Bachelor Thesis

Czech
Technical
University
in Prague

F3

Faculty of Electrical Engineering
Department of Cybernetics

Autonomous road crossing with a mobile robot

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Supervisor: Mgr. Martin Pecka, Ph.D.
Field of study: Cybernetics and Robotics
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BACHELOR'S THESIS ASSIGNMENT

I. Personal and study details

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Study program: **Cybernetics and Robotics**

II. Bachelor's thesis details

Bachelor's thesis title in English:

Autonomous Road Crossing with a Mobile Robot

Bachelor's thesis title in Czech:

Autonomní přejezd silnice mobilním robotem

Guidelines:

The goal of the thesis is design, implementation and experimental verification of an algorithm for safe crossing of roads with public traffic with a mid-sized mobile robot. The student should review existing approaches to the problem and assess their suitability for use on target robotic platforms. Also, a method for evaluating performance of road-crossing algorithms should be proposed and applied. In the implementation, sensor data from color cameras, 3D lidars and public cartographic data can be used to improve performance of the algorithm. The algorithm should also expect an input with poses and velocities of detected vehicles, although the detection itself is not a part of this thesis. Other contextual inputs can be given, like maximal or expected velocity of incoming vehicles, road type, number of lanes on the road or presence of a pedestrian crossing with or without traffic lights. Given this context and vehicle velocity data, the algorithm should be able to safely assess the situation and decide whether it is safe to cross the road in a given moment or not. In the safe case, a control algorithm should be developed that will perform the actual road crossing (with continuous checking of safety of the maneuver).
Experimental verification of the work should be done both in simulation and in a controlled real-world experiment. In the real-world experiment, the robot will not enter a real public driving road, but an experimental setup in a non-public area will be set up (in cooperation with thesis supervisor) to demonstrate behavior of the algorithm even in case of incoming traffic (which will be driven by faculty staff). Results of these experiments should be evaluated according to the proposed performance metric.

Bibliography / sources:

[1] https://wiki.openstreetmap.org
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Date of bachelor's thesis assignment: **03.02.2023** Deadline for bachelor thesis submission: __________

Assignment valid until: **22.09.2024**

Mgr. Martin Pecka, Ph.D. Supervisor's signature	prof. Ing. Tomáš Svoboda, Ph.D. Head of department's signature	prof. Mgr. Petr Páta, Ph.D. Dean's signature

III. Assignment receipt

The student acknowledges that the bachelor's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the bachelor's thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt	Student's signature

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I would like to express my sincere gratitude to everyone who supported me throughout the completion of this bachelor's thesis. My most profound appreciation goes to my advisor, Martin Pecka, for his invaluable guidance, feedback and support throughout the research and development process.

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Declaration

I declare that the presented work was developed independently and that I have listed all sources of information used within it in accordance with the methodical instructions for observing the ethical principles in the preparation of university theses.

Prague, April 28, 2023

Prohlašuji, že jsem předloženou práci vypracoval samostatně a že jsem uvedl veškeré použité informační zdroje v souladu s Metodickým pokynem o dodržování etických principů při přípravě vysokoškolských závěrečných prací.

Praha, 28. dubna 2023

Abstract

In this thesis, our task was to design, implement and evaluate an algorithm for the safe crossing of public roads with a middle-size mobile robot.
The first part of this task is to conclude whether it is safe to cross the road in the robot's current location. If it is, the second part of the task is developing a control algorithm to perform the movement needed to cross the road. Continuous monitoring of the traffic situation is necessary for the safety of the maneuver. We are also to provide evaluation metrics for determining the functionality and optimality of developed algorithms. The verification and evaluation of the developed algorithm will be conducted in simulation and a controlled real-world experiment.

Keywords: Autonomous robot operation, behavior trees, collision avoidance, collision detection, finite-state machines, road crossing, ROS

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Abstrakt

V této práci je naším úkolem navrhnout, implementovat a vyhodnotit algoritmus pro bezpečný přejezd silnic s mobilním robotem střední velikosti.
První část úkolu je zjistit, zda je bezpečné přejít silnici v místě, kde se robot právě nachází. Pokud ano, druhá část úkolu je navrhnout algoritmus pro řízení pohybu potřebného k přejetí silnice. Pro bezpečnost manévru je nutné provádět kontinuální monitorování dopravní situace.
V neposlední řadě je třeba navrhnout metriku pro vyhodnocení funkčnosti a optimálnosti vyvinutých algoritmů. Verifikaci a vyhodnocení vyvinutého algoritmu provedeme nejprve v simulaci a následně i v kontrolovaném experimentu v reálném světě.

Klíčová slova: Autonomní operace robota, detekce kolizí, konečné stavové automaty, přejíždění silnic, ROS, rozhodovací stromy, vyhýbání se kolizím

Překlad názvu: Autonomní přejezd silnice mobilním robotem

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Introduction

In today's world, mobile robots are increasingly being utilized in a variety of applications. In many of these applications, the robots must cross roads to achieve their goals, making it essential to design an algorithm that enables the robot to cross the road safely.

The algorithm should be able to determine whether the current place is suitable for crossing. The algorithm will accept contextual inputs such as vehicle velocity data, road type, number of lanes, and the presence of a pedestrian crossing with or without traffic lights. These data will be used to assess the current situation and determine whether it is safe to cross the road. If it is, it should facilitate the crossing itself. If the location is not suitable, the algorithm should provide a reason and suggest a more appropriate location nearby. The algorithm must also be designed to operate on different robots with various sensor configurations and on different road types without any limitations.

This thesis aims to provide a theoretical background to the problem and explore possible solutions. We will also present the hardware and software used for real-world and simulation experiments. We will discuss our chosen approach and its functionality and present the algorithms we developed and implemented. Finally, we will explain the results of our experiments and discuss their significance.

Our work also depends on the output of other projects, such as vehicle detection and localization or path planning. We cannot rely on these projects to be completed or entirely functional. Therefore, we need a way to simulate and test our algorithm without them.

In simulation experiments, we will inject data directly into our algorithm. For real-world experiments, we will use the outcomes of the respective projects. However, we can inject data directly into our algorithm, provided the projects are not finished or functional. mework, a collection of tools, libraries and conventions for robot software development.

Used abbreviations

- **AI** – Artificial Intelligence
- **API** – Application Programming Interface
- **BT** – Behavior Tree
- **CRAS** – Center for Robotics and Autonomous Systems
- **ENU** – East-North-Up
- **FSM** – Finite State Machine
- **GPS** – Global Positioning System
- **GUI** – Graphical User Interface
- **HFMS** – Hierarchical Finite State Machine
- **LiDAR** – Laser imagining Detection and Ranging
- **NED** – North-East-Down
- **NPC** – Non-Player Character
- **OSM** – Open Street Map
- **REP** – ROS Enhancement Proposals
- **RL** – Reinforcement Learning
- **ROS** – Robot Operating System
- **TPI** – Terrain Profile Index
- **UTM** – Universal Transverse Mercator
- **WGS84** – World Geodetic System 1984
- **ZABAGED** – Základní báze geografických dat (Basic database of geographic data)

Chapter 1

Theoretical background

1.1 Behavior trees

A behavior tree (BT) is a way to structure algorithms – the switching between individual tasks in an autonomous agent. It was created to express behavior patterns for NPCs (non-playable characters) in computer games. Since then, it has found many more applications, and nowadays, it is also widely used in robotics and AI applications.

BTs, as the name suggests, are tree-like structures where each node represents an action, a condition, a control, or a decorator node. Action and control nodes are leaves of the tree structure. Control nodes are used to control and modify the flow of the tree. Examples of these nodes are `sequence`, `fallback`, or `repeat`. Decorator nodes are used to modify the return values, thus modifying the behavior of its children. Examples of these nodes are `force-success`, `force-failure`, or `inverter`.

The execution of a BT commences at the root node and then progressively traverses the tree structure in a depth-first fashion polling its nodes. The nodes' polling, more frequently called the ticking, is periodically repeated. Each node, once ticked, begins its execution process, and once finished, it returns a status. This status can be either `SUCCESS`, `FAILURE`, or `RUNNING`. The action and control nodes are responsible for determining and returning these states. The control nodes alter the tree's flow and tick handling based on its children's return states. Decorator nodes modify the return states of their children. The return status of some nodes is shown in table 1.1.

Node type	`SUCCESS`	`FAILURE`	`RUNNING`
`Action`	Succesful completion	Unable to complete	During completion
`Condition`	Condition is true	Condition is false	N/A
`Sequence`	All children succeed	One child fails	One child running
`Fallback`	One child succeeds	All children fail	One child running
`Parallel`	N children succeed	$< N$ children succeed	All children running
`Repeat`	Child succeeds	Child fails x times	Child running

Table 1.1: Return states of some nodes.

A more thorough explanation of the behavior trees can be found in the first chapter in [1].

1.1.1 Commonly used nodes

Here we will present the most commonly used nodes and their functionality.

Sequence – Control node that polls its children one at a time in a predefined order. If one of the children were to return `FAILURE`, the polling of other children is stopped, and the `sequence` node returns `FAILURE`. The same happens if one of the children returns `RUNNING`. If all children return `SUCCESS` the `sequence` node returns `SUCCESS`.

Fallback – Also known as `Selector` is a control node that polls its children one at a time in a predefined order. If one of the children were to return `SUCCESS`, the polling of other children is stopped, and the `fallback` node returns `SUCCESS`. The same happens if one of the children returns `RUNNING`. If all children return `FAILURE` the `fallback` node returns `FAILURE`.

Parallel – Control node that allows multiple actions to run concurrently. It returns `SUCCESS` if N or more children return `SUCCESS` and `FAILURE` if less than N children return `SUCCESS`. If all children return `RUNNING` the `parallel` node returns `RUNNING`.

Repeat – Control node that polls its child a specified number of times or until the child returns `SUCCESS`, whichever comes first. If the child returns `RUNNING`, the `repeat` node returns `RUNNING`. If the child does not return `SUCCESS` before the number of repetition is reached the `repeat` node returns `FAILURE`.

Inverter – Decorator node that inverts the return state of its child. If the child returns `SUCCESS`, the `inverter` node returns `FAILURE` and vice versa. If the child returns `RUNNING` the `inverter` node returns `RUNNING`.

Force-success – Decorator node that returns `SUCCESS` regardless of the return state of its child.

Force-failure – Decorator node that returns `FAILURE` regardless of the return state of its child.

1.1.2 Graphical representation of BTs

We will represent the BTs in this work in the following way. Action nodes will be rectangular with the name of the action written inside. Control nodes will be elliptical with the name of the condition written inside. Control and decorator nodes will be rectangular with a corresponding symbol inside. The symbols are shown in a table 1.2.

If the BT has a sub-tree in its structure, we will represent it as a diamond shape node with the sub-tree name written inside.

Node type	Description	Symbol
`Root`	The root of the tree	*Root*
`Sequence`	Ticks its children if the return is `SUCCESS`	$\rightarrow$
`SequenceStar`	Ticks its children if the return is `SUCCESS`	$\rightarrow^*$
`Fallback`	Ticks its children if the return is `FAILURE`	?
`Parallel`	Allows multiple actions to run concurently	$\rightrightarrows$
`Repeat`	Repeats the child node (x) times	$\circ(x)$
`ForceSuccess`	Allways returns `SUCCESS`	✓
`ForceFailure`	Allways returns `FAILURE`	$\times$
`Inverter`	Inverts the return value of its child	$\neq$

Table 1.2: Symbols used for control and decorator nodes in BTs.

