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REAL-TIME GNSS POSITIONING BASED VIRTUAL WORKING GAUGE FOR SERIAL ROBOTIC MANIPULATOR

Master of Science Thesis
Faculty of Engineering and Natural Sciences
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ABSTRACT

Olli Mäkinen: Real-time GNSS positioning based virtual working gauge for serial robotic manipulator
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In this thesis a control system that could limit robot manipulators reach when its global position was know was developed. The reach was limited to a virtual working gauge using global navigation satellite system data on the manipulators position and a building information model of the environment. The control system was designed such that these limits would not be violated. Functionality of the control system was simulated in MATLAB Simulink environment.

Building information model and satellite positioning can be used to infer different infrastructure elements exact location in relation to the manipulator. If the manipulator was to move, the global navigation satellite system can sense that and update its relative position in regards to the building information model. Utilising building information model is also especially useful in defining virtual limits for features for which their exact location is hard to define using traditional perception methods. To maintain manipulator movements inside these defined limits, the control system will calculate the shortest distance from the manipulator to the limits. Defining exact distances between complex shapes is resource intensive and therefore the manipulator representation was simplified to each of its links bounding boxes. This way the distance calculations could be ensured to work in a real time system. Two control methods were implemented for modifying the manipulator joint speeds based on the distance information. Manipulator movements could be slowed down linearly when approaching a limit or alternatively using an artificial potential field function to generate a path towards the target while repelling the manipulator away from the limits.

As an case study the thesis researched defining virtual working gauge limits for an road rail excavator that operates close to an train track open for traffic. In this situation the road rail excavators reach should be limited such that no part of it crosses the working gauge limits of the nearby train track. Building information model is suitable in this context as defining the exact location of the train track using perception methods is difficult.

Creating and maintaining virtual working gauge limits using the control system developed was deemed possible. For infrastructure elements that are normally expressed as just lines of connected points in current building information models need to be adjusted by creating bounding volumes around them to be usable in a virtual working gauge application. The ways in which the control system modifies the manipulator movements work as desired in the simulation environment. However the manipulator representation as bounding boxes can lead to singularities, where there are multiple options for the location of the shortest distance. Ways of calculating multiple shortest distances along the manipulator bounding boxes need to be utilised to eliminate slight vibrations in the controller desired velocity signal that are caused by singularities when calculating only single shortest distance per bounding box.

Keywords: robot control, BIM, collision avoidance, excavator

TIIVISTELMÄ

Olli Mäkinen: Reaaliajassa toimiva GNSS signaaliin perustuva virtuaalinen liikkeiden rajoitus
Diplomityö
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Tässä työssä kehitettiin ohjausjärjestelmä, jolla voidaan rajoittaa manipulaattorin ulottumaa, kun tiedossa on manipulaattorin sijainti. Ulottuma rajoitettiin virtuaalisesti määritettyihin rajoihin hyödyntäen satellittipaikannusta manipulaattorin sijainnista ja ympäristöstä saatavilla olevaa BIM-mallia. Määritettyjä rajoja käyttäen ohjausjärjestelmä muokkaa manipulaattorin liikkeitä varmistaen, että rajoja ei ylitetä. Ohjausjärjestelmän toiminnallisuutta tutkittiin simuloimalla järjestelmää MATLAB Simulink ympäristössä.

BIM-mallin ja satelliittipaikannuksen pohjalta voidaan tiedostaa infrastruktuurin määritettyjen piirteiden tarkka sijainti suhteessa manipulaattoriin. BIM-malli on hyödyllinen määrittämään virtuaalisia rajoja piirteille, joiden määrittäminen visuaalisilla metodeilla voi olla hankalaa. Määritettyjen virtuaalisten rajojen ylläpitämiseksi ohjausjärjestelmä laskee rajojen ja manipulaattorin välisen lyhimmän etäisyyden. Etäisyyksien määrittäminen kompleksisten muotojen välillä vaatii paljon resursseja tietokoneelta, joten manipulaattorin akselien esitys päätettiin yksinkertaistaa niitä ympäröiviksi suorakulmaisiksi särmiöiksi. Näin etäisyyksien määrittäminen voitiin varmistaa reaaliaikasessa ohjausjärjestelmässä. Etäisyystietoutta hyödyntäen toteutettiin kaksi eri tapaa muokata manipulaattorin nivelten kulmanopeuksia, joilla estetään manipulaattorin törmäykset esteisiin. Manipulaattorin liikkeitä voitiin hidastaa lineaarisesti etäisyyden lähestyessä rajaa tai vaihtoehtoisesti käyttäen potentiaalifunktiota, jolla manipulaattori generoi haluttua liikerataa kohti määränpäätä samalla väistäen rajoja.

