

Általános információk, a diplomaterv szerkezete

A diplomaterv szerkezete a BME Villamosmérnöki és Informatikai Karán:

1. Diplomaterv feladatkiírás
2. Címoldal
3. Tartalomjegyzék
4. A diplomatervező nyilatkozata az önálló munkáról és az elektronikus adatok kezeléséről
5. Tartalmi összefoglaló magyarul és angolul
6. Bevezetés: a feladat értelmezése, a tervezés célja, a feladat indokoltsága, a diplomaterv felépítésének rövid összefoglalása
7. A feladatkiírás pontosítása és részletes elemzése
8. Előzmények (irodalomkutatás, hasonló alkotások), az ezekből levonható következtetések
9. A tervezés részletes leírása, a döntési lehetőségek értékelése és a választott megoldások indoklása
10. A meghalászott műszaki alkotás értékelése, kritikai elemzése, továbbfejlesztési lehetőségek
11. Esetleges köszönhetők
12. Részletes és pontos irodalomjegyzék
13. Függelék(ek)

Felhasználható a következő oldaltól kezdődő L^AT_EX-diplomatervsablon dokumentum tartalma.

A diplomaterv szabványos méretű A4-es lapokra kerüljön. Az oldalak tükörmagjával készüljenek (mindenhol 2,5 cm, baloldalon 1 cm-es kötéssel). Az alapértelmezett betűkészlet a 12 pontos Times New Roman, másfeles sorközzel, de ettől kismértékben el lehet térdíni, ill. más betűtípus használata is megengedett.

Minden oldalon – az első négy szerkezeti elem kivételével – szerepelnie kell az oldalszámnak.

A fejezeteket decimális beosztással kell ellátni. Az ábrákat a megfelelő helyre be kell illeszteni, fejezetenként decimális számmal és kifejező címmel kell ellátni. A fejezeteket decimális aláosztással számozzuk, maximálisan 3 aláosztás mélységen (pl. 2.3.4.1.). Az ábrákat, táblázatokat és képleteket célszerű fejezetenként külön számozni (pl. 2.4. ábra, 4.2. táblázat vagy képletnél (3.2)). A fejezetcímeket igazitsuk balra, a normál szövegnél viszont használunk sorkiegynítést. Az ábrákat, táblázatokat és a hozzájuk tartozó címet igazitsuk középre. A cím a jelölt rész alatt helyezkedjen el.

A képeket lehetőleg rajzoló programmal készítsék el, az egyenleteket egyenlet-szerkesztő segítségével írják le (A L^AT_EX ehhez kézenfekvő megoldásokat nyújt).

Az irodalomjegyzék szövegközi hivatkozása történhet sorszámozva (ez a preferált megoldás) vagy a Harvard-rendszerben (a szerző és az évszám megadásával). A teljes lista névsor szerinti sorrendben a szöveg végén szerepeljen (sorszámozott irodalmi hivatkozások esetén hivatkozási sorrendben). A szakirodalmi források címeit azonban mindenkor az eredeti nyelven kell megadni, esetleg zárójelben a fordítással. A listában szereplő valamennyi publikációra hivatkozni kell a szövegben (a L^AT_EX-sablon a Bib^TE_X segítségével mindenkor automatikusan kezeli). minden publikáció a szerzők után a következő adatok szerepelnek: folyóirat cikkeknél a pontos cím, a folyóirat címe, évfolyam, szám, oldalszám tól-ig. A folyóiratok címét csak akkor rövidítsük, ha azok nagyon közismertek vagy nagyon hosszúak. Internetes hivatkozások megadásakor fontos, hogy az elérési út előtt megadjuk az oldal tulajdonosát és tartalmát (mivel a link egy idő után akár elérhetetlennek is válhat), valamint az elérés időpontját.

Fontos:

- A szakdolgozatkészítő / diplomatervező nyilatkozata (a jelen sablonban szereplő szövegtartalommal) kötelező előírás, Karunkon ennek hiányában a szakdolgozat/diplomaterv nem bírálható és nem védhető!
- Mind a dolgozat, mind a melléklet maximálisan 15 MB méretű lehet!

Jó munkát, sikeres szakdolgozatkészítést, ill. diplomatervezést kívánunk!

FELADATKIÍRÁS

A feladatkiírást a tanszéki adminisztrációban lehet átvenni, és a leadott munkába eredeti, tanszéki pecséttel ellátott és a tanszékvezető által aláírt lapot kell belefűzni (ezen oldal helyett, ez az oldal csak útmutatás). Az elektronikusan feltöltött dolgozatban már nem kell beleszerkeszteni ezt a feladatkiírást.



Budapest University of Technology and Economics

Faculty of Electrical Engineering and Informatics
Department of Measurement and Information Systems

Development of Navigation Methods in Dynamic Environment for an Intelligent Model Car

BACHELOR'S THESIS

Author

Soma Veszelovszki

Advisor

Domokos Kiss

November 24, 2019

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HALLGATÓI NYILATKOZAT

Alulírott *Veszelovszki Soma*, szigorló hallgató kijelentem, hogy ezt a diplomatervet meg nem engedett segítség nélkül, saját magam készítettem, csak a megadott forrásokat (szakirodalom, eszközök stb.) használtam fel. minden olyan részt, melyet szó szerint, vagy azonos értelemben, de átfogalmazva más forrásból átvettem, egyértelműen, a forrás megadásával megjelöltem.

Hozzájárulok, hogy a jelen munkám alapadatait (szerző(k), cím, angol és magyar nyelvű tartalmi kivonat, készítés éve, konzulens(ek) neve) a BME VIK nyilvánosan hozzáférhető elektronikus formában, a munka teljes szövegét pedig az egyetem belső hálózatán keresztül (vagy autentikált felhasználók számára) közzétegye. Kijelentem, hogy a benyújtott munka és annak elektronikus verziója megegyezik. Dékáni engedéllyel titkosított diplomatervek esetén a dolgozat szövege csak 3 év eltelte után válik hozzáférhetővé.

Budapest, 2019. november 24.

Veszelovszki Soma
hallgató

Kivonat

A diplomatervezési feladat egy, a tanszéken futó kutatási projekthez kapcsolódik, amelyben egy intelligens autó tesztplatform létrehozása a cél. A platform alapja egy csökkentett méretű (kb. 1:3 méretarányú) autómodell, melyet egy távirányítható játékautóból alakítunk át. A tesztplatform létrehozásának célja különböző navigációs algoritmusok fejlesztésének és valós környezetben történő tesztelésének elősegítése.

A sikeres navigáció és az ütközések elkerülése érdekében fontos, hogy a jármű valós időben detektálni tudja a környező objektumokat, és megfelelően reagáljon rájuk. Ennek elősegítése érdekében az autóplatformon elhelyezésre került egy-egy vízszintes síkban pásztázó lézeres távolságszkenner (lidar) a jármű elején és hátulján.

A feladat keretében ezekre a szenzorokra építve kell megvalósítani mozgó objektumok felismerését, azok méretének és sebességvektorának becslésével együtt. Fontos, hogy a jármű el tudja különíteni a statikus és a mozgó akadályokat egymástól. További feladat egy olyan akadályelkerülési módszer megvalósítása az autón, amely az objektumok mozgását is figyelembe véve hozza meg a megfelelő navigációs döntést minden időpillanatban.

A megvalósított algoritmusok működését mind szimulált, mind valós környezetben szükséges ellenőrizni. A valós tesztelés történhet a tanszéki járműplatformon, vagy egy kisméretű, egyedileg felépített modellautón is.

Abstract

The theme of the thesis is a subtask of a research project at the Department of Automation and Applied Informatics, with the purpose of designing an intelligent car testing platform. The platform is based on a decreased-size (1:3 scale) remote control car model, that has been modified to support self-driving program control. The platform aims to support the development of different navigation algorithms and helping the testing in real environment.

For a successful navigation and obstacle avoidance, the detection of the surrounding objects and reacting accordingly are essential. For the purpose of detection, two horizontal distance scanning sensors (lidars) have been placed on the car - one on the front and one on the back.

Part of the task is to implement the detection of the moving obstacles and estimate their sizes and speed vectors. It is important for the car to be able to separate static and moving objects from each other. The other part is developing an obstacle-avoidance method, implemented as an application on the car, that takes the moving objects into consideration while making navigational decisions at every time step.

The implemented algorithms need to be tested both in simulation and in real environment, that may be executed on the department's vehicle platform or on a small-scale, custom-build model car.

Chapter 1

Introduction

Nowadays, self-driving cars gain more and more attention, both their technology and their effect on people's daily routines and their lives overall. Several articles are published every year about how these cars will change the way people commute to work, visit their friends or go on a family vacation. These articles often point out the decrease of the number of accidents, an optimized load of traffic and thus a reduced fuel consumption as the major advantages of this technology-to-come.

The release date of these cars, however, is still a matter of question. In 2015, Mark Fields, president and CEO of Ford at the time estimated their first fully autonomous car in 2020. 2 years later, at CES 2017 Nvidia announced that with the partnership of Audi they would develop a self-driving vehicle - also, in market by 2020. Both of these statements are considered too ambitious guesses today, as there is a high probability that we need to wait until at least 2025 for reliable fully autonomous vehicles to hit the roads. Claiming that there are no viable signs of these cars in traffic would be a false statement, as there are several companies who have been testing their vehicles on public roads for the last years, but these prototypes are very far from reliable products yet. The company that seems to be ahead of the competition in this race is Tesla. Their self-driving software is already in their products, but it still needs millions of hours of testing and the responsibility is still the driver's if an accident happens.

But why is this delay of release dates? One possible answer is that manufacturers have the tendency to exaggerate when asked about new products, and thus the users' need and the other competitors development speed urged them to make such estimations they could not keep up with. Another theory is that the companies at that time didn't acknowledge how many hours and kilometers of testing is needed to finalize a self-driving product.

However, the spreading of autonomous vehicles is blocked by several legislative and technological obstacles. As this thesis describes an engineering problem and its solution, I will reflect on the technological blockers that both car manufacturers and other self-driving software developer companies need to face. Just to list some of these problems, we can name reliable object detection, error insensitive, robust decision-making, fast, well-tuned physical control, and to meet the safety and quality requirements set by the market, determinant scheduling and redundancy throughout the whole software are also essential.

Chapter 2

Mapping

2.1 Existing implementations

This chapter describes the process of building a separate static and a dynamic map (containing non-moving and moving obstacles, respectively) based on radial distance measurements (in this case provided by a LIDAR). Isolating the static and the moving obstacles from each other has its difficulties but also its advantages. First of all, the implemented local track planner calculates safer, more optimized paths if it is informed of both the static and the dynamic obstacles along the path. Secondly, [SLAM](#) (Simultaneous localization and mapping) algorithms work better if their input contains only static objects in the space, because they build an internal map of the world. Passing detections of moving obstacles to a SLAM algorithm may lead to worse localization quality, as they may ruin this map.

As a first subtask of the mapping project, I checked if any implementation is available already, that can handle dynamic objects. The only possible candidate was [gmapping](#), which is a popular ROS package, used in a wide variety of applications that require map-building and localization. Its SLAM algorithm takes LIDAR measurements as its input and generates an occupancy grid (a 2D map) of the car's environment. By using this map it is able to make corrections to the car's odometry-based position and orientation, which is usually inaccurate. I tried out the package, and the result maps were promising, the generated map was insensitive to the car's longitudinal movements and its rotations. But unfortunately, gmapping's SLAM does not support dynamic objects. See Section 2.6.1 for further details. Therefore, gmapping could not be used as the producer of the static map. But that didn't mean it couldn't be used for its second feature, localization. Note, that the mapping implementation I made is not a SLAM algorithm, it is not able to make corrections to the car's pose. So for that purpose, I still needed the help of gmapping, which proved to be very reliable at localization. But the static map-building needed to be implemented internally.