1.1.3 BT example

We will present a simple example demonstrating the BTs structure and design principles.
The example BT is shown in figure 1.1. This BT was created in the algorithm design's beginning phase, and its modified version will be presented later as it is used in the final implementation. The goal of this sub-tree was to position the robot so that it would cross the road as fast as possible, meaning we wanted the robot to stand perpendicular to the road.

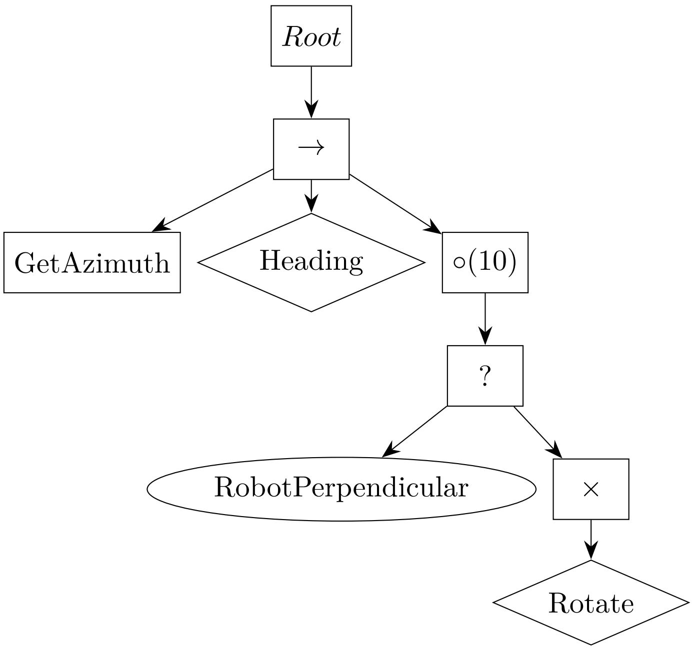


Figure 1.1: BT example.

We start in the root node and continue straight to the `sequence` node. From there, we go to the action node GetAzimuth, which gives us the current heading of the robot. If the execution of the GetAzimuth node is successful, we continue to the Heading sub-tree node. This sub-tree aims to calculate the heading the robot needs to achieve in order to be perpendicular. If all nodes inside the sub-tree are successful, we continue to the `repeat` node. This node will repeat its children ten times (or less if success is achieved sooner). The first child we will tick is a `fallback` node, with its first child being a condition node RobotPerpendicular. The condition node return value states whether or not the robot is already perpendicular to the road, we mean to cross. If we are not yet perpendicular, we continue. The next node we tick is a `force-failure` node with a sub-tree node as its child. The sub-tree is responsible for rotating the robot to the desired heading.

1.1.4 Other BT nodes

Here we will present other BT nodes. These nodes are an expansion on the common ones and are implementation specific.

SequenceStar ($\rightarrow^*$) – Also know as `SequenceWithMemory`, a control node that functions in the same way as `Sequence`. The only difference is that this node does not repeat children that returned `SUCCESS` until all children have. Meaning until the `SequenceStar` node return `SUCCESS` it will tick only the children that have not succeeded yet.

ReturnSuccess – A leaf node that returns `SUCCESS` once ticked. We will represent this node as an ellipse with a checkmark character (✓) inside.

ReturnFailure – A leaf node that returns `FAILURE` once ticked. We will represent this node as an ellipse with a cross character ($\times$) inside.

1.1.5 Common BT structures

Common programming principles can explain some BT structures. We will present a few of these structures that we have used in our BT structure.

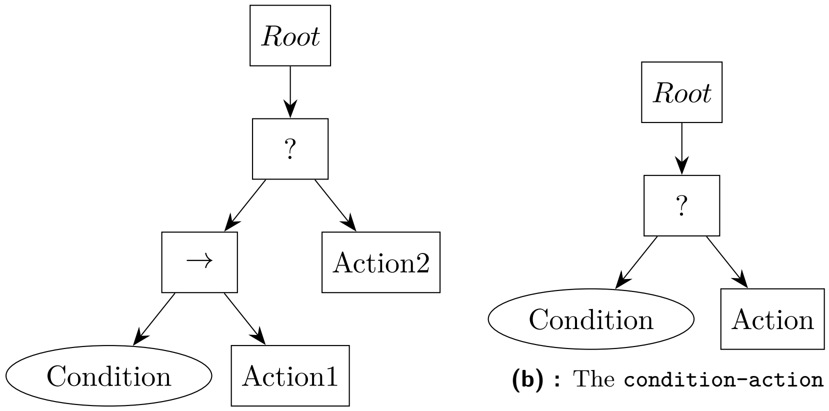
If-else

The `if-else` structure starts with a `Fallback` node, and the first child a `Sequence` node with its first child a condition node and second child an action node, ticked if the condition is true. The second child of the `Fallback` node is also an action node that is performed if the condition is false.
The structure is shown in figure 1.2a.

Condition-action

We could also name this structure as `if not`.
The `condition-action` structure starts with a `Fallback` node. Its first child is a condition node, and its second is an action node. The idea behind this structure is we want to check if an action has been performed, and if it has

not, we want to perform it.
The structure is shown in figure 1.2b.



(a) : The `if-else` structure.

(b) : The `condition-action` structure.

Figure 1.2: The common structures used in the creation of BTs.

1.2 Finite-state machines

Finite-state machines (FSM) are a mathematical model of computation. They are used to model the behavior of a system in a finite number of pre-defined states. The system can be in only one state at a time. In each state, a computation or an action is performed. The change of a state is possible only via predetermined transitions triggered by a condition.
FSMs are a common method of describing and solving high-level sequential control problems. They are used in many fields, such as robotics, computer science, electrical engineering, etc.
FSM offers a very effective method in the implementation of complex robot behavior in comparison to monolithic programming.[2] Moreover, the learning curve for using FSM is minor; it is quite likely the reader already knows about FSMs from math or logic courses. Secondly, the integration itself is almost painless, especially when one takes the FSM into account from early stages of the design.[3]
However, the FSMs are unsuitable for large and complex systems as they tend to become unmanageable and difficult to extend and reuse. This becomes more evident for a fully reactive system, where each state must be able to transition to any other state. Such a condition imposes the FSM to become a fully connected graph ($\mathcal{O}(n^2)$). Maintaining and modifying such a graph is quite a labor-intensive and error-prone task.
FSMs are also unsuitable for systems requiring a high degree of autonomy. The FSMs are not able to learn and adapt to the changing environment.
The formal definition of a FSM and several examples can be found in [3].

1.2.1 FSM example

Here we will show the FSM for the example BT (figure 1.1) from the previous section.

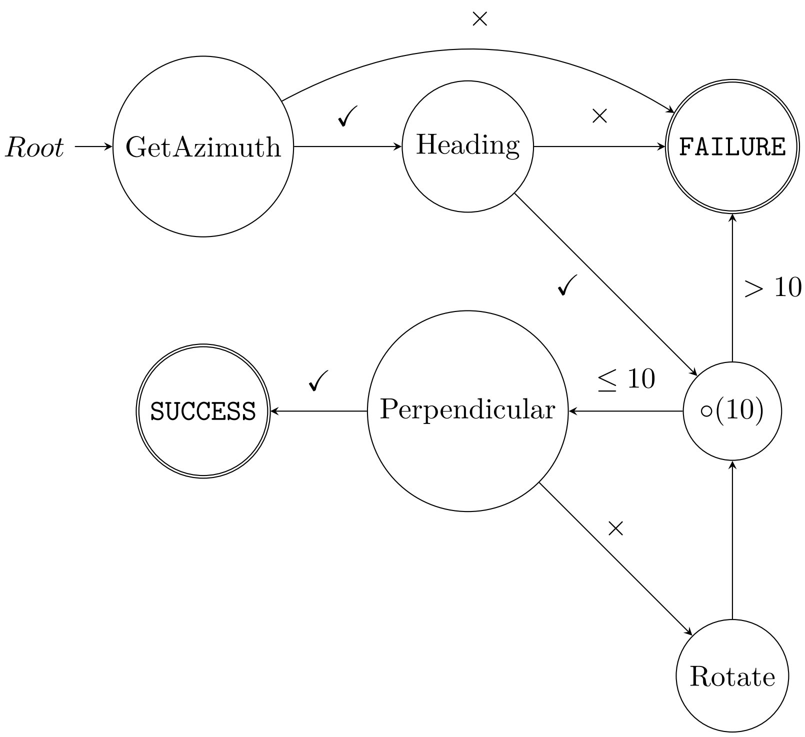


Figure 1.3: FSM for the example BT.

This is not a typical representation of a FSM. It is a one to one rewrite of the BT example. If we were to develop the algorithm using FSMs, the FSM would look different. BTs and FSMs require different mindsets and design principles and while they may be rewritten from one to the other, it usually results in a nonoptimal structure.

1.3 Hierarchical FSMs

Hierarchical state machines (HFSM), also known as statecharts, were developed to alleviate the cumbersome transition duplication required in large FSMs and add structure to aid comprehension of complex systems. It clusters states into a group (named superstate) where all the underlying internal states (substates) implicitly share the same superstate.[4]
While the HFSM solves the problem of transition duplication, it does not solve the complexity problem. The HFSM is still a fully connected graph unsuitable for large and complex systems.

1.4 Comparison and chosen approach

There are several design approaches we can use to solve the task of crossing a street. We will briefly present them and state few advantages and disadvantages for each one. We will mainly use the informations and insights from [1].

Monolithic approach

We can use a monolithic approach, where we write a single program that will handle all the tasks.
This approach is the most straightforward and easiest to implement but is not very flexible. It would be complicated to modify or extend the abilities of our program to the point where we would be forced to rewrite it in its entirety. This approach also generates a design that is not easily readable, and it would be almost impossible to find and correct bugs and glitches.
For all those reasons, the monolithic approach is unsuitable for anything other than elementary systems, and we will not use it for our solution.

FSM approach

The second approach is to use an FSM. More specifically, HFSM as it is an improvement over FSM and addresses a few of the FSM issues.
The advantages of HFSMs are that the structure is intuitive and generally easy to understand. Being common in many parts of computer sciences and used for quite some time, they are also quite easy to implement. FSMs also offers good flexibility and maintainability for many problems.
The main disadvantage of HFSMs is that the flexibility is limited to certain areas of use and systems with limited scale. It is impossible to easily add new states or transitions in complex systems.
Scalability of FSMs is also a problem. With rising demands on agent AI complexity, game programmers found that the FSMs that they used scaled poorly and were difficult to extend, adapt and reuse.[5]
The FSM's poor scalability means that this approach is also unsuitable for our solution.

BT approach

The third approach is to design the algorithm in the form of a BT.
The advantages of this approach are its modularity, reusability, reactivity, readability, and scalability. Modularity is closely linked with reusability. The design principles of BTs allow us to decompose the algorithm into sub-trees which may be implemented and tested separately. This allows us to tackle large complex systems with relative ease. The BTs are reactive in the sense that they can react quickly and effectively to the changing environment. Even though they require a different design approach than FSMs, they provide a coherent and compact structure that is easy to understand and maintain.
The main disadvantage of BTs is that they are not very common in the industry and are not as well known as FSMs. For this reason, the tools and libraries are not as numerous or mature as those available for FSMs.

As mentioned earlier, they are different from FSMs and, as such, require a different approach to designing an optimal solution.

Chosen approach

The approach we have chosen to use in this thesis is the BT approach. We have chosen it for many reasons. Mainly for its scalability, readability, and maintainability of large complex systems are excellent. The BTs are also very flexible and can be easily extended and modified. The BT approach was also suggested by the supervisor.