Esimerkkitapauksena työssä tutkittiin rajojen määrittämistä kiskopyöräkaivurille, joka työskentelee liikenteelle avoinna olevien rautateiden läheisyydessä. Tässä tilanteessa kiskopyöräkaivurin ulottumaa tulisi rajata siten, että mikään osa siitä ei ylety viereisten rautateiden suojaulottumien sisälle. Rautateiden sijainti ja täten myös näiden suojaulottuma on hankala määrittää käyttäen yleisiä mittausmenetelmiä.

Virtuaalisten rajojen määrittäminen ja ylläpitäminen todettiin mahdolliseksi kehitetyllä ohjausjärjestelmällä. Nykyisissä BIM-malleissa osa infrastruktuurin piirteistä esitetään pisteitä yhdistävinä viivoina. Nämä tulee esittää geometrisinä malleina, jotta niitä voidaan hyödyntää virtuaalisina esteinä liikkeiden rajoittamiseksi. Ohjausjärjestelmän tavat muokata manipulaattorin liikkeitä toimivat halutulla tavalla simulointiympäristössä. Manipulaattorin esittäminen pelkkinä suorakulmaisina särmiöinä voi johtaa singulariteettin, jossa lyhimmän etäisyyden sijainnille on olemassa monta eri vaihtoehtoa. Tämä johtaa värinään säätäjän nopeussignaalissa käytettäessä potentiaalifunktiota halutun radan määrittämiseksi.

Avainsanat: robotin ohjaus, BIM, törmäyksen esto, kaivinkone

PREFACE

This Master of Science thesis was undertaken as a part of research in Faculty of Engineering and Natural Sciences at Tampere University in the spring and summer of 2021.

I would like to thank my supervisors at Tampere University, Prof. Jouni Mattila and DI Lionel Hulttinen for being supportive and sharing their wide knowledge on the subject with me as well as guiding and helping me improve throughout this project.

Finally, I want to thank my family as well for all their support and encouragement from beginning to end of my study journey. Without you I would not be here now.

Tampere, 26th July 2021

Olli Mäkinen

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LIST OF SYMBOLS AND ABBREVIATIONS

AABB	Axis aligned bounding box
APF	Artificial potential field
BIM	Building information model
C++	General purpose programming language
CAD	Computer assisted design
DOF	Degrees of Freedom
ETRS89-GK26FIN	Projected coordinate system for Finland
FCL	Flexible Collision Library
GJK	Gilbert–Johnson–Keerthi algorithm for computing distances between convex objects
GNSS	Global Navigation Satellite System
IMU	Internal measurement unit
MATLAB	programming and numeric computing platform created by MathWorks
ROS	Robot operating system
RRE	Road-rail excavator
TCP	Tool Center Point
VWG	Virtual working gauge

1. INTRODUCTION

Heavy-duty hydraulic manipulators, such as excavators are a commonly used tool in railway construction and maintenance applications where the work process requires moving heavy equipment or heavy loads. Excavators are versatile and can perform multiple different tasks based on what working attachment tool is attached to the excavator manipulator arm. Depending on the manufacturer and model of the excavator, different tools can be used depending on the application. Tools can often be easily decoupled and a new one fitted directly at the work site.

Traditionally excavator movements are controlled by a operator inside the excavator cabin using joystick inputs to directly control the motion of all the links of the manipulator. Without safety devices, direct manual control of an excavator could lead to accidents where the excavator collides with other machines or infrastructure elements.

In recent years, more intelligent systems and sensor technologies have been developed that when integrated into excavators can assist the operator in everyday operations. For example accurate measurements of tool position and orientation when combined with a computer system can improve the repeatability and accuracy of operations and allow direct movements in Cartesian coordinates. With such systems excavators can more easily be programmed to work as an serial robotic manipulator, defining paths for the manipulator to follow.

1.1 Working limits

Earth moving machinery such as excavators by nature can exert large forces into their environment. Careless control of the manipulator can potentially cause accidents or serious damage to infrastructure elements if handled in an undesired manner.