2.2 Method

This chapter describes the process of building a separate static and a dynamic map (containing non-moving and moving obstacles, respectively) based on radial distance measurements (in this case provided by a LIDAR). Isolating the static and the moving obstacles from each other has its difficulties but also its advantages. First of all, the implemented

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In order to create two disjunct maps, one static and one dynamic, the key element of the process is the separation of the moving and non-moving obstacles of the measured points. After determining these two disjunct set of points, the maps can be converted to any desired or required format. Static maps are usually published as occupancy grids, while dynamic obstacles need to present information about their speed vector. Occupancy grids do not group the grid points according to their probabilities, therefore they do not know about the obstacles' borders and areas¹. Dynamic obstacles however can be either represented as separate points with their own speed vectors, or groups of points, each group having one speed vector. I chose the latter representation, thus publishing groups that contain a set of points (all the points, ideally) of the same obstacle. This way there is a one-to-one relationship between moving obstacles and groups. The separation and grouping methods of the mapping process is shown on diagram 2.1.

The diagram consists of 3 subgraphs - these are also marked on the diagram. The first, and most important is the separation and grouping of dynamic points. The second subgraph describes the additional calculations that need to be done for the dynamic obstacles, and consists of the documentation for the message structure defining these dynamic obstacles. And the third one is about the static map that is built from the static points. The sections under 2 explain these subgraphs in detail.

2.3 Input parameters

The following input parameters can manipulate the mapping node:

LIDAR_MAX_DIST [meter]

¹In this project, 2D LIDARs were used, therefore the measured objects were seen as 2D shapes that have areas, not 3D objects that have volumes

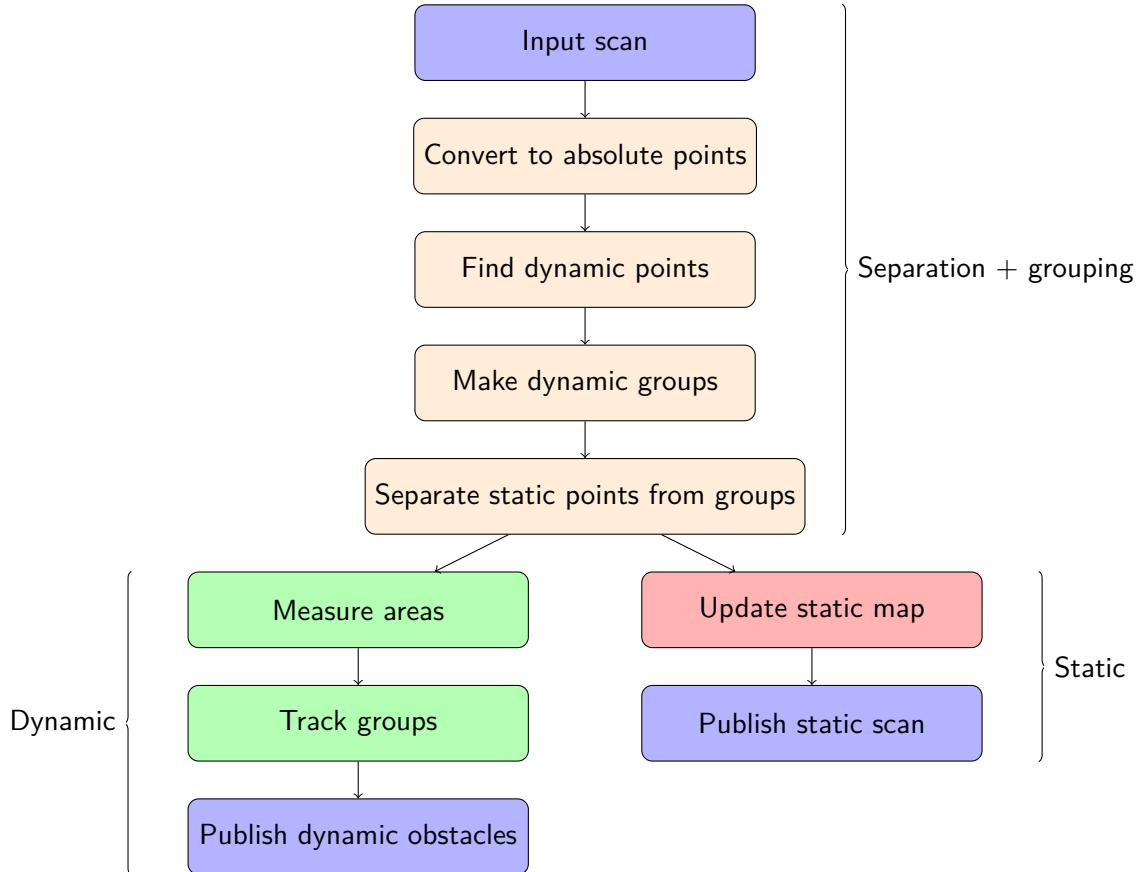


Figure 2.1: Mapping method

The maximum measurable distance by the LIDAR(s). Depends on the LIDAR's characteristics.

MAP_RES [meter]

The resolution of the built static map. Increasing this value helps building a better quality map, but also increases the node's resource need.

MAP_SIZE [meter]

The size of the built static map. Increasing this value helps building a better quality map, but also increases the node's resource need.

SINGLE_LIDAR [boolean]

Defines if the node's input is one LIDAR scan, or a separate front and rear scan that needs to be handled separately.

2.4 Separation and grouping

This section describes the method of separating dynamic and static points of the input scan. This step is essential in the pipeline of creating two disjunct maps.

2.4.1 Input scan

The input of the mapping algorithm is a 2D LIDAR scan, consisting of radial distance measurements. Two types of LIDARs were used in the project, [RPLidar A1](#) and [RPLidar A2](#). Both types have the following specifications:

Scan rate	10 Hz
Sample rate	8000 samples/sec
Distance resolution	0.2 centimeters
Angular resolution	1°
Detection range	12 meters

The devices proved to be reliable, and for a project of this volume, their frequencies, resolutions and ranges were adequate. Their output after each measurement sequence is an array of radial distances, that can be visualized easily using rviz.

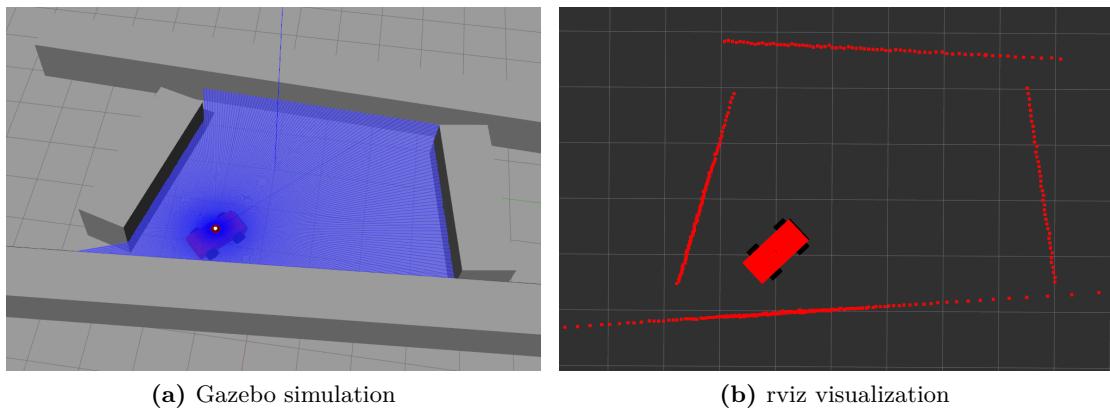


Figure 2.2: LIDAR scan

2.4.2 Absolute points

For static map-building, absolute points² are needed in the space, and static-dynamic point separation also uses absolute points, so firstly, these radial distances need to be transformed. However, the internal static map and the static-dynamic separation use different coordinate systems. In order to understand the need for this, let's take a look at figure 2.3.

As the figure shows, there are 3 coordinate frames that are important to the current case. The *odom* frame is the car odometry's coordinate system. It is calculated from values measured on the vehicle, such as servo position and speed. The *scanner* frame is the LIDAR's coordinate system. The transformation between *odom* and *scanner* is basically the pose of the LIDAR, relative to the car. The *map* frame is the output of gmapping's localization. Basically, gmapping takes the car odometry and the LIDAR scans as its input, and corrects the odometry using SLAM. As a result the difference between frames *map* and *odom* will increase with time.

The internal static map in my implementation uses this corrected *map* frame as the base for its points, so that its error is minimized. But unfortunately, the static-dynamic separation

²Absolute points are not relative to the car, but to a fix base point.

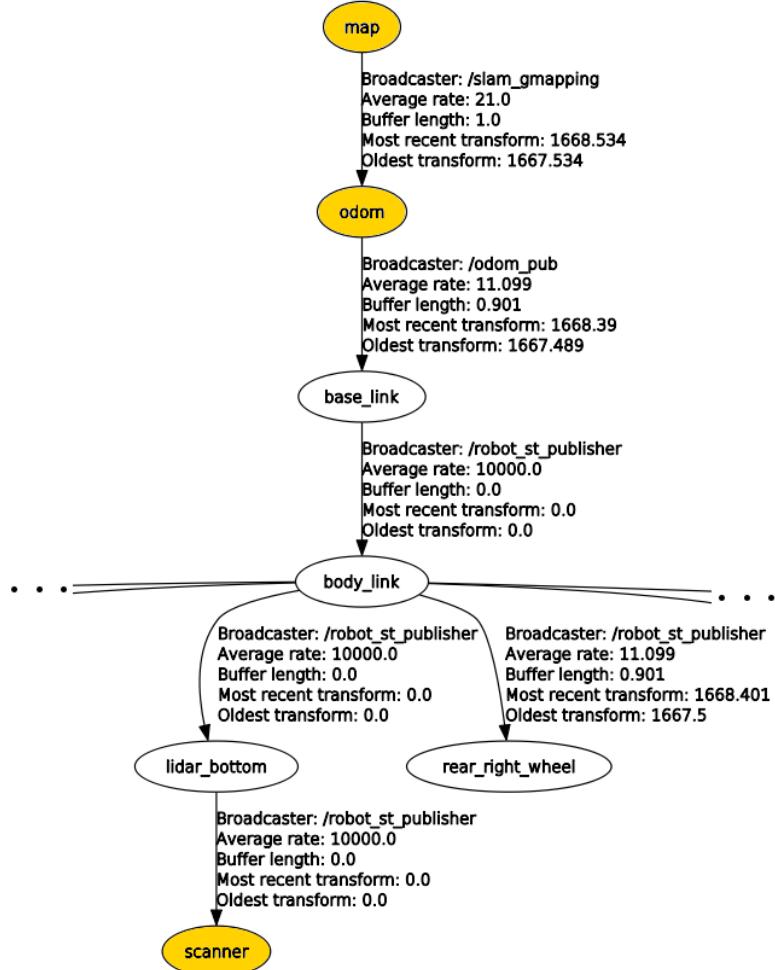


Figure 2.3: Coordinate frames

method cannot use this frame. The reason is that this frame does not get updated on every new scan, but with a much slower frequency. Therefore there are 'jumps' in the *map* frame, which would cause false dynamic point detections (see Section 2.4.3). To avoid this undesired situation, the static-dynamic separation uses the *odom* frame as its base, which is more continuous than the *map* frame.

Therefore, two transformations are needed for each input point. The transformations are calculated using `tf`, which maintains the relationship between coordinate frames in a tree structure (see figure 2.3) buffered in time, and makes the transformation of points, vectors, etc possible at any desired point in time.

2.4.3 Dynamic points

The next step is similar to creating a subtraction image in image processing, where subtracting two images, taken from the same position but at a different time, results in an image that amplifies the movements between the snapshots. Previous methods[1] that I studied before starting my implementation are also based on this step. The aim of this algorithm unit is basically the same: selecting the points from the input that are likely to be part of a moving mass. This is done by finding the points among the current measurements that have not been present in the previous ones.

This step is best explainable in practice. Let's assume that the position and orientation of the LIDAR is fix, and one object (e.g. a car) in the detected area is moving. Figure 2.4 shows this situation. On the image, the pale contour represents the previous pose of the object, and the current state is blue.

