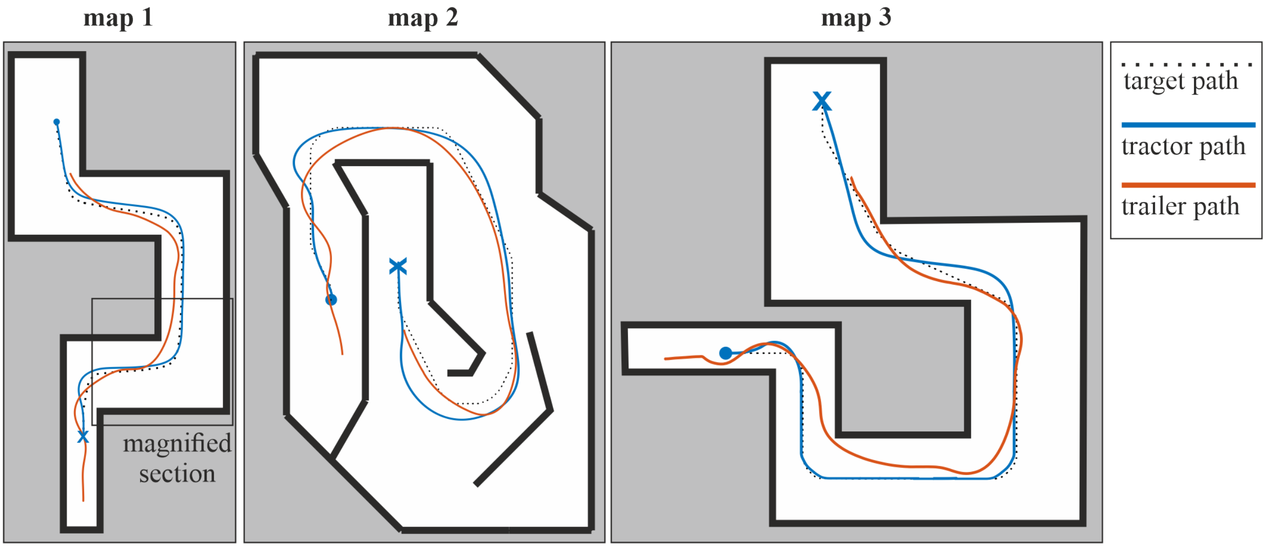

Figure 7: The three maps used for evaluation. The start of the global trajectory is marked with a circle and the end with an x.

The global path was set as the target path for the TTR and then modified as described in section 3.2. Looking at the tractor path compared to the target, both are very similar on straights and light curves. This is expected, as we only modify curves with high curvature. In modified curves, the modification results in a larger curve radius. The larger radius is especially noticeable at the end of the tractor path in map 2. Here, two curves with a high curvature are positioned closely, which causes our planner to combine both curves into one (see section 3.2.2). The increase in the curve radius also leads to an extension of the path length, as described previously. In map 1, the path length increases from 35 m to 36.2 m, in map 2 from 42 m to 45.1 m, and in map 3 from 40 m to 42.2 m. Figure 7 shows that the path modification works as intended. No collisions occur between the RB and the environment, although it appears as if the minimum distance threshold has been violated in some curves. However, this is only a visualization issue. As shown in the magnified section from map 1 (Figure 8), the higher cost region is not entered. In summary, this means that our approach is capable of generating a collision-free trajectory for a TTR.

The main disadvantage of our approach arises from the calculation of the trailer trajectory via numerical simulation. Since the calculations are currently performed on the low-powered robot computer, they can only be performed with a real-time factor (RTF) of one. This means that the RB trajectory calculation with simultaneous collision checking takes roughly the same amount of time as traversing the trajectory. However, using faster external computation, the simulation could be performed at much higher RTFs in the future.

Regarding the simulation accuracy, we observed that qualitatively the calculated trailer path corresponds to the physical trajectory. As mentioned previously, we use the manipulator to couple the trailer to the tractor. The manipulator uses an impedance controller to allow for force-free rotation of the profile around the coupling point. However, unlike the simulated manipulator, the real manipulator cannot control the rotational stiffness and rotational damping exactly to zero. This means that a small amount of stiffness and damping remains, which counteracts the RB's rotation around the coupling point. Therefore, the real profile does not rotate as much as in the simulation, causing the RB to be slightly steadier and have a slightly larger curve radius. After the first tests, it looks like this difference could be mitigated by altering the simulation model and not requiring a change in path modification.

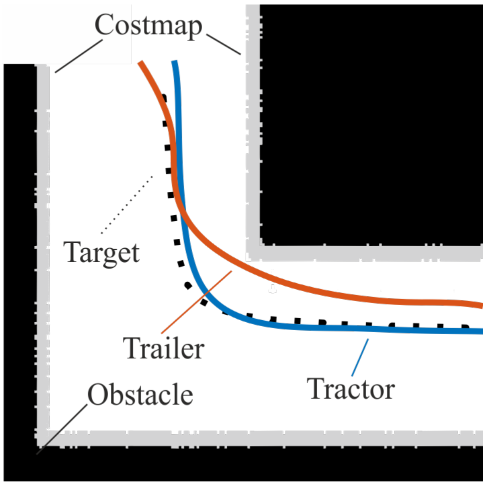

Figure 8: Magnified section from Figure 7 (map 1)

5. Conclusion and outlook

We have presented an approach that extends a single mobile robot's capabilities regarding object size and weight using an ordinary roller board. The addition of a passive RB introduces several issues for navigation and manoeuvring confined environments. To overcome these issues without significantly increasing complexity, we have presented an intuitive approach to modify an existing path that takes inspiration from a human truck driver. For this purpose, our algorithm is inserted as a module between the existing global and local planner. The modification works by first detecting all curves of the path. A simulation model then determines in which curves a collision potentially occurs. Next, we use a Bézier spline to increase the respective curve radius. This approach allows the separation of global path planning and kinematic/dynamic modelling, thereby simplifying the planning process and model design. We tested this approach in various scenarios and demonstrated its effectiveness in simulation. The transport of a construction profile shows that even minor modifications to the path can significantly reduce collision risk. For future work we plan to develop a visual system for tracking the trailer. In this way, we can perform a quantitative evaluation of physical experiments. We are also looking for a suitable analytical model. Currently, the time-consuming trailer trajectory estimation is the biggest disadvantage of our approach. The estimation time could be drastically lowered if an analytical model is established for the specific system.

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Biography

Tobias Recker (*1991) has been a research assistant at the Insitute of Assembly Technology (match) at the University Hanover since 2017. Tobias Recker is reasearching multi-robot-collaboration as well as human-robot-collaboration. His main research topic is the design and implementation of multi-robot object manipulation using mobile robots.

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