Standard excavator has no means of distinguishing where nearby obstacles that it can collide with are. They do not contain the required information of their surrounding environment or the control possibilities to determine what should and should not be avoided. Generally decision making on avoiding collisions from happening is left to the hands of the machine operator. For improving the safety of excavator operations, defining clear working limits and control methods that would abide these limits would be desired. Normal excavator work space includes infrastructure and other environmental features that it should not come in contact with. These define the working limits for the excavator at its given location. Clearly visual infrastructure elements can include objects such as walls of buildings, electrified power lines and streetlamps. Some infrastructure elements such as piping and wires dug underground can be harder to be visually detected and avoided by an operator without before knowledge of their existence trough external tools or markings. The natural environment can introduce other limits to the working area such as trees or large rocks.

In addition to avoiding collisions with physical objects, sometimes it is beneficial to set working limits on areas where the excavator should not operate in even though it could. For example working near roads or railways working limits could be set such that any possible accidents when colliding with passing traffic could be avoided. Especially in railway applications potential collisions with an excavator and an moving train could lead to potentially fatal accidents.

Work at railway work sites is heavily regulated and multiple standards that define how to perform work safely at railway working sites exists. The demand for better safety features exists in that field. The work done in this thesis focuses on railway applications but could be easily adapted to work in other infrastructure building contexts as well.

1.2 Railway specific working limits

Work performed near railways always requires a permit and accompanying safety measures to be implemented depending on the environment where the work happens. Two main safety concerns define the working limits for excavators working near railways. These are adjacent railway tracks open to traffic and overhead power lines. Both of these infrastructure elements have safe distances defined that state how close any machine is allowed to work near them. Catenary poles that support the power lines don’t have designated safe working limits assigned to them but naturally, colliding with them should also be avoided.

In railway applications a working gauge is defined as the limit in which a machine can work without interfering with the kinematic envelope of vehicles on adjacent operating tracks [1]. Excavator can be situated either by the side of a railway or be equipped with a road-rail interface with which it can travel on a railway track. For a Road-rail excavator (RRE) the working gauge does not consider the railway the excavator is travelling and working on but only any other adjacent tracks that are within the RRE reach. If the adjacent track is close enough that any part of the excavator could reach inside the adjacent track, safety measures have to be implemented.

When an RRE works on a electrified railway its height must be limited to avoid colliding with any overhead power lines. Different countries use different standardized voltages in their rail network. A safe distance must be maintained between the RRE and the electrified power lines. The required safe distance varies and increases as the voltage running in the power lines increases. Each country has set their own safe distances that correspond with the voltages present in their country.

Figure 1.1 showcases a general representation on the distances for safe working limits respect to mentioned infrastructure elements. The image in figure is modified from a publication by aforementioned Finnish transport infrastructure agency on railway maintenance in Finland [2].

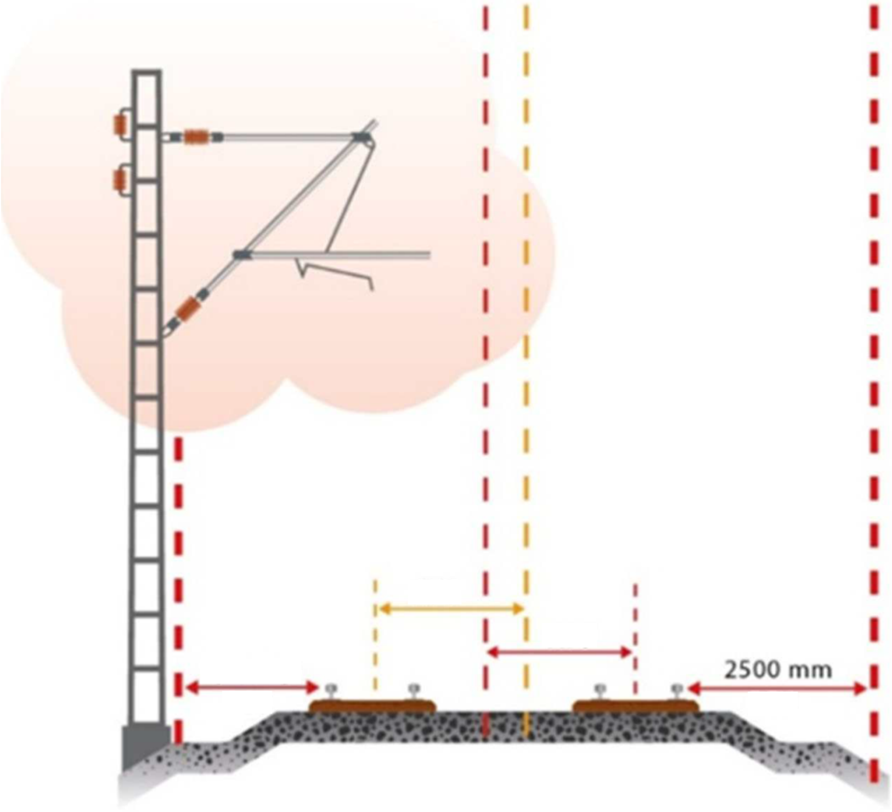


Figure 1.1. *Example Railway safety distances with regards to adjacent tracks, power lines and a catenary pole.*