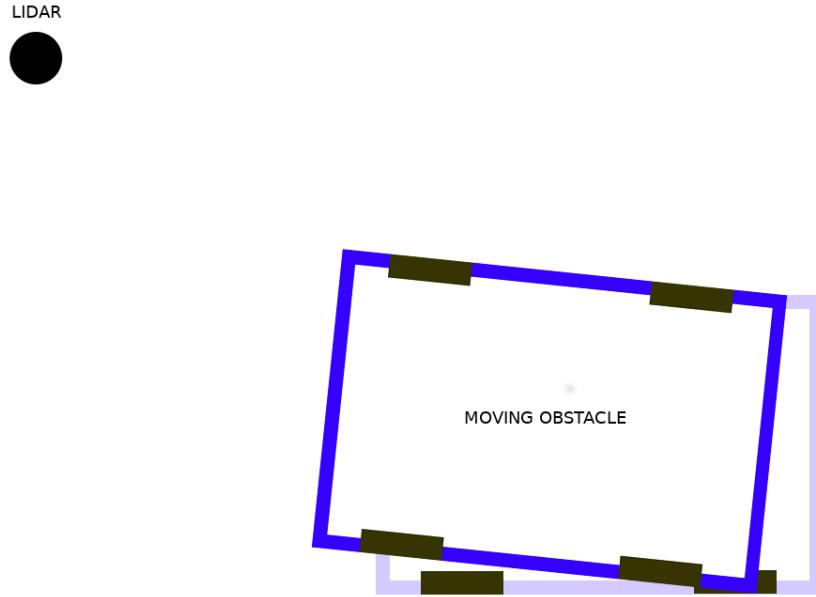


Figure 2.4: The obstacle is moving

Figure 2.5 shows how the LIDAR detects the moving object in two different timesnaps. I marked the points corresponding to the current position with red color, and the ones of the previous measurement are pale red. As it is suggested in the figure, the measurements are far from ideal, the detected points are noisy.

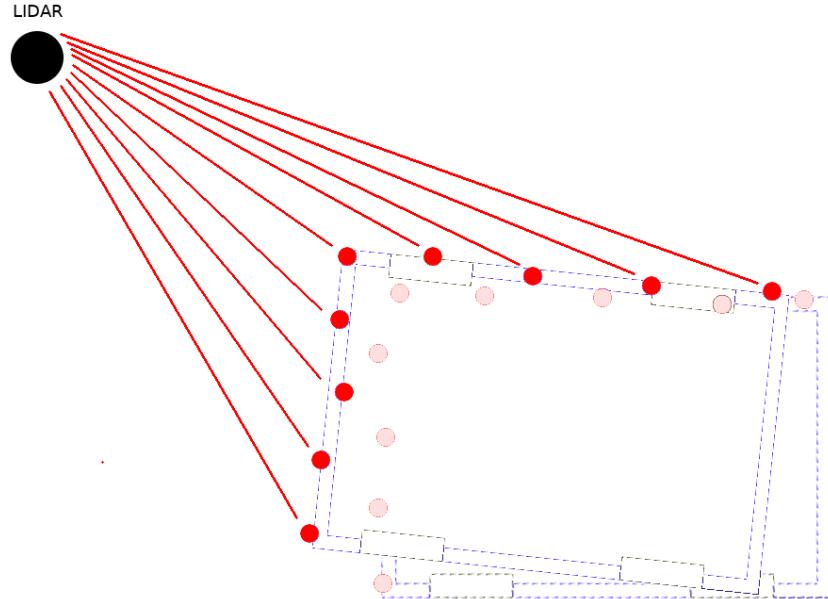


Figure 2.5: The detected points of the moving obstacle

To understand the method of dynamic point detection, I removed the LIDAR, its virtual rays and the obstacle's contour from the image, thus leaving only the measured points of the two timesnap. The result, which is basically a time-buffered array of 2D

points, is presented on figure 2.6. The algorithm iterates through each point in the current measurement, and checks if any point in the previous measurements³ is within its compliance radius⁴.

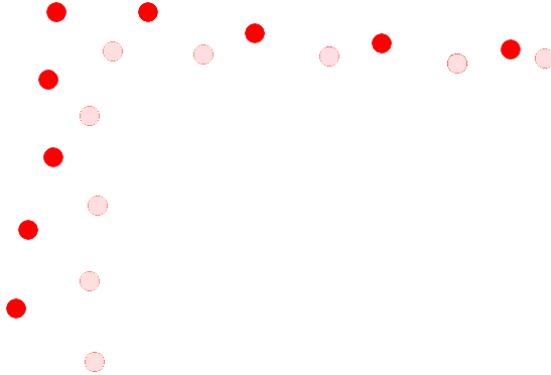


Figure 2.6: The detected points of the two timesnaps

The measured points with their compliance radiiuses are presented in Figure 2.7. The possible dynamic points, that have no points from the previous measurement within their radius, are marked with blue, and their compliance radius with yellow. The possible static points are marked with red, along with their radiiuses. Note, that these points are *possible* dynamic and static points. The final classification will be preceded by multiple filtering mechanisms and point grouping, but this is the base for finding dynamic objects.

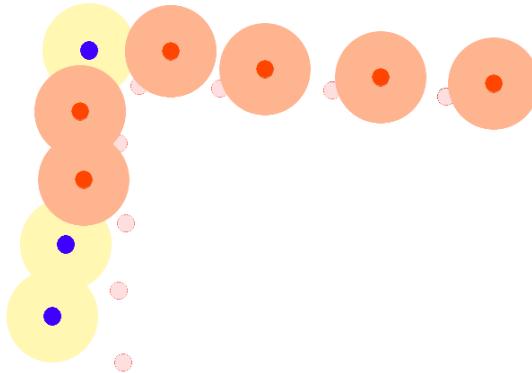


Figure 2.7: The compliance radiiuses and the dynamic points

Several conclusions can be drawn from Figure 2.7. The one, and probably most important is that with right parameterizing (number of 'look-up' measurements, compliance radius, etc) this method amplifies the positive⁵ and negative⁶ changes of the scans. The second remark is that the method does not detect all the points of a moving object. However, due to measurement noise, false detections may happen, and non-moving points may be marked as dynamic.

³The number of measurements to 'look up' is configurable.

⁴The compliance radius is a maximum allowed distance between measurements representing the same physical point but measured in different timesnaps. If the distance between two measurements is greater than this value, the measurements are assumed to represent different points of the space. The compliance radius is calculated for each measurement separately, and it is proportional to the distance of the LIDAR and the measured point.

⁵Previously a distant background was detected, but now a closer object appears.

⁶Previously a close object was detected, but now it disappears, and the distant background becomes visible.

Therefore, the result of this separation step needs to be filtered. I implemented a filtering step that only keeps those samples in the set of dynamic points, of which the left and right neighbour in the scan has also been marked dynamic. It can be easily compared to [erosion](#) in image processing, which is able to remove peaks from the image. Let's take a look at Figure 2.8. The possible dynamic points are marked with blue. The filtering mechanism iterates through each of them, and check both neighbours. As it can be easily read from the figure, point *A* has two neighbours that have been marked static, therefore it will be removed from the set of dynamic points. However, points *B* and *C* both have dynamic neighbours (each other), so they will not be filtered out. This algorithm removes the single-size false detections from the result of the separation.

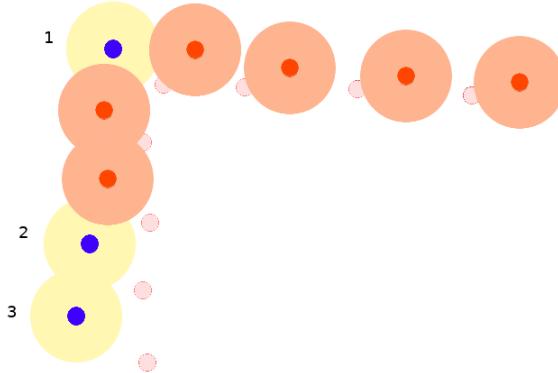


Figure 2.8: Point *A* will be filtered out

2.4.4 Grouping

After the filtering, we can safely assumed that the elements in the dynamic point set are in fact points of a moving obstacle. The next step is grouping the corresponding dynamic points, and also adding those points to these groups that were previously marked as static, but they are part of a moving group. For example in Figure 2.8, after the separation and filtering, only points *B* and *C* were marked dynamic, but actually, all the points in the image are points of the same object, that is moving. The grouping algorithm needs to be able to add these other points to the group as well.

The grouping algorithm is based on the supposition that coherent points are close to each other, while the distance between points of separate objects is larger. With a few exceptions, this statement holds its stand, by practice it proved to be a reliable base for grouping. The algorithm itself is quite simple, it separates the list of measurements (including the static and dynamic points as well) into subsets - groups. A new group is started when the distance between two adjacent points is larger than the permitted maximum within a group. This maximum is an empirical constant, with experiments of valid use cases. The result of the step is shown in 2.9b.

As it is clearly visible on the image, far points that are correspondent to the same object may be separated from each other, and grouped one by one - see the bottom right corner of the picture. However, the further an object is from the LIDAR, the less important it is for the local trajectory planner, which needs to avoid close obstacles. But still, they are not valid groups, so as the last step of the grouping mechanism, these single-point groups will be removed from the list of groups. But before doing that, there is still one special case that needs to be handled by the grouping unit - the *wall following car*. Let's imagine the situation represented in Figure 2.10. The detected obstacle (represented by the box)

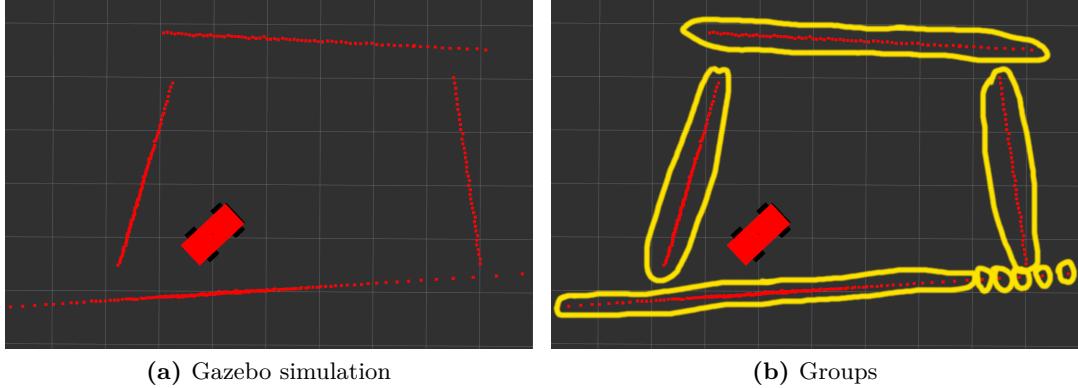


Figure 2.9: Distance-based grouping

is moving alongside the wall, and within the maximum group point distance. Therefore, the grouping algorithm will join the groups. This wouldn't be a problem if the box wasn't moving, but as soon as it changes its position, grouping it together with the wall would ruin the mass center and speed vector calculation, described in Section 2.5.2.

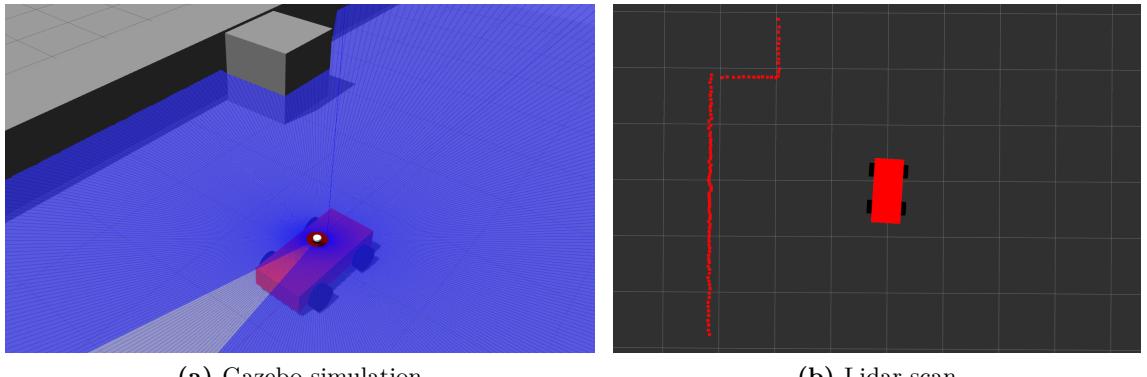


Figure 2.10: The *wall following car*

To avoid this problem, the algorithm detects if an obstacle is unusually large, and cuts off long 'tails' from the group. Figure Figure 2.11 explains this step in practice.