1.5 Mathematical aparatus

This thesis will use chapters from linear algebra, calculus, geometry, and probability theory.
The used theory will be shown and briefly explained in sections where it is needed. We will not provide precise definitions or state used theorems as it is outside the scope of this work. However, a book, a paper, or an online document with the corresponding information will be provided should the reader require a more thorough explanation.

1.6 Maps

We will use the maps from the OpenStreetMap (OSM) project[1]. The maps will be used to determine the surroundings of the robot and whether the current position is suitable for crossing.
OSM is a project that creates and distributes free geographic data. The data is created by the community of users and is available for anyone to use.[6]
The map data are expressed either by a node, a way, or a relation. Node is a singular point in map, it could be a landmark, a corner of building or a spot on the road. Way is an object created from multiple nodes. It can be either closed or open. Closed ways may represent a park, building or a some other type of area. Open ways commonly represent roads, rivers, or other linear features. Relation is a collection of nodes, ways, or other relations. It is used to describe more complex objects, such as a bus line, a building complex etc.

[1] `https://www.openstreetmap.org`

Chapter 2

Used hardware and software

2.1 Software

All work in this thesis is aimed to work with Robot Operating System (ROS) [7]. We will use ROS1 in version Noetic Ninjemys[1].

Programming languages

The majority of implementation work will be done in a C++ programming language. The version of C++ standard used is C++14, as it is the default for ROS1.
The C++ language was chosen for its speed and efficiency. It was also chosen for some of the libraries we need to use for our project.
The second programming language we will use is Python in version 3.8. Python was chosen for its simplicity and ease of use, as well as for using our previous work in OSM data processing.

BT library

There are a few possibilities regarding the BT library we can use for our solution. As BTs are not very commonly used, the choice is more limited than if we use FSM. Another limiting factor we have is support or direct integration with ROS.
We still have a few options, and we can even choose a programming language in which to implement the BT nodes. The two programming languages with the most library options are C++ and Python. This copies the ROS mentality, where these two languages are natively supported. Some possibilities are discussed here [8].
We have decided to use a C++ behaviortree-cpp-v3 library[2]. The choice was made for multiple reasons. This library was written with deployment in ROS in mind. It is regularly updated and maintained, making it the safe choice for us. It also comes with a documentation that will be helpful during the implementation process. There are two version of the documentation [9] and [10]. We will mainly use the newer one (the second mentioned), but we will

[1] `http://wiki.ros.org/noetic`
[2] `https://github.com/BehaviorTree/BehaviorTree.CPP`

cross reference it with the older one.
Another benefit of this implementation is that it comes with a GUI application for creating BTs called Groot[3]. This application creates an `.xml` file with the BT structure we can import into our code later.

Libraries for OSM and work with geographical data

There are a lot of libraries to choose from when it comes to working with OSM data. These libraries are created for different programming languages and have different features.
Even though the majority of our work was written in C++, we were building on top of previous work of assigning costs to road segments in OSM data. This work was done during the 2022 summer as a part of the RobInGas project here at the CTU under the Center for Robotics and Autonomous Systems (CRAS[4]) group.
The work was done in Python, and the library used was the overpy library[5]. This library is used to access the OSM Overpass API and download the map data. The Overpass API (formerly known as OSM Server Side Scripting) is a read-only API that serves up custom-selected parts of the OSM map data. The difference between the main API is that the Overpass API is optimized for small to large consumers (up to roughly 10 million elements). Many services and applications use it as a database backend.[11]
Other libraries used for work with the OSM data were shapely[12], numpy[13] and utm[6]. These libraries were used to classify and assign costs to individual road segments in the downloaded OSM data.
In our work, we also need to convert the coordinates of the robot from the GPS coordinate system to the UTM coordinate system. The conversion is done using the GeographicLib library[14].

2.2 Hardware for real-world experiments

2.2.1 Robots

This section will present the robots we will use in real-world experiments. We will use two robotic platforms: Husky and Spot.

Husky

Husky is a medium all-terrain robot developed by Clearpath Robotics. It is a four-wheeled robot with a payload capacity of 75 kg. The weight of this robot without the payload is 50 kg, and its maximal speed is 1 [m/s]. This robot is mainly used outside of urban areas. The photo of Husky is shown in figure 2.1a.

[3] `https://github.com/BehaviorTree/Groot`
[4] `https://robotics.fel.cvut.cz/cras`
[5] `https://github.com/DinoTools/python-overpy`
[6] `https://github.com/Turbo87/utm`

More information is available at the Clearpath Robotics website[7].

Spot

The spot is a medium all-terrain robot developed by Boston Dynamics. It is a four-legged robot with a payload capacity of 14 kg. The weight of this robot without the payload is 33 kg, and its maximal speed is 1.6 [m/s]. This robot is mainly used in urban areas. The photo of the spot is shown in figure 2.1b.
More information is available at the Boston Dynamics website[8].

(a) : Robot Husky. **(b) :** Robot Spot.

Figure 2.1: Robots used in the real-world experiments.

Photos are courtesy of CRAS at FEE CTU.

2.2.2 Sensors

The robots we use are highly dependent on the sensors we attach to them. Without them, the possibilities and options for the mission are limited. We will use some sensors directly and some indirectly. The indirect usage of sensors is due to the need to work with detected vehicles and other obstacles. This detection is not in the scope of our work but is instrumental to its success.

Magnetometer

This is a sensor we use directly. We use it to determine the heading of our robot and help it position itself perpendicular to the road it will try to cross.

Camera

Our robots are fitted with cameras pointing forward, backwards, left, right, and up. This sensor is mostly used to determine the classification of obstacles rather than detecting the obstacles themselves.
The cameras on our robots are GigE Basler ace2 PRO.

[7] https://clearpathrobotics.com/husky-unmanned-ground-vehicle-robot/
[8] https://www.bostondynamics.com/sites/default/files/inline-files/spot-specifications.pdf

LiDAR

Another sensor our robots are equipped with is LiDAR (laser imaging, detection, and ranging). This sensor detects incoming vehicles and determines their speed and position vectors. It is probably the most important sensor due to its processed data being our algorithm's main switching condition.
The LiDARs used on our robots are Ouster OS0-128.

GPS

Robots also have a GPS sensor. We use this sensor for precise localization of the robots in global coordinates.
The GPS sensors we use are Emlid Reach M+.

2.3 Simulation environment

We will simulate the behavior of our robot in the Gazebo simulator[9]. Gazebo is a 3D simulator for robots. Its biggest advantage is its direct integration with ROS. This means that we can simulate similar behavior to the one expected of the robot in real-world experiments.
We will use the Husky robot model for our simulations. The Husky was chosen as it is one of the robots we may use in the following real-world experiments, and its model was available to us.
As the creation and implementation of the simulation were not the main focus of this thesis, we have used previously created simulation environments. As the basis for our simulations, we used the `robingas_mission_gazebo` project[10]. This project was created by the CTU CRAS group. We have modified the project to fit our needs.

[9] `https://gazebosim.org/`
[10] `https://github.com/ctu-vras/robingas_mission_gazebo`

Chapter 3

Behavior tree algorithm structure

3.1 Creating a behavior tree structure

There are several possible approaches to creating a BT structure. We will present a few of these approaches and state the used one. In this section, we used the insight from [15].

The first approach is creating the complete BT by hand. Meaning that humans must design every node and its position and function within the structure.

The second approach is creating an initial BT and letting RL algorithms improve their functionality and optimality. There are several options for this particular approach.

The third possible approach is constructing the BT from previously recorded human behavior.

The last possible approach lets the RL algorithm construct the BT structure from scratch.

Each of the presented approaches has its advantages and disadvantages. It is, therefore, vital to select the correct approach based on the possibilities and requirements of the task.

Chosen approach

We have chosen the first approach, meaning we will construct the whole tree structure by hand. This was done as it is the easiest approach to this task and requires no additional steps.

Using different approaches to designing and improving the BT structure may be an interesting task for future work.

We will design the BT structure in the GUI application designed alongside our chosen BT library, Groot. The application interface is shown in figure 3.1.

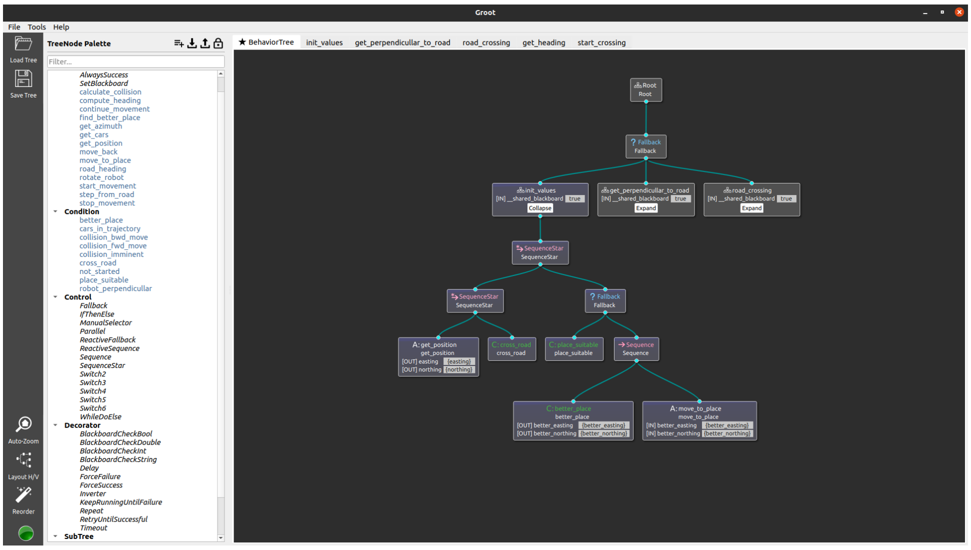


Figure 3.1: The Groot application interface.

3.2 Structure hierarchy – Main BT

We will divide the whole tree structure into several sub-trees to help with readability, modularity, and maintainability.
The first sub-tree will help with initialization and will be responsible for determining whether the tree should be run. It is also responsible for navigating the robot to a suitable crossing place. This sub-tree will be called `Init-BT`.
The second sub-tree will be responsible for positioning the robot such that it is perpendicular to the road it is trying to cross. This sub-tree will be called `Perpendicular-BT`.
The third sub-tree will be responsible for the navigation of the robot during the crossing. It will check the positions and speed of incoming traffic and determine the best strategy for the crossing. This sub-tree will be called `Crossing-BT`.
There are a few more sub-trees in our structure, but those are not that important to write about here. They will be presented when they are mentioned in the main sub-trees structure. Their main task is to help with the modularity and reusability of the behavior they encode.
The main BT is shown in figure 3.2.
The main BT starts with a `Sequence` node. First, we need to check if the algorithm should be even started – to avoid collision between two nodes trying to control the robot. This we achieve with a condition node `StartAlgorithm` node. This node will check if the algorithm should be started. If it should not, the algorithm will not progress. The second child is a `SequenceStar` node. This node will tick the sub-trees responsible for the whole algorithm. However, the first child is a `SequenceStar` node. This is done to ensure that each of the preparation sub-trees will be executed once (that is, if they return `SUCCESS`).