Different possibilities exist for an excavator to work safely in close proximity with railways and adhere to the working limits defined in Figure 1.1. Overhead power lines always require a height limiting device or that the excavator is physically far enough from reaching the designated safe distance. With regards to adjacent tracks, easiest way to ensure safe operation is to prevent any trains or other traffic from running on the adjacent track. With no possibility of collisions with traffic running on the adjacent track work can be conducted without lateral limiting devices. When the adjacent track needs to be temporarily closed for the duration of work, negative effects it causes on business should be minimised. Often this means that the work must be conducted when railway traffic is at its lowest such as at night. Working at night has its downsides such as reduced visibility and limited working hours that can affect how efficiently and safely the work can be performed. Unless the work requires that the excavator work inside the kinematic envelope of an adjacent track, it is generally preferable to keep the railway operational and look for alternative solutions.

The simplest alternative method that is still utilized is to have both audible and visual warning signals present at the worksite to warn of incoming trains. Warning signals are coupled with requiring a lowered speed limit on the adjacent track. This effectively transforms the situation the same as preventing trains from running on the adjacent railway track while work is being performed. Traditionally the task is performed by a designated person or multiple people controlling the warnings. This has inherit risks due to relying on human action. Electronic systems using sensors to detect incoming trains have been created that automatically sound the alarm. In Finland, safety personnel can be used to trigger the alarm if normally the speed limit on the adjacent tracks is below 140 km/h while higher speed limits up to 200 km/h require the use of an automatic warning system [2]. Warning signals are still only effective if the excavator operator reacts to the signals. Accidents can still happen for example if machinery operator has left the excavator unsupervised inside adjacent tracks kinematic envelope or if the excavator suffers a power failure while it is outside of its allowed working gauge. In Figure 1.2 a scenario where the reach of the RRE can extend over adjacent tracks is presented. Here, a use of lateral limiting device or preventing traffic running on the adjacent railway track is required for safe work to be conducted.

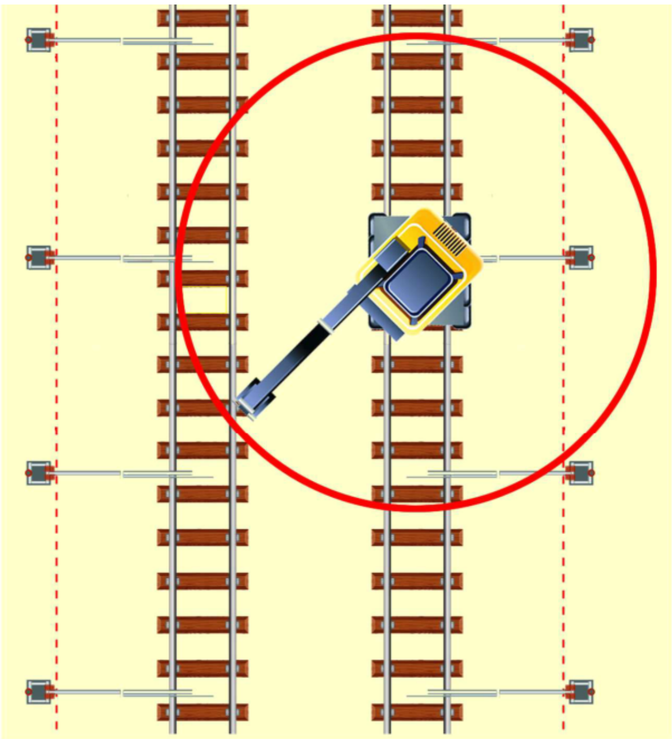


Figure 1.2. *RRE reaching inside working gauge of an adjacent track [2].*

To conclusively prevent any intrusions outside the excavator allowed working gauge and other collisions, limiting devices must be implemented for the excavator. European standard defines that in railway applications a machine must have a limiting devices capable of stopping the machines movements when lateral or height limits are reached [3]. Basic lateral and height limiting devices generally work independently and such require a separate device for each one. Use of such limiting devices are currently reserved mainly for special built machinery as such devices are not standard issue for general excavators. Limiting devices can set hard limits for the excavator movements so that they conform the movements to the working gauge. Adjusting these limits is possible and done manually either in incremental steps or as a sliding scale to the maximum allowed working gauge [3].