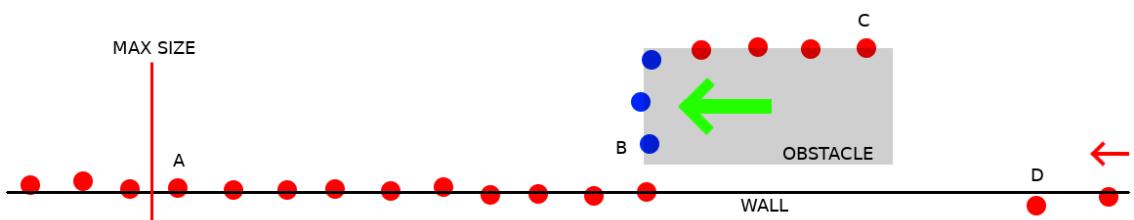


Figure 2.11: Points on the left of *B* will be cut off

Let's assume that the algorithm iterates through the points visualized in the figure from the right. The distance between points *C* and *D* is larger than the allowed maximum group point distance, therefore point *C* starts a new group. Until the program reaches point *A*, all the points are added to this group, because the distance between adjacent points is always lower than the maximum group point distance, but after point *A*, the algorithm detects that the group is larger than the permitted limit. So the iteration turns

around, and all the points are getting removed from the group, until the first dynamic point is reached - in the current example this would be point *B*. As a result, only the points between (and including) point *B* and point *C* will be grouped together.

As an undesired side-effect, this step may also remove some of those points from the group that are in fact parts of the moving object but were marked as static, because the removal only stops at the first *dynamic* point.

2.4.5 Separation of static points and dynamic groups

The previous step has successfully sorted the measured points into groups, but it is undecided yet if these groups are moving or not. This decision is made by checking the number of dynamic points in each group, which must exceed the required minimum in order to the group being marked as dynamic.

This was the last step of the separation of the groups, from this point, static points and dynamic groups will be handled differently.

2.5 Dynamic obstacles

After the dynamic groups have been separated from the static points, additional information needs to be calculated for them, so that the local track planner algorithm can use their data for its obstacle-avoidance feature. 3 pieces of information are needed for each object, its position, size and speed vector. All of these are calculated from the object's mass center, which is the average of the group points. This mass center is considered to be the object's position in space.

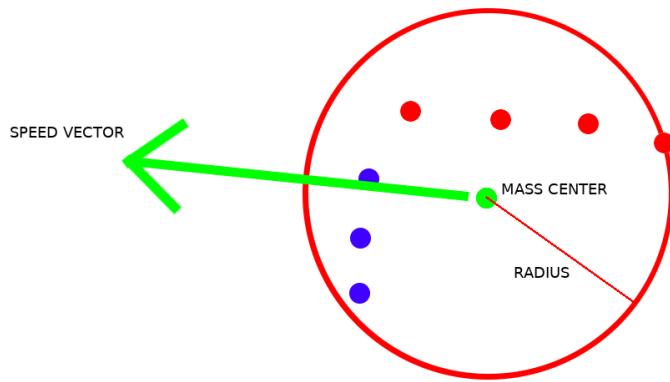


Figure 2.12: The calculated information for dynamic obstacles

2.5.1 Areas

First, the groups are substituted by bounding circles. The circle's radius is the distance between the farthest group point and the mass center. This simplification results in easier path calculation in the local planner, but also drops every information known about the obstacle's shape. For long objects, for instance, this method provides a very unrealistic image of the object, because the bounding circle is much larger than the obstacle itself. But for usual shapes such as cars, the loss that the representation causes is less than the processing time we save with the simplification.

2.5.2 Tracking

Speed vectors are calculated from the change of the mass center between measurements. But in order to be able to check the mass center of a group in any previous measurement, object tracking is needed. The tracking is done by estimating each obstacles' current position based on their previous positions and speed vectors, and finding the best fit among the current groups. Filtering is also needed for such false detections when a previously detected object is not recognized for a few cycles. Without filtering, these obstacles would disappear from the list of groups for a period of time and then they would reappear, but tracking would fail. Therefore the algorithm keeps these objects alive for a given number of measurement periods, updating their positions with their last known speed vector in every cycle.

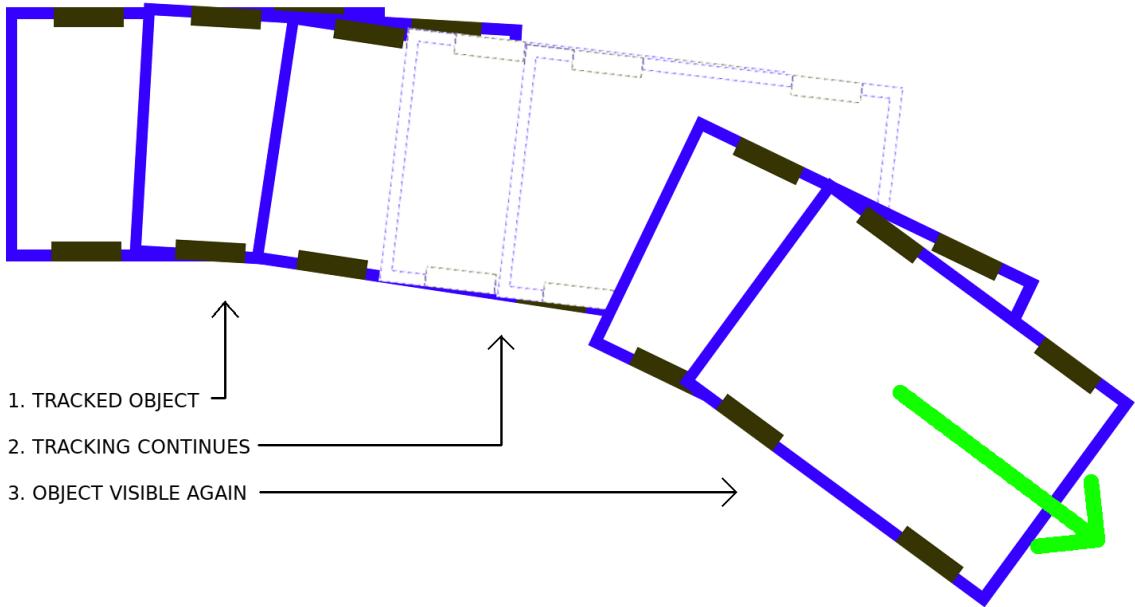


Figure 2.13: Object tracking

After the objects have been tracked, their speed vectors can be calculated. A filter is applied here, as well, for smoother obstacle paths.

2.5.3 Publishing dynamic obstacles

Dynamic obstacles - as outputs of the mapping node - are published on several topics, responsible for containing information for either further processing or visualization. The standard dynamic object structure in which moving objects are published to the local planner is not defined yet. The visualization messages, however, are implemented and in active use.

The published messages contain *visualization_msgs::Marker* instances with either *SPHERE* or *ARROW* instances with either *SPHERE* or *ARROW* type, thus representing the areas and speed vectors of the objects.

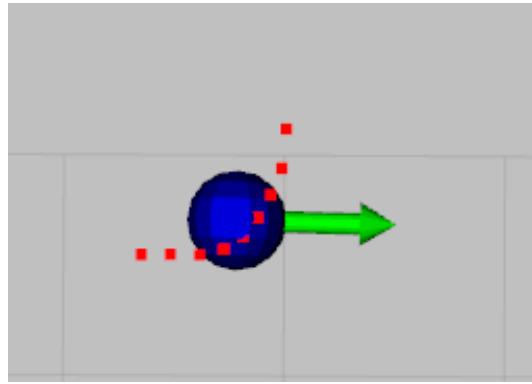


Figure 2.14: Visualizing moving objects

2.6 Static points

Static points used for two separate purposes. The first one is building a static map, the second is localization with the help of gmapping.

2.6.1 Static map

After separating the dynamic groups from the scan points, only the static points are left. These points do not change their positions with time⁷, so they can be added to the static map.

For static map-building, gmapping has already been mentioned as a candidate, but unfortunately, its algorithm does not recognize changes in the environment. In practice, if an object has been detected and placed in its map, it will not be erased from there, even after the object has moved away. Figures 2.15 and 2.16 demonstrate the problem.

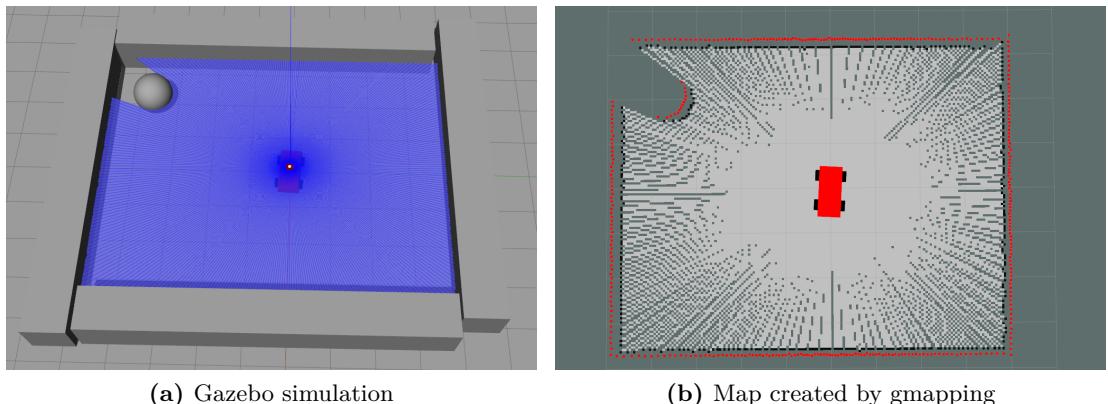


Figure 2.15: Initial state - ball is still

Figure 2.15 shows a situation where the ball is standing still. The mapping algorithm of gmapping successfully creates a map (in the form of an occupancy grid⁸) that marks the

⁷Except those obstacles that start moving only after they have already been detected as sets of static points. But these objects do not ruin the quality of the map, either.

⁸An occupancy grid represents a map in an evenly spaced field of probability values representing if the grid points are occupied by an obstacle

place of the ball as occupied. However, when the ball starts moving (see Figure 2.16), the map does not change, because the algorithm cannot handle moving obstacles.

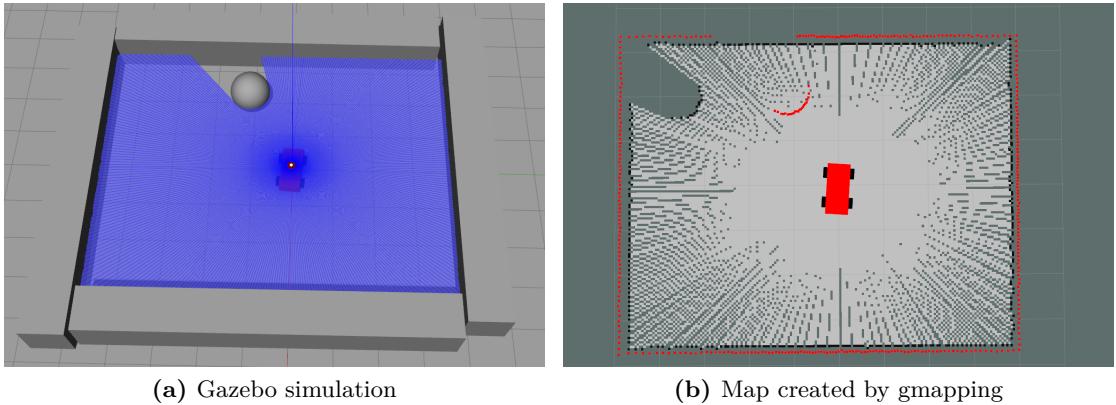


Figure 2.16: Moving state - ball has changed position

Due to the above problem, static map-building needed to be implemented internally, which is basically a 2D occupancy grid. The grid points' possible values are the following:

- Occupied (value: 100)
- Unknown (value: 50)
- Free (value: 0)

I chose the most straight-forward way of map-building - each static measurement introduces an occupied point and a free ray in the map. The map's size and resolution can be set as input parameters (see MAP_SIZE and MAP_RES in 3.3). Figure 2.17 visualizes the situation. The green and red grids are the car's current position and the measured point.