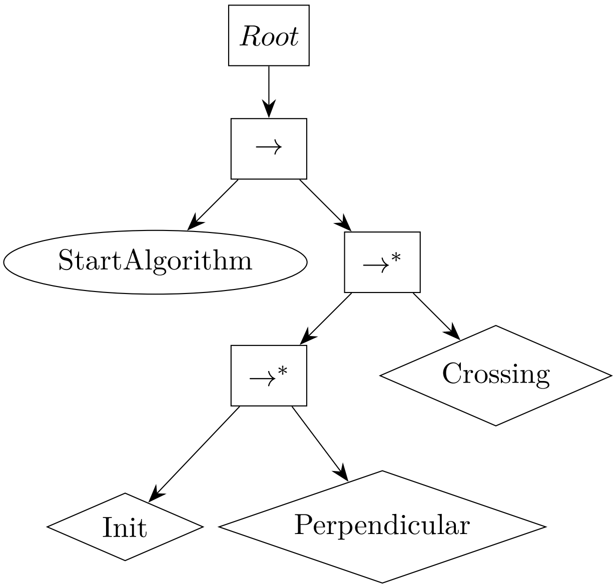


Figure 3.2: Main BT structure.

The first preparation sub-tree is the `Init-BT`, its structure shown in chapter 3.3 and its implementation in chapter 4.1.3.
The second preparation sub-tree is the `Perpendicular-BT`, its structure shown in chapter 3.4 and its implementation in chapter 4.1.4.
The last sub-tree is the `Crossing-BT`, its structure shown in chapter 3.5 and its implementation in chapter 4.1.5.

3.3 Init BT

As mentioned earlier, this BT is responsible for determining if we should start the crossing and for navigating the robot to the optimal location. This tree will be executed only once for each crossing. We accomplish this with a `SequenceStar` node as the first node after `Root`. The `Init-BT` structure is shown in figure 3.3.
The flow for the algorithm is the following. We start at a `Sequence` node. With its first child being a control node `SequenceStar`, we start the `Init-BTs` first branch. The first node in this branch is an action node `GetPosition` followed by a condition node `CrossRoad`. The idea behind this branch is to determine the proximity of the robot to the road. If the robot is too far away from the road, the algorithm should not progress. This will help combat the possibility of trying to cross the wrong road, should it happen that two roads are close by.
The second branch of this sub-tree starts with a `Fallback` node. The idea behind this branch is to place the robot in an ideal position for crossing. This action should have been done before the mission, and the robot should have been sent to the optimal location by a path-planning node.
However, if such pre-mission planning was not performed, the `PlaceSuitable`

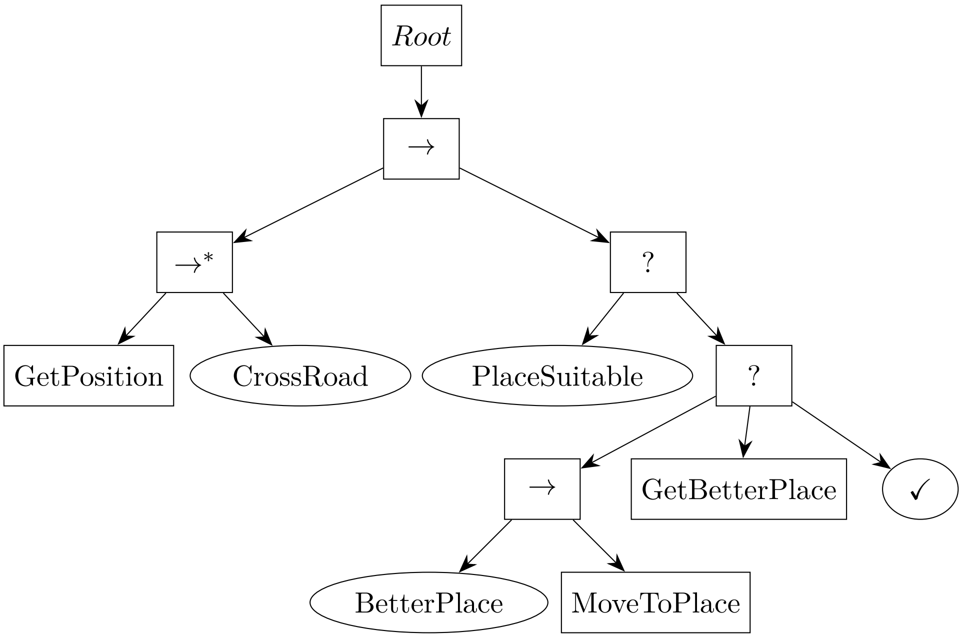


Figure 3.3: The Init-BT structure.

condition node will check if the place is suitable. If not, the `BetterPlace` condition node will return if a better location was found. An action node `MoveToPlace` will steer the robot to a better location if it has been found. Lastly, the action node `GetBetterPlace` will try to find a better place.
We will not perform the sub-tree again if a better place cannot be located. Instead, we will move on to the following sub-tree and cross the road in the position the robot is currently situated. This is done to avoid an infinite loop and is achieved with a `ReturnSuccess` node at the end of the second branch.

3.4 Perpendicular BT

This sub-tree is responsible for positioning the robot for crossing in the most optimal way. We have determined that to be the one in which the robot will cross the road the fastest. As such, the position of the robot should be perpendicular to the road it is going to cross. Figure 3.4 shows the BT structure for achieving so.
The first branch of this tree is also only needed once in each run of the crossing algorithm. Therefore, the first node after the `Root` node is a `SequenceStar` control node.
The task of the first branch is to determine the azimuth for the robot to be perpendicular to the road. This also does not need to be repeated for a single road, so we start with a `SequenceStar` node, next, we have a `Repeat` node. The action to be repeated is the obtaining of the robot's azimuth. The following steps are also behind a `Repeat` control node. This part of the algorithm calculates the azimuth the robot should have to be perpendicular.

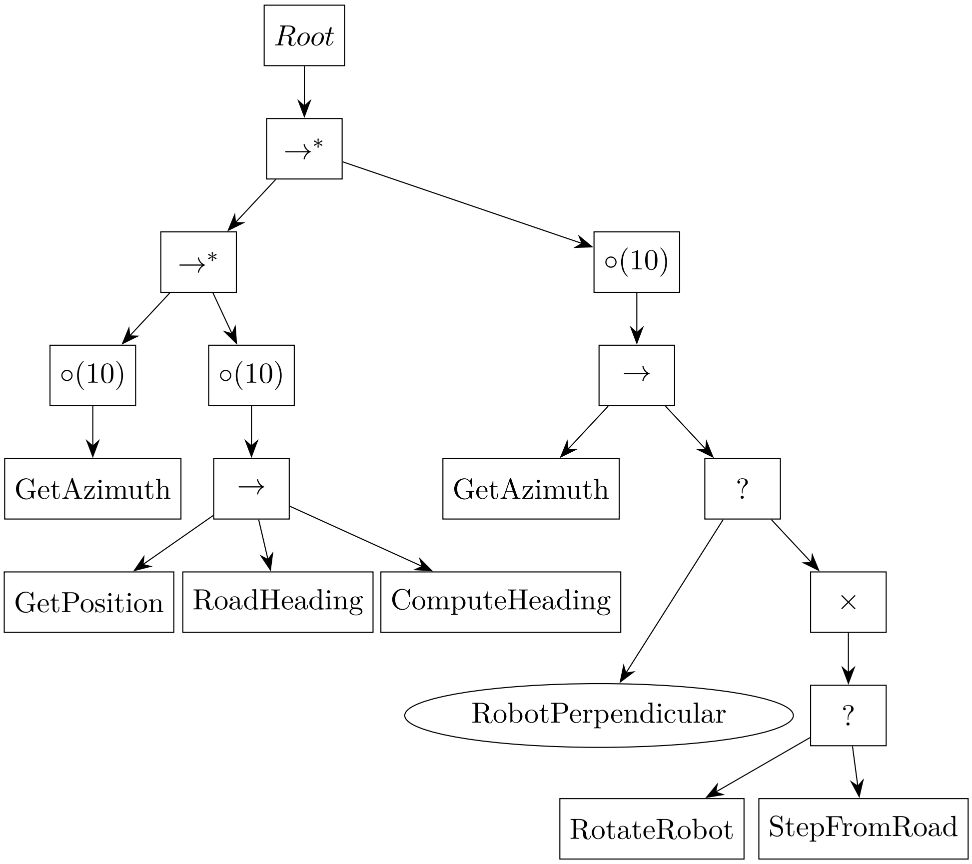


Figure 3.4: The Perpendicular-BT structure.

Firstly we need to obtain the robot's position – `GetPosition` action node. Next, we need to determine the road heading closest to the robot. For this purpose, we have the action node `RoadHeading`. Finally, we calculate the proper azimuth for the robot with the action node `ComputeHeading`. This concludes the left branch of our Perpendicular-BT.
The right branch starts with a `Repeat` node, followed by a `Sequence` node. The idea behind this branch is to utilize the azimuth value computed in the left branch and orient the robot accordingly. Firstly we need to obtain the robot's azimuth with the `GetAzimuth` action node. While this might seem redundant, we have just got the azimuth for calculation, it is vital to update the current azimuth as the value of obtained azimuth is only valid in the first run of the second branch. After receiving the current azimuth, we follow with a `Fallback` node and its first child, a condition node `RobotPerpendicular`. This node tells us if the robot has achieved the optimal azimuth we calculated earlier. If it has not, we continue, thanks to the `Fallback` node to the last part of this sub-tree. We want this part to always return `FAILURE`. This is necessary because we check the correct position before the movement. The last part is responsible for the movement of the robot. Firstly we try to rotate the robot with `RotateRobot` action node. If the rotation was unsuccessful, we tried to move the robot away from the road with `StepFromRoad`. This is

implemented as the robot rotation could have brought the robot onto the road, which is forbidden.
While we could unite the first two `Repeat` nodes, maybe even all three, we chose not to do so. The reason for not merging the nodes is to allow each algorithm part to fail independently. The number of repetitions for each node was set to 10, which we determined to be the optimal value.

3.5 Crossing BT

This tree is the most important part of the whole algorithm as it facilitates road crossing. Figure 3.5 shows the structure of the tree.
This tree starts in the `Sequence` node with five children. This tree also contains two further sub-trees. These sub-trees are shown in figures 3.6a and 3.6b, and will be explained separately at the end of this section.
The first branch of this tree is responsible for obtaining the data of all detected vehicles from other ROS nodes. This functionality is implemented in just one action node `GetCars`.
The second branch starts with the `Fallback` node. The first child of this node is a condition node `CarsInTrajectory`. This node checks if any cars are in the robot's trajectory. If there are not, we are free to continue with our movement or start it if we have not done so yet. This is performed with a sub-tree `StartCrossing`, followed by the `ContinueMovement` action node. These nodes are connected behind a `Sequence` node.
The following two branches are responsible for crossing the road if cars are detected in the robot's trajectory. The third node is the `StartCrossing` sub-tree.
The fourth branch is the decision-making part of the tree. It starts with the `Sequence` node with its first child, the `CalculateCollision` action node. This node is responsible for calculating the velocities for the robot to collide with all detected vehicles. These velocities are vital information on which all the decision-making is based.
The second child of the `Sequence` node is a structure of cascading if-else statements. The structure gradually checks the following conditions and performs the corresponding actions based on the results.
The first condition is the `CollisionImminent` condition node. This node checks if the robot is about to collide with any of the detected vehicles. If it is not, the robot will continue its current movement.
If a collision is detected, we check if the collision would be on moving forward with a `CollisionFwdMove`. If not, we can continue with the forward movement. However, the speed could change.
If the collision would be on forward movement, we check if the robot can move backward with a `CollisionBwdMove` condition node. If it can, we move backward with the `MoveBwd` node. If not, we stop the robot using the `StopMovement`.