Limiting device working principle can be achieved by mechanical, electronic or hydraulic means [3]. Mechanical limiting devices are generally simple and limit the excavator movements to set allowed limits. Hydraulic and electronic devices allow more control over the working gauge limits by being able to be controlled with software.

The main problem with existing limiting devices is that the limits have to be set to specific values and can not be changed dynamically. The shortcoming is exemplified in that work done with an excavator can often require the excavator to move from one place to another. Moving the excavator changes the relative distance and direction to obstacles and can therefore change the allowed working gauge limits. If moving does not change the relative distances to working gauge limits drastically, limits can be set tighter than the allowed working gauge to work along the whole path. This leads to needless restrictions on the excavator movements. When relative distances to working gauge limits would change significantly when moving, such as when working near a curved railway track, limits should be able to changed dynamically which is not possible with current limiting devices. RRE movements are more predictable being confined to travel along a railway track. There it is theoretically possible to set individual limits to number of points along the railway track. This would again lead to needless restrictions on the RRE movements as well as time waste if the limits need to be defined manually beforehand and set again every time movements are made.

1.3 Goals of the thesis

The main goal of the thesis is to design and demonstrate a control system that can limit and modify robotic manipulators movements in real time based on the current geolocation of the robotic manipulator. A RRE capable of being controlled as an robotic manipulator is simulated and used to test the effectiveness of the control system. The limited work space is constructed using virtual walls to define the allowed three-dimensional working gauge, thus naming it Virtual working gauge (VWG). VWG limits the movement of the RRE as a function of its location and manipulator arm configuration with respect to the geometry of avoidable infrastructure elements and other features. Functionality of the VWG can define limits in 3D space regardless of the limits position and orientation relative to the manipulator. Using the same control system functionalities of both lateral and height limiting devices can be emulated often with higher accuracy. Use of VWG aims to introduce new level of autonomy in railway operations of excavators and increase the overall safety and quality of the work being performed.

In addition to prevent exceeding the VWG limits, as a secondary goal, the VWG is used in path planning to modify the trajectory of the manipulator to reach desired positions efficiently while staying withing the confounds of the designated limits. Path planning enables more autonomous operations to be performed in railway applications.

The limits for the VWG are constructed from infrastructure Building information model (BIM) and the manipulators known geolocation using Global Navigation Satellite System (GNSS). Accuracy of these limits can be further updated to better match the real world environment by using a perception system to detect the environment in real time. By using GNSS the VWG limits can be changed automatically regardless if the manipulator moves during operations.

The control system is made as modular as possible so that it can be easily adapted to be installed and used with any standard hydraulic excavator. Required sensors and computer systems can be retrofitted to existing excavator models. This reduces the initial monetary costs of the desired machine and enables further development of other control systems. The same control system can be applied to any excavator with similar manipulator structure with only minor tweaks regarding the dimensions and structure of the excavator.

Sensor technology and ways to utilise BIMs in machine control with heavy machinery already exists. For example Novatron Oy has developed machine control systems that can determine excavator location based on GNSS and use BIM of the working area as reference when working [4]. VWG can be constructed on top of such systems using the already existing sensors and the control systems implementations of determining features from BIM.

1.4 Structure of the thesis

This thesis consists of 5 chapters. Following the introduction in chapter 2, necessary data acquisition methods for determining the VWG limits and calculations for determining the closest obstacle points between the manipulator and the environment are discussed. Distance calculations can be computationally heavy operation and therefore methods on how to simplify them are presented. In chapter 3 the distance calculations achieved are used to implement the different control functions that limit the manipulator movements to the VWG. These include linearly slowing the manipulator joint velocities down when approaching VWG limits as well as control method that can achieve efficient path planning operations within the. At the end of the chapter a general architecture for how different parts of control system come together to form the functionality of VWG is explained. The control system was simulated in MATLAB to test and verify the results. In chapter 4 the simulation environment is introduced and different test cases are outlined with their results explained. Lastly in chapter 5, conclusions regarding the results and future work and implementations are discussed.