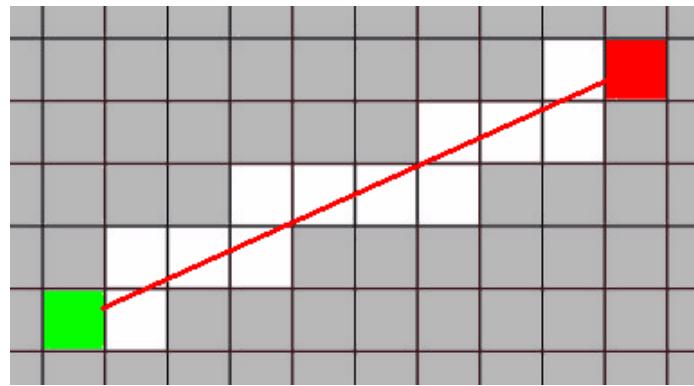


Figure 2.17: Introducing a free ray

2.6.2 Publishing static scan

As I mentioned already, gmapping is not used as a primary map-builder node, but its localization is still useful, therefore LIDAR measurements still need to be published for it. As the algorithm already separated the static points from the dynamic ones, it is handy to publish only the static measurements to gmapping. So in this step, a new scan structure is created, but the dynamic points are not added to it, only the static ones.

2.7 Conclusion

As a conclusion of the mapping sub-project, I present an example with a valid use-case. The scenario is the following. The car is standing in a closed room, the distance from the walls are smaller than the LIDAR's range. There is one other object in the room, in the simulation, this is a ball, its size similar to the car's. The ball is standing in one place at first, but after a while, it starts moving in a straight path with constant speed. Finally, the car starts moving as well - first in a straight path, then turning.

Figure 2.18 presents the initial situation of the demonstration. The left image shows the simulation - the car is standing in the middle of the room, the object in the top left corner is not moving yet. On the right image, the created static map is visible. The number of unknown (grey) grid points is large at this state of the simulation, it will dramatically decrease once the car starts moving. This effect is caused by the LIDAR's finite angular resolution and ray characteristics. The black grid points represent statically occupied positions. All the walls are marked static, and the ball as well.

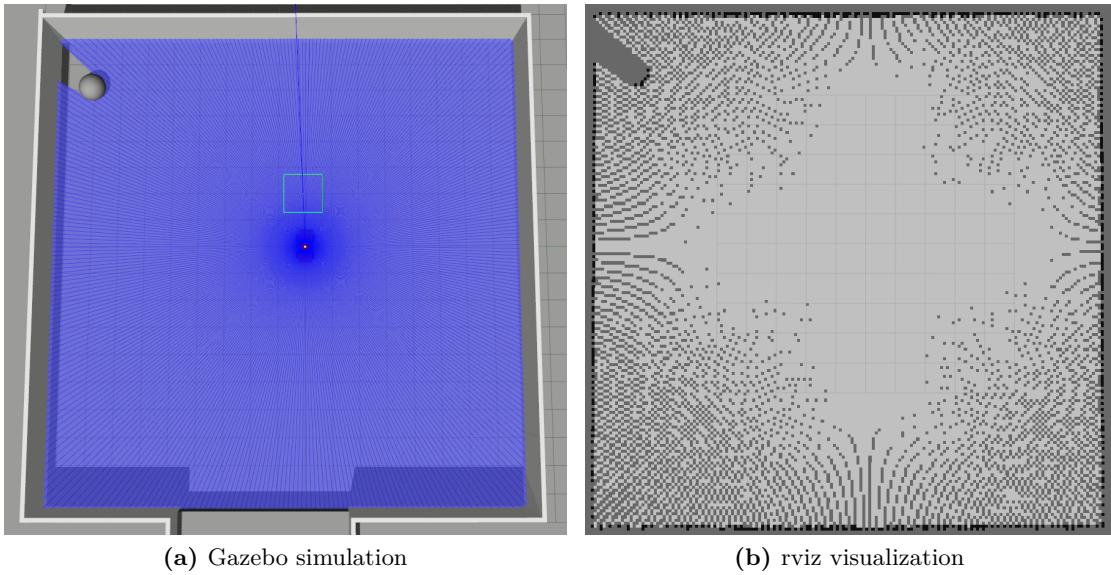


Figure 2.18: Initial state - ball is still

Once the ball starts moving (Figure 2.19), it stops being marked as static, but is handled as a moving object. The static block at the top left corner has been removed, and the ball is displayed using the dynamic visualization toolset - a sphere and an arrow, representing the ball's area and speed vector.

When the car starts moving, the map immediately starts to clear out. If we compare Figure 2.19 and Figure 2.20, it is clear that the latter contains less unknown grid points.

Due to the map implementation being very simple, and updating each map point without handling its history, the mapping node can only be used with certain limitations regarding obstacle speed and the car's angular velocity. But the main task for the mapping algorithm was not to create a static map with the best possible quality, but to separate the static points from the dynamic objects.

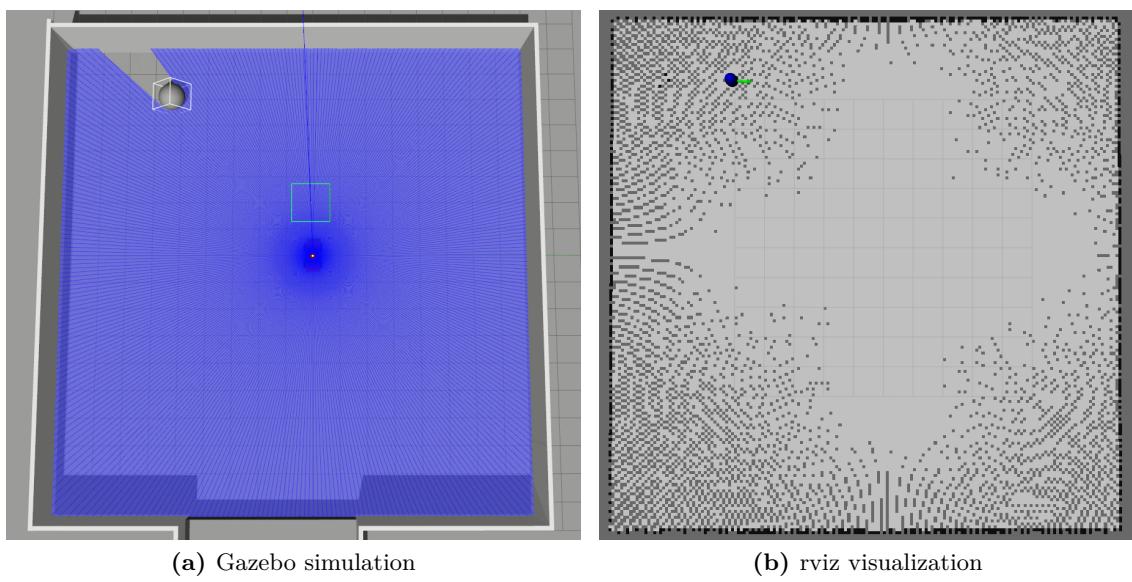


Figure 2.19: The ball is moving

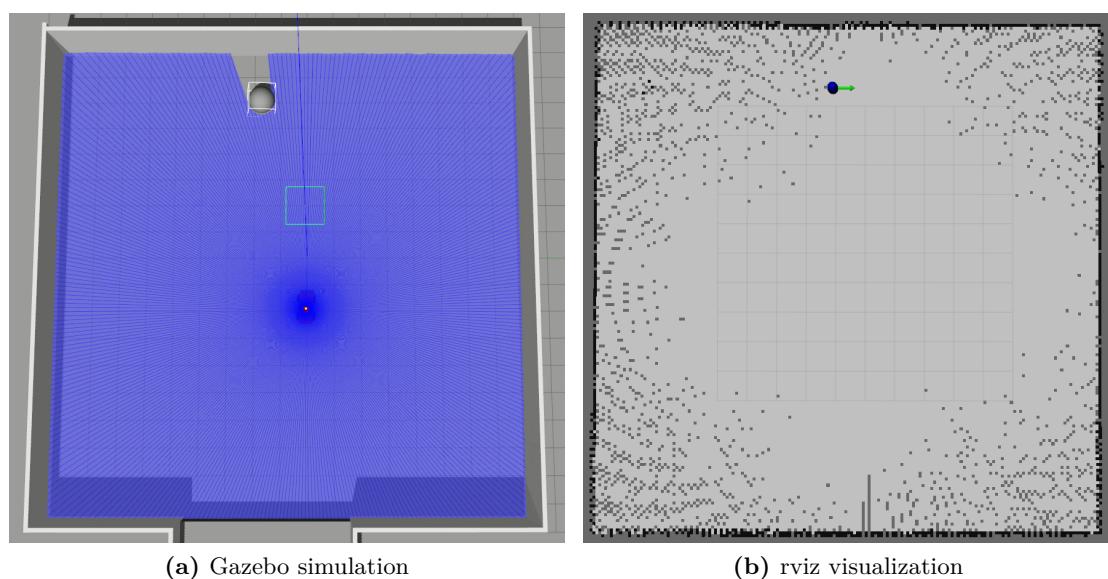


Figure 2.20: The car is moving

Chapter 3

Motion planning

3.1 Existing local planner algorithms

After building a map of the static and dynamic objects surrounding the vehicle, the next step is motion planning, which consists of two sub-tasks - global trajectory planning and local obstacle avoidance. As a result of global planning, a trajectory is created that - without taking the moving obstacles into consideration - leads the car to the target configuration, without making it collide with any static objects in the way. Local obstacle avoidance takes this trajectory as its input, and updates the car's actuators (acceleration and steering) to follow this trajectory, while also preventing collisions with dynamic objects.

As a part of my diploma project, I implemented the latter, a local obstacle avoidance algorithm, that relies on the previously created static and dynamic maps, and gets its input trajectory from a global planner node¹. According to [4], there exists a wide range of local planner algorithms, and they can easily be grouped by their complexity:

- Velocity-based methods, most of the times combined with the dynamic window approach
- Predictive and probability-based methods
- Complex methods based on visual detection and AI
- Other methods

Out of these methods, velocity-based algorithms are by far the most popular, due to their being relatively easy to comprehend and implement and because of their low hardware requirements. As the mapping node and the local planner that I designed need to run on a processor with limited resources, I also chose a velocity-based obstacle avoidance method, using velocity obstacles, with dynamic windowing.

3.2 Method

The planner algorithm I implemented uses velocity obstacles to determine which configurations of the car are safe. Velocity obstacle methods (described in [2] and in [3]) are based

¹Implementing a global motion planner was not part of my diploma project, but is considered a necessary condition for the local planner to work properly.

on the following statement: *Assuming a given vehicle configuration (position, orientation, speed and wheel angle), the time until collision with a given static or dynamic object in the map can be calculated.* Therefore, velocity obstacle-based methods calculate this collision time for all surrounding objects and for all vehicle velocities, thus creating a velocity obstacle map, or forbidden velocity map (also referred to as dynamic velocity space in [4]). Using the dynamic window approach is advised in this step, as it filters out non-reachable velocities before collision-time calculations, thus decreasing the execution time of the algorithm.

Given this velocity obstacle map, the algorithm has a basic knowledge of the reachable velocities and their level of safety. These safety levels provide a good starting point for further calculations, trajectory and collision estimations. My algorithm converts the forbidden velocity map's collision times to safety factors, but also takes the destination point's position and the target speed into consideration when selecting the next actuator outputs. The next graph shows all the sub-tasks of the local trajectory planner algorithm.