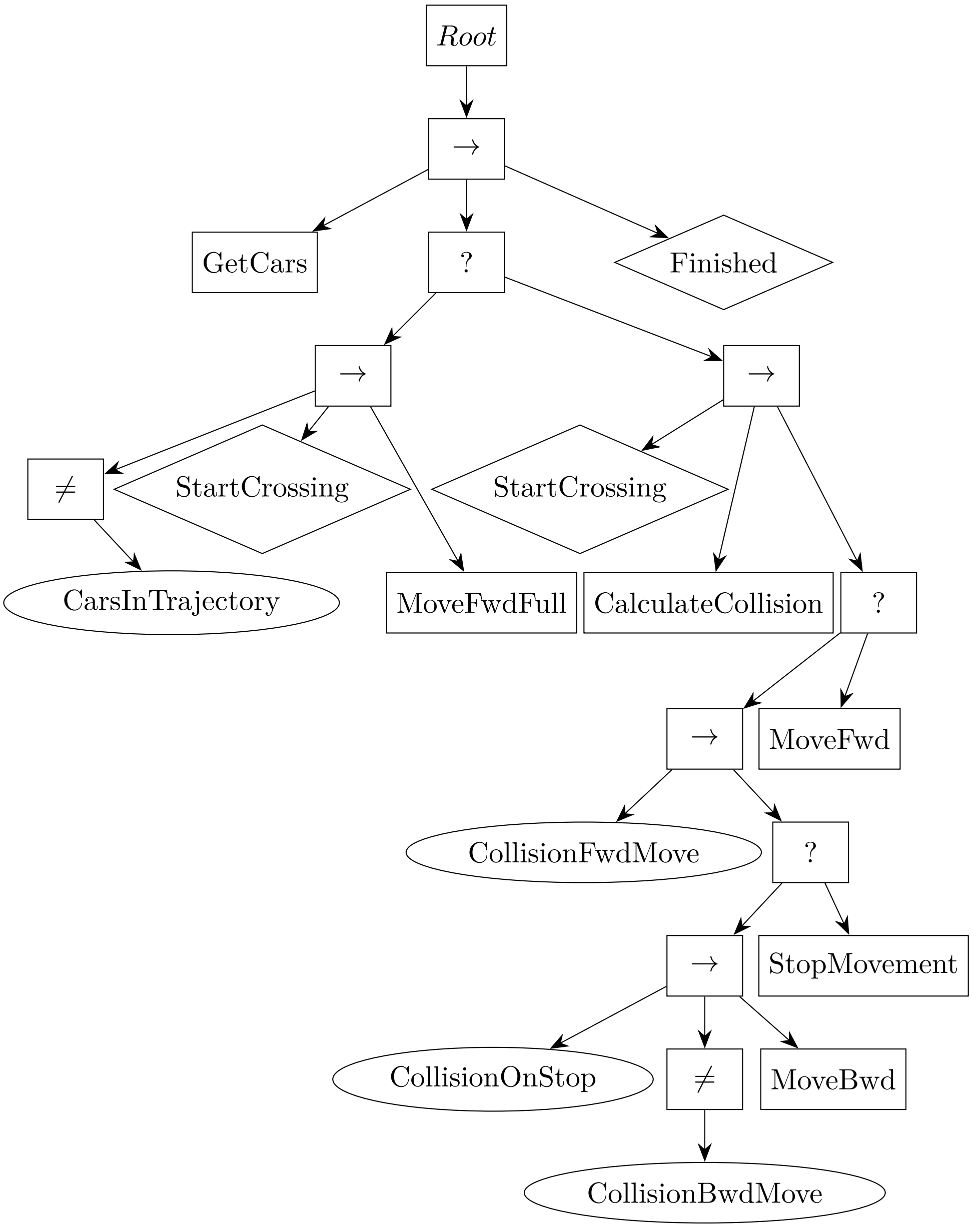


Figure 3.5: The Crossing-BT structure.

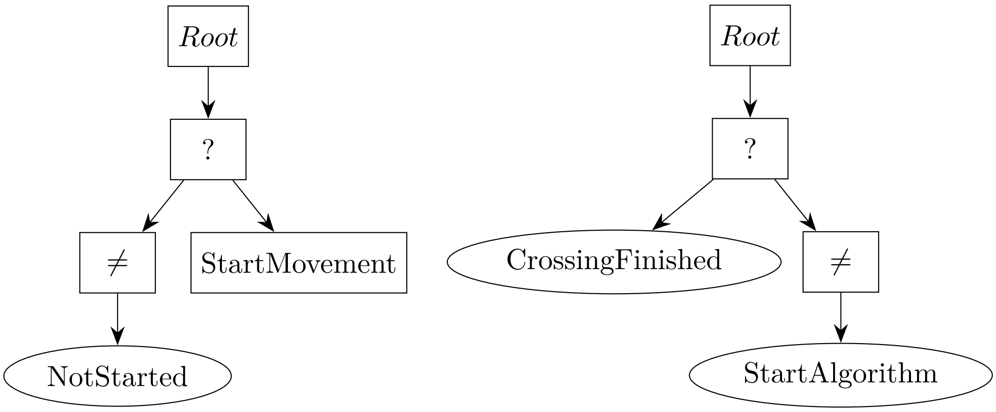
3.5.1 Crossing BT sub-trees

StartMovement BT

The `StartMovement` sub-tree is responsible for detecting if the movement process has started (the `NotStarted` condition node). If not, it starts the movement (the `StartMovement` action node).

Finished BT

The `Finished` sub-tree detects if the robot has the road. There are two ways we can detect if the road was crossed. The first condition node



(a) : The StartMovement-BT structure. **(b) :** The Finished-BT structure.

Figure 3.6: The structures of sub-trees inside the Crossing-BT.

`CrossingFinished` performs the check with the current GPS coordinates of the robot and road data, namely its GPS coordinates and width. The second check is the condition node `StartAlgorithm`, where the condition could be set from outside the algorithm, for example, from a different ROS node.

Chapter 4

Nodes implementation

This chapter will provide the implementation details for individual nodes used in our BT algorithm. We will split these descriptions into BT nodes, and auxiliary functions used in the nodes.

4.1 Behavior tree nodes

Here we will present the methods used to implement the individual nodes of our BT algorithm. We will split the nodes into categories based on the sub-tree they belong to.

4.1.1 Introduction

The BT algorithm is implemented using the behaviortree-cpp-v3 library. Therefore, we will present how we create, implement and run the tree. We will also show how nodes are created, implemented, and used.

Creating the node

To create the node, we need to create a class that inherits from one of the parent classes in the library. The parent classes depend on the type of node we want to create. If we create an action node, we inherit from the `SyncActionNode` class. If we create a condition node, we will inherit from the `ConditionNode` class.
We must define two functions for all nodes, the `tick` and `providedPorts` functions.
The `tick` function is responsible for the actual implementation of the node. It is called every time the node is executed. It is also responsible for returning the state of the node.
The `providedPorts` function defines the ports the node will use. This function must be defined even if the node does not use any ports.

Using the node

To use the node, we first have to create a tree. We create a class `Road_cross_tree` with a `BehaviorTreeFactory` object. This object is used to create the tree. We also have a `Tree` object used to store and run the tree.

To use a node, we must register it in the `BehaviorTreeFactory` object. We do this by calling the `registerNodeType` function. For this function, we need to specify the class of the node we want to register, e.g., one of the nodes we created. It also takes one `std::string` parameter, which identifies the name of the node in our BT algorithm `.xml` file.

Creating and running the tree

To create the tree, we first must have a `.xml` file with the tree structure. This file is then parsed by the `BehaviorTreeFactory` object using the `createTreeFromFile` function. The result is a `Tree` object which we can then run.
To run the tree, we call the `tickRoot` function on the `Tree` object. This function returns the state of the root node of the tree.

Blackboard

The blackboard is a shared memory between the nodes of the tree. It is used to store data that is being used by multiple nodes.
It is also the reason why we implement the `providedPorts` function. This function specifies the ports the node will use. These ports can take a constant value (specified during the creation of the tree structure) or look for a value in the blackboard.

Logging

The BT library also provides us with logging functionality. This functionality is useful for debugging and testing.
We can use different types of loggers. The most common one is the `StdCoutLogger` which logs to the standard output. We can also use the `FileLogger`, which logs to a file.
We will use the `FileLogger` to log the tree execution. This logger is useful for its integration with the `Groot` application as we can import the produced file and visualize the tree execution.
The logging will be used only for debugging and testing purposes and serves no other function in the final product.

4.1.2 Main BT

In this BT we have only one non-sub-tree node. This is mainly for the reason, that this tree mostly just encodes the algorithms structure, rather than having nodes for execution.

StartAlgorithm – Condition node

This node is responsible for determining whether the robot is in the phase of crossing the road during its mission. It is necessary to implement such a node to facilitate the transfer of control from path planning to road-crossing. In contrast, we could determine if the crossing should start based on the distance of the robot from the road. This method would fail whenever our robot needs to walk alongside any road.

This node is a ROS service updating a variable, which is checked when the node is ticked.
This service should be used mostly by other nodes outside of the package itself, with one notable exception. The exception being the very last node of the tree to prevent the tree from looping.

4.1.3 Init BT

Here we will present the nodes used in the Init sub-tree. This sub-tree is used to initialize the BT algorithm. It is the first sub-tree to be executed.
This tree is going to be executed only once per road to cross. We will achieve this by using the `SequenceStar` node as the root of this sub-tree.

GetPosition – Action node

This node is responsible for obtaining the current GPS position of the robot and converting it to the UTM coordinate system. It is implemented as a ROS topic subscriber. The topic subscribed is `fix/` where the GPS data are being published.
The obtained data are then converted to UTM using the `gps_to_utm` function defined in 4.2.3. The result is then stored as two BT blackboard variables – `easting` and `northing`.
For each of the obtained values, it also calls a ROS service `place_suitability` to determine the suitability of the crossing place.

CrossRoad – Condition node

This node tells our algorithm if we are close enough to a road to take over the robot's controls. If we are not the path-planning or other node is left in control.
We use the return values of the ROS service call issued in the GetPosition node. This service has two return values – validity and suitability. Suitability uses the road cost as well as context score to judge the place for crossing. Validity only calculates the distance of the current location to road segments from OSM.
Therefore the validity variable is the one determining the output of this node. The distance limit we proposed as sufficient is 10m from the center of the road.

PlaceSuitable – Condition node

This node states whether the stored robot's location, as blackboard variable, is suitable for crossing.
It uses the second return value from the ROS service called from the GetPosition node. As stated, this value takes into account the road cost for our location from the road-cost algorithm (4.2.1) and the context score calculated separately before the service call.
The context score is based on the contextual information that is available to us. This information may be passed from other nodes (e.g., computer vision node for detecting road parameters) or set by the operator.
The calculation of the context score and the process of obtaining the contex-

tual information is described in 4.2.4.

Other nodes shown it the BT structure (fig 3.3) are currently returning `FAILURE`. These nodes are there to show the potential for further work. Their main purpose is to steer the robot to a more optimal location for crossing. In this work, we assume that the correct location was chosen in the pre-mission planning.

4.1.4 Perpendicular BT

This tree is used to position the robot perpendicular to the road. It is the second sub-tree to be executed, and as well as Init BT, it is used to prepare the robot for the crossing.

GetAzimuth – action node

This node is responsible for obtaining the robot's current azimuth. We have a ROS subscriber listening to topic published by `compass` node[1].
The compass node may publish the azimuth in several different formats. In our program, we use the ENU format in radians. But if the compass node publishes the azimuth in a different format, we have subscribers that can convert it to the desired format.
The azimuth is then stored as a blackboard variable `azimuth`.

RoadHeading – action node

This node calculates the heading of the closest road to the robot. We take the current robot's position from the blackboard variable `easting` and `northing` and send a request to the ROS service `get_road_heading`.
The service returns the two coordinate points representing the closest road segment's starting and ending points.
We then calculate the heading of the road segment using the function defined in this section 4.2.3.
The calculated road heading is then stored as a blackboard variable `road_heading`.

ComputeHeading – action node

This node uses the blackboard variable `azimuth` and `road_heading` to calculate the azimuth the robot should achieve to be perpendicular to the road.
The calculation is defined in section 4.2.3.
The result is stored as a blackboard variable `req_azimuth`.

RobotPerpendicular – condition node

This node checks if the robot is perpendicular to the road. It works by comparing the current azimuth with the required azimuth. Both of these values are stored on the blackboard.
We use the function defined in section 4.2.2 to compare the values to calcu-

[1] https://github.com/ctu-vras/compass

late the difference between two angles. The result is then compared to the threshold value, which is set to 0.1745 rad or 10°.

RotateRobot – action node

This node rotates the robot to the required azimuth.
First, we calculate the difference between the robot's current and desired azimuth. Then, based on the difference, we proportionally set the rotation direction and speed.
The calculated movement is then published to the `cmd_vel` topic.

StepFromRoad – action node

If, for whatever reason, the robot is not able to rotate safely, primarily due to the possibility of ending on the road, we use this node to move the robot away from the road.
Firstly we check the difference between the robot's current azimuth and the road heading. Based on the difference, we set the direction of the movement. The movement is then published to the `cmd_vel` topic.

4.1.5 Crossing BT

This tree is used for the main decision-making process. It is the third sub-tree to be executed, and the only one to be executed repeatedly.
In multiple nodes we will use information about the detected vehicles, and collision parameters for each vehicle. Therefore, we first need to define the data structures used to store this information.

Vehicle data

The data structure for storing the information about the detected vehicles is defined as follows:

Listing 4.1: Vehicle data structure

```
struct vehicle_info {
    int id;
    double x_pos;
    double y_pos;
    double x_dot;
    double y_dot;
    double x_ddot;
    double y_ddot;
    double length;
    double width;
};
struct vehicles_data {
    int num_vehicles;
    std::vector<vehicle_info> data;
};
```

The first struct `vehicle_info` is used to store the information about single detected vehicle. The position of the vehicle is expressed in relation to the robot's frame. The robot frame means, the center of the robot is the origin of the coordinate system. The x-axis points forward from robot and the y-axis points to the left.
The second struct `vehicles_data` is used to store the `vehicle_info` structs of all detected vehicles.

Collision data

The data structure for storing the collision parameters has the following definition:

Listing 4.2: Collision data structure

```
struct collision_info {
    int car_id;
    double v_front;
    double v_back;
    bool collide;
    bool collide_stop;
};
struct collisions_data {
    int num_collisions;
    std::vector<collision_info> data;
};
```

The first struct `collision_data` is used to store the collision parameters for single vehicle.
The `v_front` and `v_back` variables are the velocities of the robot to come into contact with the front or back of the vehicle. The figure 4.1 shows the contact points we are calculating the velocities for. The figure is explained in the next part.
The `collide` variable is a boolean value that tells us if the robot is going to collide with the vehicle. It is calculated based on the current velocities of the robot and the vehicle.
The second struct `collisions_data` is used to store the information about collisions with all detected vehicles.

Used units

We use these units for the measured and calculated parameters:

- **Position** – meters [m]
- **Time** – seconds [s]
- **Velocity** – meters per second [$\mathrm{m\,s^{-1}}$]
- **Acceleration** – meters per second squared [$\mathrm{m\,s^{-2}}$]
- **Dimensions** – meters [m]

Calculating the collision parameters

First, we need to state the assumptions we are making in order to simplify the calculation.
The first assumption is about the coordinate system we are using. We are using the robot's frame, where the robot's center is the system's origin, and all the positions are expressed in relation to this origin. The x-axis points forward, and the y-axis points to the left. We can assume this because the calculations are done periodically, and the results are only relevant for the current time step. It also simplifies the process, as the vehicle positions are already expressed in the robot frame.
The second assumption is about the movement of the robot. We assume the robot is moving in a straight line with constant velocity. This is reasonable as we want the robot to be as predictable as possible, so we do not want to move the robot to the side. The assumption about the constant velocity, meaning the acceleration is zero, is also reasonable. The speeds the robot can achieve are much lower than the robot's acceleration, we can therefore neglect the acceleration.
The third assumption is about the movement of the vehicle. We assume the vehicle's acceleration is constant. This is a reasonable simplification as the calculation is done periodically.
The fourth assumption is that we will calculate the collision only in two dimensions. This is reasonable as the z-axis will not impact the occurance of a collision. Moreover, the area over which the collision can occur is relatively small, and therefore, any terrain deviation will not impact the collision significantly.

Figure 4.1 depicts a schematic view of the collision. There are two contact points, both on the robot and the vehicle. The first one (blue) is the point where the robot is going to collide with the front of the vehicle. The second one (red) is the point where the robot is going to collide with the back of the vehicle.
For the first point, we calculate the velocity `v_front`. This velocity depicts the minimal speed of the robot to cross in front of the vehicle. We calculate the velocity `v_back` for the second point. This velocity depicts the maximal speed of the robot to cross behind the vehicle.
The subscript `r` is used for parameters of the robot, and the subscript `v` is used for parameters of the vehicle.
The calculation is divided into three parts. In the first part, we determine the starting positions of the robot and the vehicle. In the second part, we calculate the time when the vehicle will reach the intersection point $(x_\mathrm{i}, y_\mathrm{i})$. In the last part, we calculate the velocities for the robot to collide with the vehicle.

The first part is necessary as the coordinates of both the robot and the vehicle are at the center of their respective bodies. We need to move the starting points concerning the robot's and vehicle's length and width. The

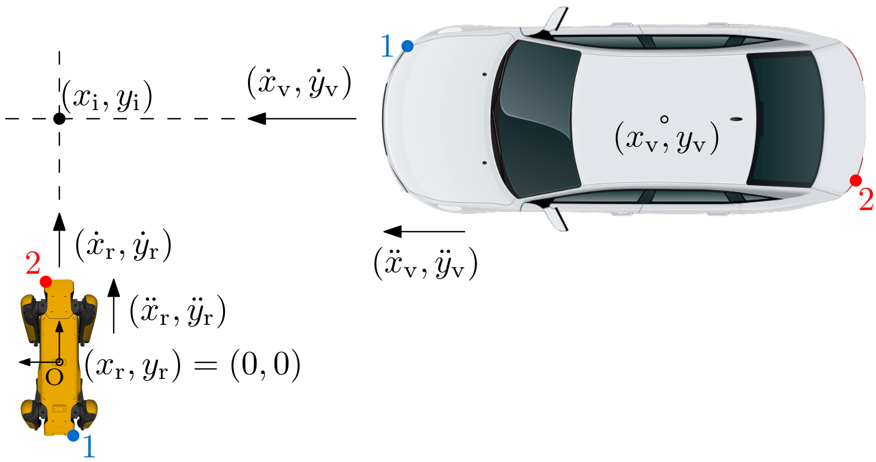


Figure 4.1: Visualization of collision points, coordinate system, and vehicle parameters.

starting points for the robot are calculated using these equations:

$$x_{\mathrm{r,f}} = \frac{l_{\mathrm{r}} + w_{\mathrm{v}}}{2}, \tag{4.1}$$

$$x_{\mathrm{r,b}} = -\frac{l_{\mathrm{r}} + w_{\mathrm{v}}}{2}, \tag{4.2}$$

$$y_{\mathrm{r,f}} = y_{\mathrm{r,b}} = 0, \tag{4.3}$$

where l_{r} is the length of the robot and w_{v} is the width of the vehicle.
The starting points for the vehicle are calculated as follows:

$$x_{\mathrm{v,f}} = x_{\mathrm{v}} + \frac{l_{\mathrm{v}} + w_{\mathrm{r}}}{2} \cos(\varphi_{\mathrm{v}}), \tag{4.4}$$

$$x_{\mathrm{v,b}} = x_{\mathrm{v}} - \frac{l_{\mathrm{v}} + w_{\mathrm{r}}}{2} \cos(\varphi_{\mathrm{v}}), \tag{4.5}$$

$$y_{\mathrm{v,f}} = y_{\mathrm{v}} + \frac{l_{\mathrm{v}} + w_{\mathrm{r}}}{2} \sin(\varphi_{\mathrm{v}}), \tag{4.6}$$

$$y_{\mathrm{v,b}} = y_{\mathrm{v}} - \frac{l_{\mathrm{v}} + w_{\mathrm{r}}}{2} \sin(\varphi_{\mathrm{v}}), \tag{4.7}$$

where $\varphi_{\mathrm{v}} = \arctan\left(\frac{\dot{y}_{\mathrm{v}}}{\dot{x}_{\mathrm{v}}}\right)$ is the angle of the vehicle, l_{v} is the length of the vehicle and w_{r} is the width of the robot.
We put the width of the robot to the calculation of the vehicle's starting points and vice versa because we want to flatten the dimensions of the objects. This is done to simplify the calculation of the intersection point of the robot's and vehicle's trajectory.
The second part of the calculation is further divided into two parts. The reason is, that there are two possible scenarios for the calculation. We will use the general equation of motion [16] for both calculations.
In the first scenario, the vehicle's acceleration in the y-axis is zero. That

means we can calculate the time using the following equations:

$$t_{\mathrm{f}} = -\frac{y_{\mathrm{v,f}}}{\dot{y}_{\mathrm{v}}}, \tag{4.8}$$

$$t_{\mathrm{b}} = -\frac{y_{\mathrm{v,b}}}{\dot{y}_{\mathrm{v}}}. \tag{4.9}$$

In the second scenario, the acceleration of the vehicle in the y-axis is non-zero. This scenario is more probable, as vehicles rarely drive at a constant speed. In this case, the time is calculated in the following way:

$$t_{\mathrm{f},1,2} = \frac{-\dot{y}_{\mathrm{v}} \pm \sqrt{\dot{y}_{\mathrm{v}}^2 - 2\ddot{y}_{\mathrm{v}} y_{\mathrm{v,f}}}}{\ddot{y}_{\mathrm{v}}}, \tag{4.10}$$

$$t_{\mathrm{b},1,2} = \frac{-\dot{y}_{\mathrm{v}} \pm \sqrt{\dot{y}_{\mathrm{v}}^2 - 2\ddot{y}_{\mathrm{v}} y_{\mathrm{v,b}}}}{\ddot{y}_{\mathrm{v}}} \tag{4.11}$$

There are two possible solutions for each time. The reason is that the vehicle may be decelerating and therefore change the direction of its travel. The interpretation of the results and the selection of the correct solution is discussed in the next section.