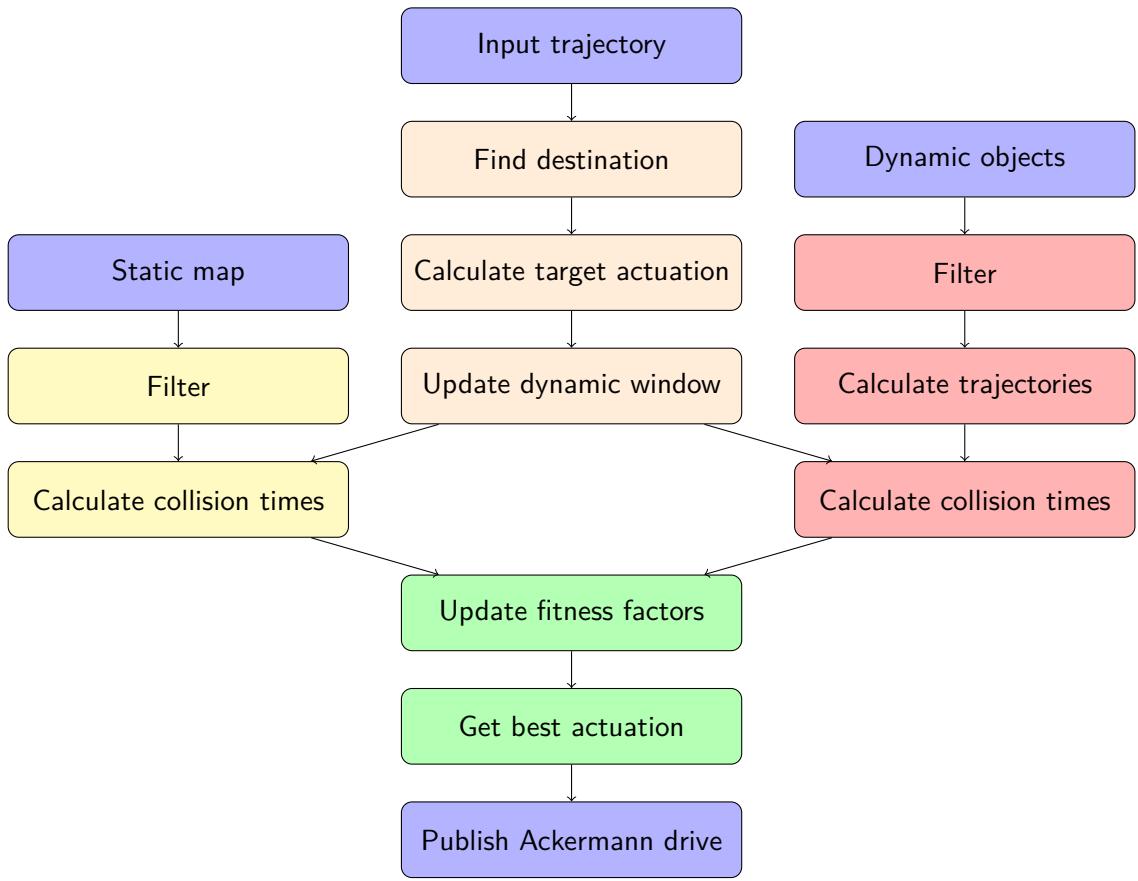


Figure 3.1: Motion planning method

The diagram consists of 4 subgraphs - these are also marked on the diagram with different colors. The orange subgraph describes the environment-independent sub-tasks of the algorithm - finding the next destination point, updating the target actuation and the dynamic window. The yellow one is about the method of reducing the size of the static map by filtering out those points that are not needed for the trajectory planning. The red side subgraph shows that for dynamic objects, trajectory calculation is also necessary besides filtering. And the last one (populating the bottom area of the graph, marked with green colour) contains the main planning logic. The sections under 3 explain these subgraphs in detail.

3.3 Input parameters

The following input parameters can manipulate the motion planning node:

CAR_FRONT_REAR_WHEEL_AXIS_DIST [meter]

The distance between the front and rear wheels axles of the car.

CAR_LENGTH [meter]

The length of the car.

CAR_WIDTH [meter]

The width of the car.

COLLISION_CHECK_TIME_STEP [millisecond]

The resolution of the iterative collision check.

DYNAMIC_WINDOW_ANGLE_RESOLUTION [radian]

The wheel angle resolution of the dynamic window.

DYNAMIC_WINDOW_SPEED_RESOLUTION [meter/sec]

The speed resolution of the dynamic window.

MAX_ACCELERATION [meter/sec²]

The maximum permitted acceleration.

MAX_DYNAMIC_OBSTACLE_DISTANCE [meter]

The radius of the dynamic obstacle filter.

MAX_SPEED_BWD [meter/sec]

The maximum permitted backward speed.

MAX_SPEED_FWD [meter/sec]

The maximum permitted forward speed.

MAX_STATIC_OBSTACLE_DISTANCE [meter]

The radius of the static obstacle filter.

MAX_WHEEL_ANGLE [radian]

The maximum permitted wheel angle.

MAX_WHEEL_ANGULAR_VELOCITY [radian/sec²]

The maximum permitted angular velocity of the steered wheels.

MIN_KEPT_DISTANCE [meter]

The minimum distance to keep from objects

W_DIRECTION_FACTOR [dimensionless]

The weight of the direction factor when finding the best possible actuation.

W_SAFETY_FACTOR [dimensionless]

The weight of the safety factor when finding the best possible actuation.

W_SPEED_FACTOR [dimensionless]

The weight of the speed factor when finding the best possible actuation.

3.4 Target actuation and dynamic window

In every loop (at each new incoming map data), the target actuation and the dynamic window are updated. The target actuation describes the desired speed and steering wheel angle for the next step, therefore the desired linear and angular speed vectors. The dynamic window is independent from the target actuation, but depends on the current actuation. It contains a set of speeds and wheel angles that are reachable by the car within the next step. The width and height of the window (the maximum speed and wheel angle change in one step) are defined by the mechanical characteristics of the car. So basically, the aim of this subtask is to provide the algorithm a target actuation, and a set of reachable actuations.

When I implemented the target actuation update mechanism, that leads the car according to the input trajectory, I had several options to choose from. The first option was to split the trajectory into line-segments, and implement and tune a steering angle controller (e.g. a PD controller) to follow this line. I dropped this idea to prevent the re-tuning that would have been needed for each target vehicles (simulation, real-life test vehicles). Another option was the 'invisible string' the 'dog bone' method, where a target destination point is always in front of the car, and the car is always trying to reach this point, as if the point was pulling it by a string. The target actuation's wheel angle defines a trajectory curve, that goes through the destination point. If the destination point is always on the trajectory, and in front of car (within the right distance range), the car is going to follow the trajectory. I chose the latter (the 'invisible string') method.

3.4.1 Finding the next destination point

This method requires a destination point in each iteration. This point is preferably on the trajectory, in front of the car, 'pulling' the car to the right direction. The destination point search starts with finding the point in the trajectory nearest to the car's current position. The destination point needs to be in front of the car, but its distance from the car (which is nearly equal to its distance from the previously found nearest point) is not trivial (see figure 3.2).

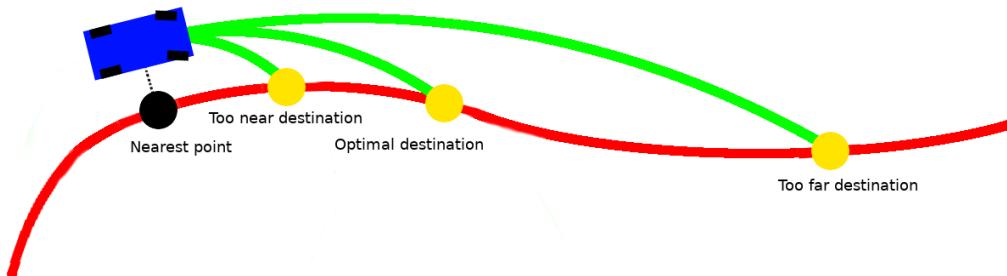


Figure 3.2: Updating the destination point

Choosing a too near destination will result in the car starting to oscillate around the target trajectory with an increasing amplitude, until a point where the angular difference between the car and the trajectory will be too large for the car to find the path again. This situation is displayed in figure 3.3.

However, the destination point must not be chosen too far, either, because it straightens the curves of the trajectory, rounds its sharp peaks, and adds an offset to the long circular



Figure 3.3: Oscillation around the target trajectory

sections. Figure 3.4 demonstrates these effects. The effect shown on the left side might even be advantageous, but the right-hand side effect is certainly not.

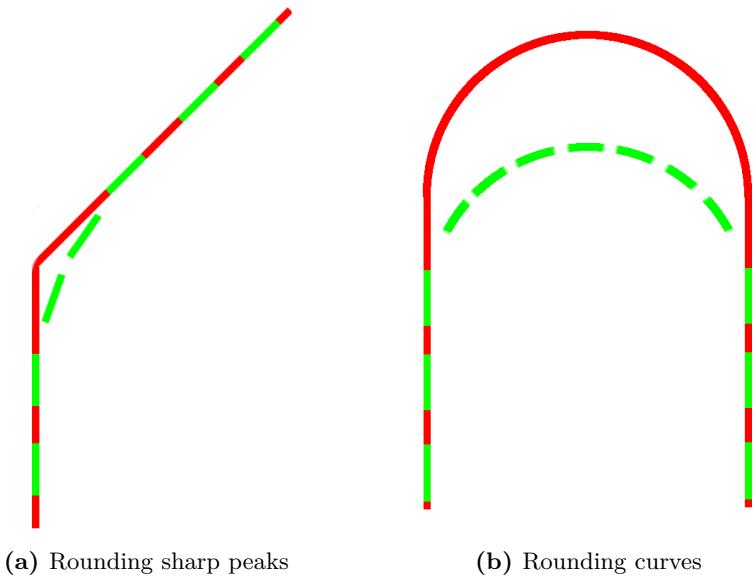


Figure 3.4: Trajectory rounding

After empirical testing, the optimal distance of the destination point and the nearest trajectory point (marked with yellow and black dots in figure 3.2) proved to be around 4 times the distance between the car's front and rear axles (see CAR_FRONT_REAR_WHEEL_AXIS_DIST in 3.3). Note, that this value largely depends on the dynamic window's maximum angular velocity limit and the car's mechanical characteristics (e.g. using a faster steering servo or a 4-wheel steering car would reduce the optimal distance). In order to follow the straight segments of the target path before curves, I implemented the length of the invisible string (the distance in front of the nearest trajectory point) to change dynamically, according to the car's current distance from the trajectory. This tweak suppressed the rounding effect mentioned above, but not entirely. This is now considered a limitation of the algorithm's efficiency.

3.4.2 Calculating the target actuation

After the destination point has been selected, the next step is to calculate the target actuation - the speed and steering angle pair that would lead the car to the destination point. First, the target wheel angle is calculated using linear algebra (see figure 3.5). The target speed calculation is based on two factors. The first is the target speed limit, which we expect the car to keep, given no extraordinary circumstances. This should be set to a safe speed that the car can keep up during its travel (see MAX_SPEED_FWD and MAX_SPEED_BWD in 3.3). The actual target speed will never exceed this limit. But

the target steering angle may require this target speed to be lower, because the car can manage to reach higher speeds safely when going straight, than when in a sharp bend.

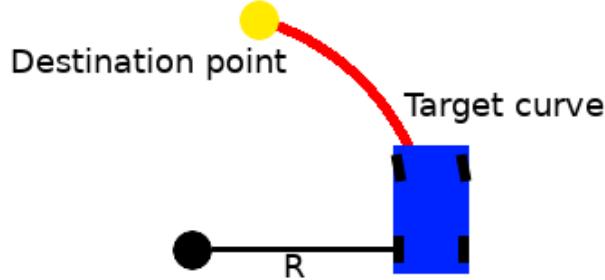


Figure 3.5: Calculating the target steering angle

3.4.3 Updating the dynamic window

In every iteration, the dynamic window must also be updated, which is independent from the target actuation, but depends on the current actuation. The 'width' and 'height' of the window (which is defined by the maximum speed and wheel angle change in one iteration) mostly depends on the car's physical, mechanical and other characteristics (motor-wheel dead-time, maximum motor torque, speed controller's parameters, maximum angular velocity of the steering servo), but the environment's characteristics (air resistance, friction) also influence them. The maximum speed and wheel angle change are settable parameters (see `MAX_ACCELERATION` and `MAX_WHEEL_ANGULAR_VELOCITY` in 3.3). The dynamic window is represented in figure 3.6. The red arrow shows the current actuation (speed and wheel angle pair). The dynamic window itself appears on the image as the grey area under the arrow heads. Every actuation within the dynamic window's area is reachable within the next step. When the current actuation is not near a hard limit, it is the center of the dynamic window.