The last part of the calculation is the calculation of the velocities. First, we need to calculate the position of the vehicle in the x-axis at the time of the collision. We use the general equation of motion with $t_0 = 0\,\mathrm{s}$:

$$x_{\mathrm{i,f}} = x_{\mathrm{v,f}} + \dot{x}_{\mathrm{v}} t_{\mathrm{f}} + \frac{1}{2}\ddot{x}_{\mathrm{v}} t_{\mathrm{f}}^2, \tag{4.12}$$

$$x_{\mathrm{i,b}} = x_{\mathrm{v,b}} + \dot{x}_{\mathrm{v}} t_{\mathrm{b}} + \frac{1}{2}\ddot{x}_{\mathrm{v}} t_{\mathrm{b}}^2. \tag{4.13}$$

Now we can calculate the velocities of the robot.

$$\dot{x}_{\mathrm{r,f}} = \frac{x_{\mathrm{i,f}} - x_{\mathrm{r,b}}}{t_{\mathrm{f}}}, \tag{4.14}$$

$$\dot{x}_{\mathrm{r,b}} = \frac{x_{\mathrm{i,b}} - x_{\mathrm{r,f}}}{t_{\mathrm{b}}}. \tag{4.15}$$

The calculated velocities may be positive or negative. The interpretation is explained in the following section.

Interpretation of the calculated collision parameters

We will divide this section into two parts. The first part is the interpretation of the calculated time. The second part is the interpretation of the calculated velocities.

If the calculated time is positive, the intersection point of the robot's and vehicle's trajectory is in the future. This means that the robot can collide with the vehicle without either of them changing the direction of travel.

If the calculated time is negative, it means that the intersection point of the robot's and vehicle's trajectory is in the past. This means that the robot can collide with the vehicle, but only if the vehicle or the robot changes the

direction of travel.
The time can also be zero. This means that the robot and vehicle already collided. Therefore, we do not expect such time to arise as a result of the calculation.
We may have up to two solutions when calculating the times for non-zero acceleration. If we have none, the robot's and the vehicle's trajectories do not intersect.
If we have one solution, the robot's and the vehicle's trajectories intersect only once. The interpretation is that the vehicle is decelerating and will stop at the intersection point and then start reversing.
If we have two solutions, the robot's and the vehicle's trajectories intersect two times. Multiple intersections could have several physical interpretations. We can interpret this as the vehicle decelerating, and therefore, changing the direction of travel after passing the intersection point. We can also interpret this as the vehicle accelerating, and therefore, the second time of the intersection is likely negative.
When choosing the calculated time, we will use the following criteria. If one time is positive and the second is negative, we will use the positive time. If both times are positive, we will use the shorter time. If both times are negative, we will use the larger time (the time that is closer to the present).

The velocities can also be positive or negative. The interpretation is similar to the one of time. Positive velocity means moving forward, while negative velocity means moving backward.
While it may seem irrelevant to calculate the time and velocity for backward movement, it is essential. The reason is that some other vehicle may be moving so that the robot would collide with it. In that case, the robot will have to move backward to avoid the collision, and we need to be able to set the correct backward velocity to not collide with the first vehicle.

GetCars – action node

The action node `GetCars` is responsible for obtaining information about the detected vehicles. The detection node was not yet implemented when this thesis was written. Therefore, we will use the `GetCars` node to simulate the detection of vehicles.
We will subscripe to the topic `/road_crossing/injector`. To this topic we will publish from a separate node designed solely for the purpose of simulation the detection node.
The information about the detected vehicles will be stored in a static variable for later use. The variable is of the format shown in listing 4.1.

CarsInTrajectory – condition node

This node is important for optimizing the flow of ticks in our behavior tree. The node is responsible for checking if there are any detected vehicles. If there are no vehicles we do not need to go through the calculation and decision making. This speeds up the completion of this run of the BT and allows us to start the next run sooner.

NotStarted – condition node
This node is responsible for checking if the movement across the road has been started. If it has not, we need to start the movement. If it has, we may continue in it.

StartMovement – action node
This node is responsible for starting the movement across the road. We will set the maximal forward linear velocity to the topic our inner static variable. This variable is responsible for storing the current velocity. We chose the maximal linear velocity as $1.2\,\mathrm{m\,s^{-1}}$.

MoveFwdFull – action node
This node is used when no vehicles are detected and therefore we want to move the robot across the road as fast as possible. We publish the maximal forward linear velocity to the topic `/cmd_vel`.

CalculateCollision – action node
In this node we will calculate the collision parameters. We will use the formulas described earlier. The results will be stored in the inner static variables. This node will run the calculation for each vehicle independently. As each vehicle has its own ID, we will use this ID to differentiate between the vehicles. This ID will also be used to delete all the results from the inner static variable when the vehicle is no longer detected.

MoveFwd – action node
This node is used when there are detected vehicles and a forward movement is possible. We will publish the forward velocity to the topic `/cmd_vel`. The forward velocity is determined from the calculated velocities from the `CalculateCollision` node. We will set the maximal forward velocity we can, while still avoiding the collision.

MoveBwd – action node
This node is used when there are detected vehicles and a backward movement is necessary. We will publish the backward velocity to the topic `/cmd_vel`. The backward velocity is determined from the calculated velocities from the `CalculateCollision` node. We will set the minimal backward velocity we can, while still avoiding the collision.

StopMovement – action node
This node is used when there is no possible movement forward without the robot colliding with a vehicle and movement back is not neccessary. We will stop the robot by publishing zero velocity to the topic `/cmd_vel`.

CollisionFwdMove – condition node
This node is used to determine whether there are vehicles in front of the robot in such a position and velocity that the robot would collide with them if it moved forward.

CollisionBwdMove – condition node
This node is used to determine whether there are vehicles in such a position and velocity that the robot would collide with them if it moved backward.

CollisionOnStop – condition node
This node is used to determine whether there are vehicles in such a position and velocity that the robot would collide with them if it stopped.

CrossingFinished – condition node
In this node we check the current position of the robot with. If the distance of the current position from the middle of the road is greater then the half of the width of the road, we consider the crossing finished.
Other condition for finishing the crossing is if the robot's distance from the starting point is greater than the width of the road.
It is beneficiary to have both of these conditions as the position of the robot may be imprecise.

4.2 Auxiliary functions

In this section, we will present the auxiliary function used in the nodes of our BT algorithm.
These will include the functions used for conversions, more complex or repetitive mathematical operations, and other functions that are not directly related to the BT algorithm.
One of the big sections will be the algorithms used for determining the classification and cost of roads in the road network.
We will split the functions into categories based on their purpose.

4.2.1 Road cost algorithm

We will use the algorithm developed during the summer of 2022 for the RobInGas project at the CTU CRAS. The algorithm was designed to determine the cost of crossing the road based on the road classification, curvature, and other factors.
We will briefly present the functionality of the algorithm. The full description with implementation details can be found in [17].
This is also the only part of our thesis written in Python instead of C++ this is due to it being part of a different project. Other reasons include the usage of libraries for Python. While we could rewrite the code to C++ it was not deemed necessary as this part is run only once at the beginning of the mission and therefore does not need to be optimized for speed.

Overview

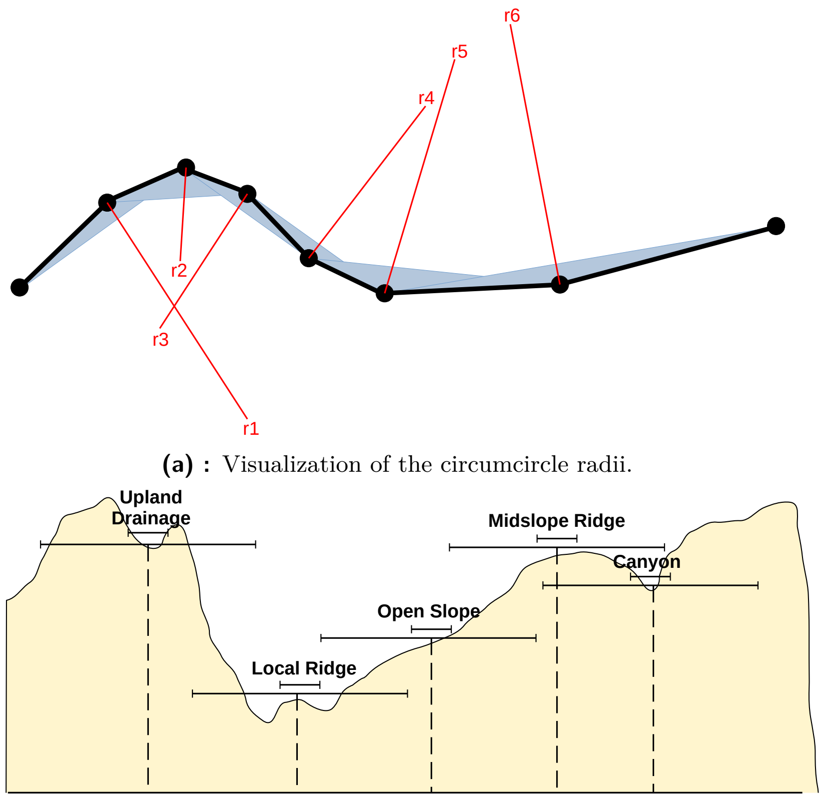
We use multiple parameters to determine the cost of crossing. The most important ones are the geometrical properties of the road. This includes the curvature of the road, the elevation profile, and the proximity to intersections. We also use the road classification to add to the cost function.
Other parameters would be beneficiary, such as the road width, the presence of a pedestrian crossing, and the expected traffic speed.
Unfortunately, we do not have access to all of these parameters. We use the OSM data, which does not necessarily contain all those additional parameters. Therefore, we will inject this information directly into the algorithm and deal with these parameters separately.
The OSM data also do not contain the elevation profile of the road. This data is also not easily obtainable from free or open-source sources. The elevation data we use were purchased from the Land Survey Office of the Czech Republic. We use the ZABAGED[18] data. This data from the Land Survey Office are available only for the area of the Czech Republic. However, any file with elevation data with the correct formatting can be used. The used file format is as follows. A text file with the easting, northing, and altitude of one point is on one line separated by a space. The lines are separated with a newline character `\n`, each describing exactly one point.
If the elevation data are not provided, the algorithm will still function. It will just not take the elevation profile into account. The road cost will be determined only from the curvate and road classification.

Algorithm

The algorithm is divided into several parts.
The first part is obtaining the road segments from downloaded OSM data. This part is also responsible for logging the road classification for each segment.
The second part is responsible for determining the curvature of the roads. This is done by calculating the radius of the circumcircle of the triangle formed by the two adjacent road segments. This approach is visualized in image 4.2a. We then sort the road segments into multiple classes based on their radius. In this part, we also detect road junctions and penalize the road segments close to the junction.
In the third part, we determine the elevation profile of the road. We then classify the individual road segments with the TPI (Terrain Profile Index) method. Some TPI classes are presented in image 4.2b.
In the last part, we combine the results from the previous parts and calculate the final cost of crossing for each segment. These costs are than saved to a file, to be used later.

Usage

As was stated earlier, this algorithm is executed only once at the beginning of the mission. Later we only keep the final costs, and based on them, we determine if the location where the robot is trying to cross is suitable and



(a) : Visualization of the circumcircle radii.

(b) : Representation of certain TPI classes.

Figure 4.2: Visualization of key elements in the road cost algorithm.

safe.
We rely on ROS to enable the communication between our main algorithm and the algorithm for determining the suitability of the location for crossing. We use the ROS service for this purpose.
Another part of the algorithm is to try and provide the robot with a more suitable place for crossing if the current location is unsuitable. If such a place is found and provided we will publish a cost map that will be used to change the current cost map of the path planner. This is done so that we do not need to override the robot's controls until we begin the crossing itself.

4.2.2 Mathematical functions

Difference between two angles

This function is used to determine the difference between two given angles. We assume the angles given are in radians, and both are in the interval $\langle 0; 2\pi \rangle$. This difference is calculated to be the smallest possible and to fit within the interval $\langle -\pi; \pi \rangle$. The formula we use is a modified version of the one provided here [19]. The formula is as follows

$$\Delta\varphi = ((\varphi_2 - \varphi_1 + \pi) \mod (2\pi)) - \pi. \tag{4.16}$$

Before returning the result, we check whether the result is within the specified interval.