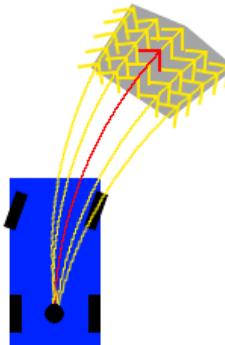


Figure 3.6: The dynamic window

However, the size of the dynamic window may reduce when its size is limited by the hard limits of speed and wheel angle. A perfect example for this situation is when the steering angle is at its maximum at either left or right direction (see `MAX_WHEEL_ANGLE` in 3.3), in which case changing the angle further to this direction is impossible. This results in the dynamic window getting halved - as only its original right or left side is reachable, depending on the current steering direction.

It is trivial that in these cases such as the previous example, the current actuation is no longer in the center of the dynamic window. Another important characteristics of the dynamic window is its resolution - both speed and angular velocity, which are settable parameters (see DYNAMIC_WINDOW_SPEED_RESOLUTION and DYNAMIC_WINDOW_ANGLE_RESOLUTION in 3.3). Increasing the resolution leads to smoother control, but also increases the node's resource need and runtime.

The managing the dynamic window internally, the motion planning node also publishes the dynamic window's possible actuations, so that it can be viewed on-the-fly in rviz.

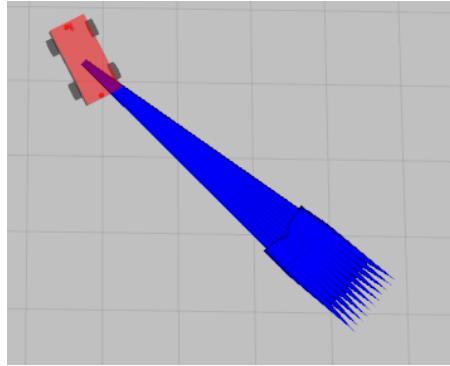


Figure 3.7: Available velocities in rviz

3.5 Static velocity obstacle map

Static points in the map populate a very large percent of the car's surroundings, so handling them efficiently can boost up the algorithms runtime performance. Therefore, they are not joined with the dynamic points, but filtered separately, and the collision times are calculated in a way that is optimized for non-moving objects to gain performance.

3.5.1 Filtering static points

Separating the static points from the dynamic objects has both advantages and disadvantages for local motion planning. The most important advantage is that the collision check with static points is much simpler and faster than with dynamic obstacles. A great disadvantage, however, is that the static map contains lots of points, and running a collision check on all of them would cause the algorithm to be unacceptably slow. To prevent this undesired behaviour, a preparatory filter is applied to the map, removing those points from the map, that are too far from the car's current position to be worth keeping. Depending on the environment's characteristics, this step may reduce the runtime of the static collision times drastically - even to zero, if all the static points are far from the car (e.g. in a large room).

Figure 3.8 shows that the mapped environment of the car is a much larger territory than what the motion planning algorithm needs to check for collisions. The circle marks the area that is kept after the filtering. In this example, this area contains the two square-shaped obstacles, all the other points in the static map are thrown. The size of the area worth keeping always depends on the actual application and the car's dynamic characteristics. But as a general rule of thumb:

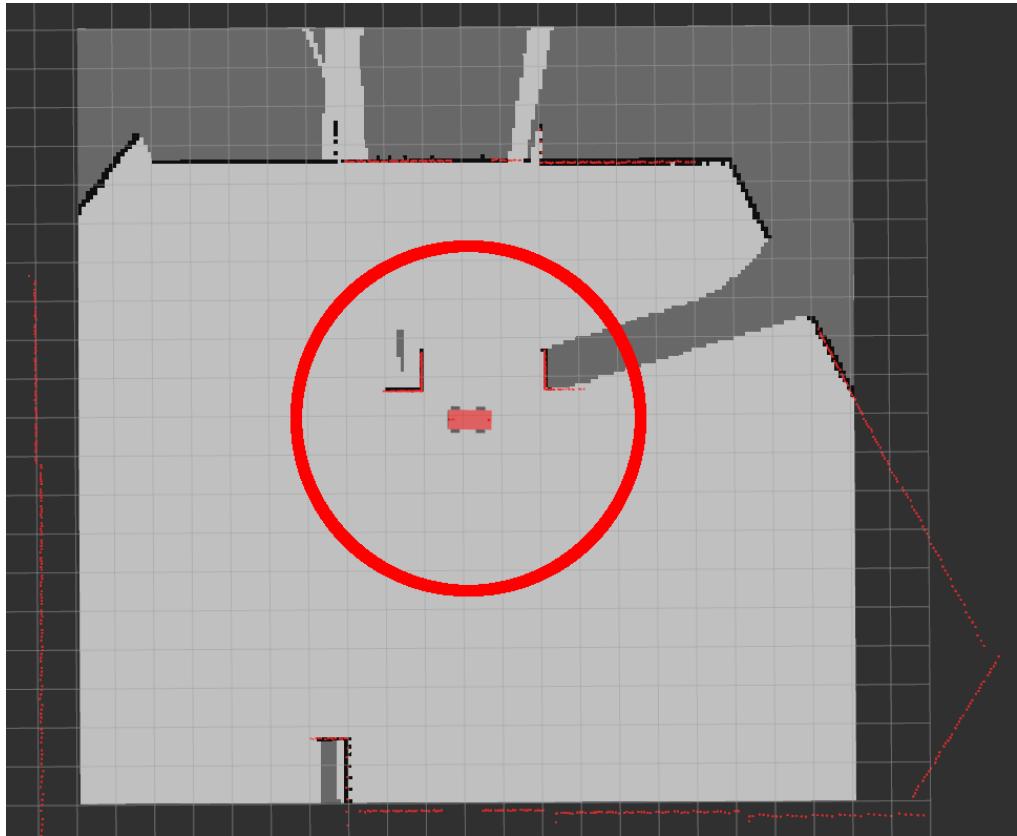


Figure 3.8: Static filtering

$$R = \frac{v_{max}^2}{a_{max}}$$

v_{max}	The maximum speed
a_{max}	The maximum deceleration
R	The radius of the kept area

is a good guess. The maximum speed and deceleration and settable parameters (see MAX_SPEED_FWD, MAX_SPEED_BWD and MAX_ACCELERATION in 3.3). Optimization is possible using the car’s speed vector, and filtering out those points that are very far from the current direction.

3.5.2 Static collision times

Collision times need to be changed for all surrounding obstacles in order to be able to build the dynamic velocity obstacle map. Due to the fact that the number of static points is usually high compared to the dynamic points, the collision times are calculated separately, so that the calculation can be optimized for static objects. Collision check needs to be executed for all the actuations within the dynamic window. The algorithm is the following.

First the car’s expected movement for the actuation is predicted with a curve. When the wheel angle is very close to 0, this curve can be approximated with a straight line, in these cases the algorithm is simplified. However, now let us consider a scenario when the angle

is not 0, and the trajectory will in fact be a curve of finite radius. Figure 3.9 shows this scenario.

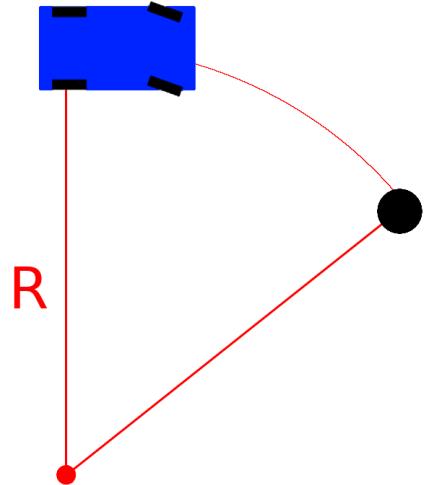


Figure 3.9: The car's expected trajectory is a curve

In order to get the collision time, first the algorithm needs to calculate the collision distance. This calculation is based on linear algebra. But in order to be able apply mathematical laws on the model, the objects need to be converted to simple geometrical forms. This simplification is represented in figure 3.10.

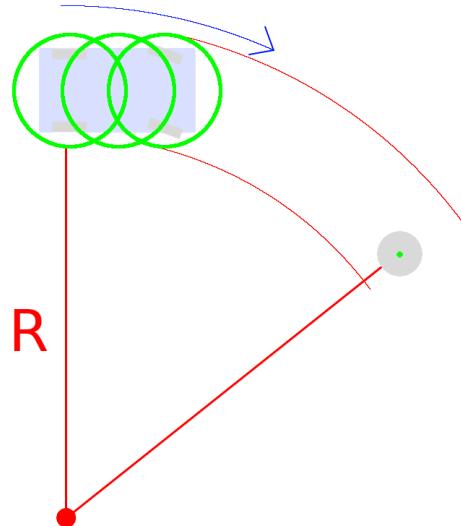


Figure 3.10: Simplifying object shapes

As it is clearly visible on the image, the car is approximated with 3 circles, fixed on the car's axles and its center, and the obstacle is simplified to one circle. In order for easier calculations, the obstacle is not handled as a circle of given radius, but as a point, and its radius is added to the radii of the car's circles. We also need to take into consideration, that the static map is always noisy, and we can never expect measurements to be noiseless, either. Therefore, a third value is added to the radii of the car's circles, which is the minimal distance that needs to be kept from static objects. Therefore the car circle radius is as follows:

$$r = \frac{w_{car}}{2} + r_{obs} + d_{min}$$

w _{car}	The width of the car
r _{obs}	The obstacle radius
d _{min}	The minimal kept distance
r	The modified car circle radius

The angular difference between the car and the obstacle (denoted γ) can be calculated easily using linear algebra (see figure 3.11).

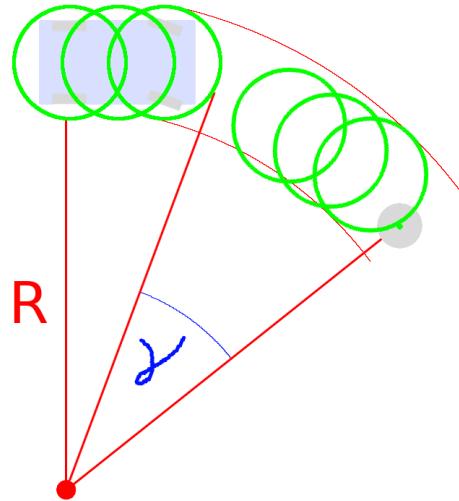


Figure 3.11: Angular difference between the car and the obstacle

After the angle is obtained, the collision distance and time can be easily calculated using the following equations:

$$s_{coll} = R * \gamma$$

$$t_{coll} = s_{coll} * v_{car}$$

R	The radius of the trajectory curve
γ	The angular difference
s _{coll}	The distance until collision
v _{car}	The car speed
t _{coll}	The time until collision

Using the method described above, the collision times for the static obstacles in the map can be calculated. Doing this for all possible actuations will provide a static velocity obstacle map, which later can be used to grade actuations.

3.6 Dynamic velocity obstacle map

Handling dynamic obstacles is more difficult than handling static points, the algorithm, however, evaluating the moving objects is more straight-forward than static method using linear algebra. The reason for the dynamic algorithm being easier to comprehend is that it uses an iterative approach instead of linear algebra. (Linear algebra with multiple objects moving in non-straight paths is not trivial.)

3.6.1 Filtering dynamic objects

This first step when evaluating dynamic objects in the map is similar to static case - removing the too far obstacles. Trajectory modelling and collision check may be resource and time heavy, so handling as few dynamic objects as possible is crucial. The size of the area worth keeping depends on the actual application and the dynamic characteristics of the car and the other moving objects. But as a general rule of thumb:

$$R = 2 * \frac{v_{max}^2}{a_{max}}$$

v_{max}	The maximum speed
a_{max}	The maximum deceleration
R	The radius of the kept area

is a good guess (note that the radius is twice as large as in the static case). Some optimizations using the car's speed vector can be made in this case, too, but keeping in mind that dynamic objects can approach from behind as well is important.

3.6.2 Trajectory calculation

Now that the irrelevant dynamic objects have been filtered out, the next step is to calculate the kept obstacles' trajectories. Trajectory calculation is done using an iterative method - foreach obstacle, with a given time step (see COLLISION_CHECK_TIME_STEP in 3.3) the algorithm start iterating, updates the obstacles's position and orientation in each step and saves into an array of configurations - this array will become the trajectory itself. *But how many steps should be saved?* may be an interesting question, to which the answer is also: it depends. It depends on how the application logic uses these trajectories. For my application, the needed number of steps is:

$$N = \frac{3 * \frac{v_{max}}{a_{max}}}{T_{step}}$$

v_{max}	The maximum speed
a_{max}	The maximum deceleration
T_{step}	The trajectory simulation time step
N	The number of needed steps

After the trajectories for all moving obstacles have calculates, the algorithm can move forward, and check for collisions with these objects.