Converting degrees to radians

While this function is elementary in its nature, it is often used in our code. Therefore it is beneficiary to create this function.
The equation for converting degrees to radians which this function uses, is as follows

$$\varphi_{\mathrm{RAD}} = \varphi_{\mathrm{DEG}} \frac{\pi}{180}. \tag{4.17}$$

4.2.3 Geographical functions

Here we will present the functions used for geographical calculations. These include conversions between coordinate systems, calculating azimuths, and others.

Converting GPS to UTM

While most geographical data are stored in the WGS84 coordinate system, the UTM coordinate system is more suitable for calculations. We, therefore, need to convert the GPS coordinates to UTM.
When working with geographical conversions in C++, we use the library GeographicLib. The function from this library that does the conversion is `GeographicLib::UTMUPS::Forward`. This function takes the point's latitude and longitude and returns the point's easting and northing in the UTM coordinate system. It also returns the zone number and whether the point is in the northern or southern hemisphere.
While the input variables are passed by value, the return variables are passed to the function call by reference.
When converting the geographical data we in Python we use the `utm` library. The function facilitating the conversion from WGS84 to UTM is `utm.from_latlon`.

Converting NED to ENU

There are two possible orientations of an azimuth. The NED (North-East-Down) and the ENU (East-North-Up).
NED means that azimuth 0 points north, and its value increases clockwise. This orientation is mainly used in cartography and everyday life.
ENU means that azimuth 0 points east, and its value increases clockwise. This orientation is mainly used in navigation and robotics, as it is consistent with REP-103[20].
In the entire project, we use the ENU orientation. However, as we rely on other ROS nodes to provide us with the azimuth, we need to be able to convert the azimuth from NED to ENU.
The conversion should be much simpler since we do not deal with coordinates but with already computed azimuths.
The image 4.3 shows the two possible orientations of the azimuth. This image

also provides us with the insight we need to determine the conversion formula. We need to divide the formula into two parts.
The first option is when the azimuth (in NED) is between 0 and $\frac{\pi}{2}$ rad. In

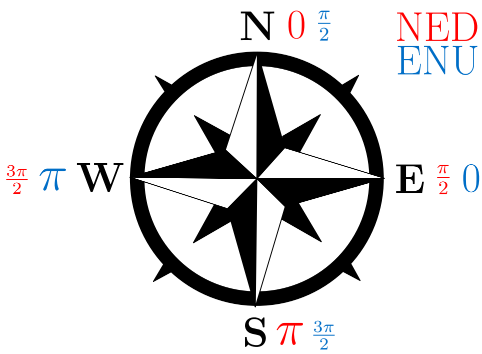


Figure 4.3: Two possible orientations of the azimuth.

this case, the azimuth in ENU is computed in the following way

$$a_{\mathrm{ENU}} = \frac{\pi}{2} - a_{\mathrm{NED}}, \tag{4.18}$$

where $\mathrm{a}_{\mathrm{ENU}}$ is the azimuth in ENU and $\mathrm{a}_{\mathrm{NED}}$ is the azimuth in NED.
The second option is for all other azimuths, e.g., when the azimuth is between $\frac{\pi}{2}$ and 2π rad. In this case, the azimuth in ENU is computed in the following way

$$a_{\mathrm{ENU}} = \frac{5\pi}{2} - a_{\mathrm{NED}}. \tag{4.19}$$

Compute azimuth from coordinates

This function is used to compute the azimuth for an observer standing at the first point and looking at the second point.
We will use a slightly modified version of the formula provided here [21]. This calculation was created for the WGS84 coordinate system, however, we use the UTM coordinate system. Having said that, we can use the same formula, as the WGS84 to UTM projection is conformal[22]. In testing the difference between calculated azimuths using the WGS84 and UTM coordinates was around $\Delta\varphi = 0.097\,\mathrm{rad}$ or $\Delta\varphi = 5.541°$.
The computation equations are as follows

$$\Delta y = y_2 - y_1, \tag{4.20}$$
$$\alpha = \sin(\Delta y)\,\cos(x_2), \tag{4.21}$$
$$\beta = \cos(x_1)\,\sin(x_2) - \sin(x_1)\,\cos(x_2)\,\cos(\Delta y), \tag{4.22}$$
$$\varphi = \arctan\left(\frac{\alpha}{\beta}\right), \tag{4.23}$$
$$\varphi = (\varphi + 2\pi) \mod (2\pi). \tag{4.24}$$

Where x_1 and y_1 are the latitude and longitude of the first point, and x_2 and y_2 are the latitude and longitude of the second point.

Compute heading for robot

The use of this function is to determine the heading of the robot. It is used to get the robot perpendicular to the road.
The function takes the robot's heading and the road's azimuth. The road azimuth was obtained using the function stated above.
The algorithm creates two new variables, one $+\frac{\pi}{2}$ and one $-\frac{\pi}{2}$ from the road's azimuth. This is necessary as we do not know in what order are road points stored and we do not need to differentiate the side we approach the road from.
Then it computes the difference between the robot's heading and the two new azimuths. The smallest difference is then returned.

4.2.4 Contextual information and score

Contextual information

The contextual information provide us with valuable information about the environment. This information is a vital part in choosing the best location for crossing.
The contextual information we use are the following

- **Maximal speed** – The maximal speed of vehicles on the road.
- **Number of lanes** – The number of lanes on the road.
- **Road width** – The width of the road.
- **Road type** – The type of the road.
- **Pedestrian crossing** – Whether there is a pedestrian crossing on the road and its location.

Obtaining contextual information

The contextual information may be obtained from several sources. One source could be the OSM database. However, this database is not always up to date, and there is no guarantee, that the neccessary information will be available. Other sources could be the direct observations of the robot or the information provided by other ROS nodes.
The contextual information in our case will be obtained in yet another fashion. The informaion will be submitted by the user. We have prepared a python class with the appropriate variables and functions. In order to use the contextual information, the user should create an instance of this class and fill in the appropriate variables.
The creation of the class is recommended to be done in advance. It could be automated or done manualy. The class also contains functions neccessary for storing and loading the contextual information.
During the execution of our algorithm the tree node will call a ROS service to obtain the contextual information. This service will return the contextual information for a closest road to requested location.
Thanks to this approach, we are able to log the contextual information for

multiple roads and use them later for the evaluation of the crossing locations.

Calculating the context score

The context score is calculated as a sum of individual point for each of the individual contextual information.

$$\xi_{\text{context}} = \sum_{i=1}^{n} \xi_{\text{context,i}}, \tag{4.25}$$

where $n = 5$ as we currently have only five different context information. The individual points are calculated as follows

- **Maximal speed** – $v_{\max}$
  - $v_{\max} \leq 30 \quad \rightarrow \quad \xi_{\text{context},1} = 3$
  - $v_{\max} \leq 50 \quad \rightarrow \quad \xi_{\text{context},1} = 2$
  - $v_{\max} \leq 80 \quad \rightarrow \quad \xi_{\text{context},1} = 1$
- **Number of lanes** – n_{lanes}
  - $n_{\text{lanes}} = 1 \quad \rightarrow \quad \xi_{\text{context},2} = 5$
  - $n_{\text{lanes}} = 2 \quad \rightarrow \quad \xi_{\text{context},2} = 4$
  - $n_{\text{lanes}} = 3 \quad \rightarrow \quad \xi_{\text{context},2} = 2$
  - $n_{\text{lanes}} = 4 \quad \rightarrow \quad \xi_{\text{context},2} = 1$
- **Road width** – w_{road}
  - $w_{\text{road}} \leq 3.5 \quad \rightarrow \quad \xi_{\text{context},3} = 4$
  - $w_{\text{road}} \leq 4.5 \quad \rightarrow \quad \xi_{\text{context},3} = 3$
  - $w_{\text{road}} \leq 5.5 \quad \rightarrow \quad \xi_{\text{context},3} = 2$
  - $w_{\text{road}} \leq 6.5 \quad \rightarrow \quad \xi_{\text{context},3} = 1$
- **Road type**
  - motorway $\rightarrow \quad \xi_{\text{context},4} = -10$
  - trunk $\rightarrow \quad \xi_{\text{context},4} = -4$
  - primary $\rightarrow \quad \xi_{\text{context},4} = 1$
  - secondary $\rightarrow \quad \xi_{\text{context},4} = 2$
  - tertiary $\rightarrow \quad \xi_{\text{context},4} = 3$
- **Pedestrian crossing**
  - if present $\rightarrow \quad \xi_{\text{context},5} = 10$

4.3 ROS specific functions

Here we will present the ROS specific parts of our algorithm. These include the ROS nodes, services, and messages.

4.3.1 ROS services

4.3.2 ROS nodes and messages

Chapter 5

Simulation experiments

The main goal of the simulation experiments was to verify the functionality of the algorithm design. The second goal was to improve the algorithm and its nodes. The third goal was to create several scenarios for the algorithm to test its behavior in different situations. These scenarios were created with later real-world experiments in mind.

5.1 Algorithm functionality experiments

The first experiments were created to test the execution capabilities of the algorithm. They aimed to test if the nodes would not crash or stall the system. These experiments helped to find and fix multiple bugs in the nodes.
Moreover, we were able to detect some weak spots in the BT structure and improve it. The `Groot` application's log viewer was an invaluable tool for detecting these weak spots. The screen of the log viewer is shown in 5.1.

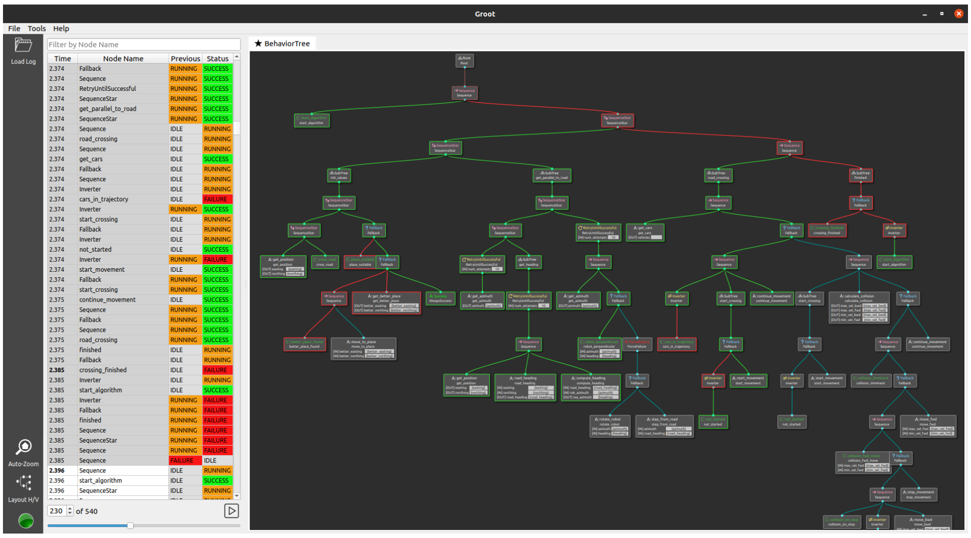


Figure 5.1: Log viewer in `Groot` application.

5.2 Algorithm behavior experiments

Once the basic functionality was verified, we created several scenarios to test the behavior and universality of the algorithm. This was done to verify that the algorithm would work in different situations.

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