3.6.3 Dynamic collision times

Calculating the collision times with the dynamic obstacles is not based on linear algebra, like in the static case, but is executed in an iterative way. For all possible actuations (actuations that are present in the dynamic window), a trajectory is calculated - the same way that it has already been calculated for the other dynamic objects in the map. Using this trajectory and the pre-calculated other trajectories the algorithm iterates through time, updates the objects' configurations in each step according to their trajectories, and checks collisions. The iteration's time step is the configurable value that has been used before (see COLLISION_CHECK_TIME_STEP in 3.3). The simulation time (until the iterations go) is:

$$N = \frac{3 * \frac{v}{a_{max}}}{T_{step}}$$

v	The speed of the current actuation
a_{max}	The maximum deceleration
T_{step}	The collision check simulation time step
N	The number of needed steps

Given that:

$$v \leq v_{max}$$

v _{max}	The maximum speed
------------------	-------------------

the following statement is always true:

$$N \leq \frac{3 * \frac{v_{max}}{a_{max}}}{T_{step}}$$

which was the number trajectory simulation time steps for the surrounding obstacles (see 3.6.2). Therefore, it is provided that all objects in the environment have a pre-calculated trajectory for the whole collision check simulation interval.

3.7 Velocity obstacle map evaluation

Let me summarize briefly what the algorithm has done so far.

In each iterations, the algorithm:

1. found a new destination point and updated the target actuation
2. updated the dynamic window of actuations
3. received a static map and an array of dynamic obstacles from the mapping node
4. filtered both in order to keep only the objects relevant for local motion planning
5. calculated trajectories for all dynamic obstacles

6. checked all available actuations for collisions with any of the static or dynamic objects
7. built a velocity obstacle map using these collision times

Now the next (and final) step is to evaluate the velocity obstacle map, and find the best actuation. But defining what 'the best' actuation is is not trivial. Let's look at the scenario represented in figure 3.12.



Figure 3.12: What is 'the best' actuation?

The target trajectory is a straight line (marked with the green line in the rviz visualization, published by the motion planning node). But there is an obstacle in the way. Without the obstacle being in the picture, one could state without hesitation, the the target actuation is always the one the keeps the car on the line. But once the object is there, this is no longer the case. Defining the best actuation to be the one that keeps car in direction would lead to collision, obviously, the car needs to steer to the right to avoid that. But this raises even more questions. *Should the car steer to the right long before the object? Is it enough to turn the wheels in the last moment? Are we sure we are able to steer away from collision, isn't an emergency brake a better solution?* I answered these questions and solved the problem of finding the best actuation with the introduction of fitness factors.

3.7.1 Fitness factors

A fitness factor is a number in the [0.0 1.0] interval describing how good (how fit) the given actuation is according to an expectation or requirement. I introduced three fitness factors in the algorithm.

Speed factor

Describes how near the actuation's speed is to the target speed.

- 1.0: The actuation's speed is exactly the same as the target speed.
- 0.5: The actuation's speed is halfway between the target speed and the worst possible candidate.
- 0.0: The actuation's speed is the maximum permitted speed to the opposite direction (worst possible candidate).

Direction factor

Describes how near the actuation's wheel angle is to the target wheel angle.

1.0: The actuation's wheel angle is exactly the same as the target wheel angle.

0.5: The actuation's wheel angle is halfway between the target wheel angle and the worst possible candidate.

0.0: The actuation's wheel angle is the maximum permitted wheel angle to the opposite direction (worst possible candidate).

Safety factor

Describes how safe the actuation is, meaning how improbable a collision is.

1.0: Using the actuation, a collision within time interval will not happen.

0.5: The actuation leads to a collision, but the obstacle is farther than the car's brake distance.

0.0: The actuation leads to an unavoidable² collision.

Let me explain these factors with two simple examples, regarding the same scenario (shown above in figure figure 3.12). The following images show two possible actuations in a situation (both are within the dynamic window). And based on their speed and wheel angles, the car's current configuration and the obstacle's position, the fitness factors can be calculated for both actuations.

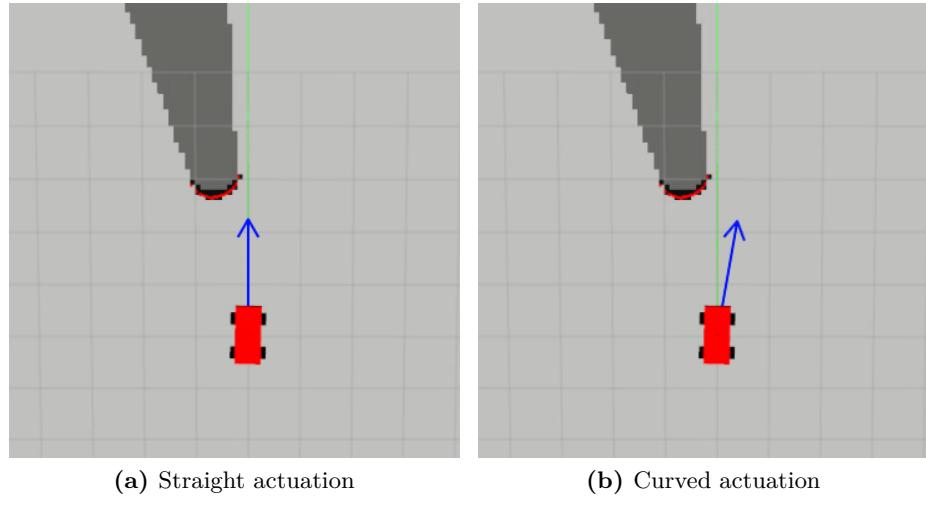


Figure 3.13: Possible actuations

Figure 3.13 shows the two example actuations. As a precondition, the target speed and wheel angle must be defined. The target speed is always defined by the maximum allowed speed (see MAX_SPEED_FWD and MAX_SPEED_BWD in 3.3) and the target wheel angle. For this is only an example, let me assume that the car is in perfect orientation and arbitrarily set the target speed to MAX_SPEED_FWD, and the target wheel angle to zero. Let us assume that we have already calculated the collision times for each possible actuation.

During factor calculations, the following acronyms are used:

²An unavoidable collision means that the obstacle is too near to stop before it using the motion planner's maximum deceleration. Note, that emergency braking may still stop the car in time, as it means a more intensive deceleration.

MAX_SPEED_FWD	The maximum permitted speed
MAX_WHEEL_ANGLE	The maximum permitted wheel angle
T_check	The collision time check interval
vtarget	The target speed
αtarget	The target wheel angle
v _i	The speed of actuation <i>i</i>
α _i	The wheel angle of actuation <i>i</i>
t _{coll,i}	The collision time using actuation <i>i</i>
F _{speed,i}	The speed factor for actuation <i>i</i>
F _{dir,i}	The direction factor for actuation <i>i</i>
F _{safety,i}	The safety factor for actuation <i>i</i>

$$MAX_SPEED_FWD = 1.5 \frac{m}{s}$$

$$MAX_WHEEL_ANGLE = 20deg$$

$$T_{check} = 3s$$

$$v_{target} = MAX_SPEED_FWD$$

$$\alpha_{target} = 0deg$$

Factor's for actuation *i* are calculated using the following equations:

$$F_{speed,i} = 1 - \frac{abs(v_i - v_{target})}{MAX_SPEED_FWD - MAX_SPEED_BWD}$$

$$F_{dir,i} = 1 - \frac{abs(\alpha_i - \alpha_{target})}{2 * MAX_WHEEL_ANGLE}$$

$$F_{safety,i} = \frac{t_{coll,i}}{T_{check}}$$

The factor calculations for the two examples are the following:

Straight actuation (figure 3.13a)

$$v_1 = 1.5 \frac{m}{s}$$

$$\alpha_1 = 0deg$$

$$t_{coll,1} = 1.5s$$

The fitness factors are the following (calculated by the equations listed above):

$$F_{speed,1} = 1.00$$

$$F_{dir,1} = 1.00$$

$$F_{safety,1} = 0.50$$

As it is clearly visible on the picture, and also from the results, the speed and direction factors are perfect, but the safety factor is low, because the leads to a collision in the near future. Now let us examine the other actuation.

Curved actuation (figure 3.13b)

$$v_2 = 1.5 \frac{m}{s}$$

$$\alpha_2 = -10\text{deg}$$

$$t_{coll,2} = 4.5s$$

Note that the collision time of the actuation is always in the $[0 \text{ } T_{\text{check}}]$ interval. The result of the collision time check method is T_{check} when the actuation does not cause a collision. The fitness factors are the following (calculated by the equations listed above):

$$F_{\text{speed},2} = 1.00$$

$$F_{\text{dir},2} = 0.75$$

$$F_{\text{safety},2} = 1.00$$

Now that the speed, direction and safety factors have been calculated for all possible actuations, the only subtask left is to find the best actuation.

3.7.2 Best actuation

The best possible actuation is always the one with the highest fitness factors. The factors of an actuation are summarized to one number (which will then become *the* fitness of the actuation) the following way:

$$F_i = \frac{F_{\text{speed},i} * w_{\text{speed}} + F_{\text{dir},i} * w_{\text{dir}} + F_{\text{safety},i} * w_{\text{safety}}}{w_{\text{speed}} + w_{\text{dir}} + w_{\text{safety}}}$$

F_i	The fitness of actuation i
$F_{\text{speed},i}$	The speed factor for actuation i
$F_{\text{dir},i}$	The direction factor for actuation i
$F_{\text{safety},i}$	The safety factor for actuation i
w_{speed}	The weight of the speed factor (see W_SPEED_FACTOR in 3.3)
w_{dir}	The weight of the direction factor (see $W_DIRECTION_FACTOR$ in 3.3)
w_{safety}	The weight of the safety factor (see W_SAFETY_FACTOR in 3.3)

In the implementation, the weights are set as follows. (Further tuning is possible and advised for more production-ready implementations.)

$$W_SPEED_FACTOR = 2.00$$

$$W_DIRECTION_FACTOR = 1.00$$

$$W_SAFETY_FACTOR = 4.00$$

As an example, let us continue the previous example with the straight and the curved actuations.

Straight actuation (figure 3.13a)

$$F_{speed,1} = 1.00$$

$$F_{dir,1} = 1.00$$

$$F_{safety,1} = 0.50$$

An the final fitness is:

$$F_1 = \frac{1.00 * 2.00 + 1.00 * 1.00 + 0.50 * 4.00}{2.00 + 1.00 + 4.00} = 0.71$$

Curved actuation (figure 3.13b)

$$F_{speed,2} = 1.00$$

$$F_{dir,2} = 0.75$$

$$F_{safety,2} = 1.00$$

An the final fitness is:

$$F_2 = \frac{1.00 * 2.00 + 0.75 * 1.00 + 1.00 * 4.00}{2.00 + 1.00 + 4.00} = 0.96$$

The results show that out these two actuations, the second one (the curve) would have been selected by the algorithm. This is mainly because safety has a much higher weight than direction when summarizing factors. Obviously, this has not been a complete actuation search because the example consisted of only two actuations, while the dynamic window can consist of tens or even hundreds of possible alternatives. As I mentioned earlier, the width and the height of the dynamic window depends on the car's and the environments characteristics, while its resolution can be set in the parameters (see DYNAMIC_WINDOW_ANGLE_RESOLUTION and DYNAMIC_WINDOW_SPEED_RESOLUTION in 3.3).

3.7.3 Publishing Ackermann driving control

The hard part of the node's work is done, the best possible actuation has been found. The very last task is to publish this desired speed and wheel angle pair to the other ROS nodes that control the car.

This publication happens using Ackermann driving messages, which are standard messages in ROS ([AckermannDrive](#) message type defined by the [ackermann_msgs](#) package). Among other fields (which are currently not used by the project) it has a *speed* and a *steering_angle* field - given in m/s and radians.

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