2. VIRTUAL WORKING GAUGE LIMITS

VWG is a control system designed to limit and modify a robotic manipulators movements in such a way as to achieve collision free operation of required task at a railway work environment. By utilizing VWG the manipulator can be confined to move inside any arbitrary 3D space desired. Usually this area is chosen such that the manipulator will not collide with obstacles around it or extend any parts of it into a pre-designated, potentially dangerous areas such as over operational railways. After the 3D environment limits are defined, a control system will control the manipulator such that any intrusion outside the allowed limits is not possible.

aim of the VWG is to be used as a control method and a safety feature to prevent collisions by an excavator. Collision avoidance system requires that information about the distances and directions of VWG limits must be calculated. It is theoretically possible to perform collision avoidance for a manipulator by just knowing whether the manipulator is in collision or not. Such operation requires that a suitable collision free path is calculated before moving. This is not practical for most excavator use cases. The excavator should also be able to be operated manually and have the collision avoidance still work.

Preventing collisions in a real time system requires calculating the distance from the manipulator to the environment. Section 2.1 discusses methods on how the environment can be can be represented in a digital format. By the name, obstacles that constitutes to the VWG can include non-physical areas such as the spaces around railways or roads where vehicles on them can be expected to travel. This area can be hard to sense and determine using only perception methods. Section 2.2 discusses how to perform distance calculations between the environment representation and the manipulator. Simplification is required to perform the collision query in real time.

2.1 Environment representation

To construct a control system that limits a manipulators movements, the surrounding environment and its limits must first be modelled and represented in an digital format. This means gathering accurate 3D location data of the environment where the manipulator will work in. Additionally to be useful, the relative location of the manipulator to the environment must also be accurately known.

Global Navigation Satellite System (GNSS) provides accurate location data that can be used to determine the exact location of the manipulator. GNSS uses multiple satellites from many different satellite systems such as GPS, GALILEO and GLONASS to provide a global coverage on location services. The location accuracy can be improved by using local reference stations to reduce the location errors. With a good signal, GNSS can measure the location to an centimetre-level-accuracy. [5]

For creation of the VWG, BIM is used to designate the static limits. Similarily a perception system can be used to complement and cover weaknesses with a pure BIM implementation. BIM of the environment enables a good starting point for establishing the 3D limits using existing data of the environment. BIM contains information on the static obstacles in the environment including ones that can't be sensed or easily computed using perception methods. The model can be loaded and processed once before operations, lessening the required calculations during real time operation. Perception system on the other hand can enhance the capabilities and used to give real time information on obstacles that are not modelled into the BIM. With image recognition it can determine if those features it sees should be avoided. Together they provide a 3D representation of the environment and can be used to construct complete VWG limits.

As a safety feature for an railway application the environment should at least represent any adjacent tracks and other infrastructure elements such as any overhead power lines in the environment. Their location can often be inferred from the modelled BIM of the environment. Perception system increases the safety by being able to account for dynamic obstacles. Therefore inclusion of a perception system is almost necessary if the excavator is to be run in an automatic fashion.

2.1.1 Building information modelling

Building information modelling is common practise in modern building and infrastructure projects trough its life cycle from design trough construction and management. Design information generated using an object or model based process is inherently superior to comparable information generated using drawing process [6]. All relevant infromation is stored into BIMs.

BIMs form a digital representation of the 3D space they model. It is constructed of multiple different elements based on the use case. For infrastructure building the model usually infers the terrain of the area as well as built infrastructure such as roads railways and buildings. BIM can contain information of the environment in its current form as well as model designed features that are to be constructed there. A well designed infrastructure BIM of an area can be utilized by future projects operating in the same area.

Especially in Europe, use of building information modelling in construction projects has increased and the use is often promoted. The more widely BIM is utilized, the easier it is to adapt for machine automation purposes. Many countries are starting to embrace building information modelling in their workflow, especially on larger projects. For example Finland plans to have all its public funded projects utilizing BIM by 2025 [7].

For the purposes of VWG in this thesis, infraBIM model from openBIM was used. OpenBIM benefits are that it extends BIM by being vendor free data format and combines many different types of data to a unified platform for reading them. It can define the digital data of infrastructure at different times throughout their life-cycle. A model in infraBIM focuses on BIM information relevant to infrastructure design, construction and management. [8]

2.1.2 Defining virtual working gauge limits

Existing BIM implementations model the environment in two distinct ways depending on the infrastructure feature being modelled. These are direct 3D models in the environment and simplified point and line data on showing position of features in the environment. For VWG purposes all features modelled must be a representation of surfaces in 3D space. 3D models come in the form of a triangle mesh information about the environment such as the topography of the earth or the shapes of buildings. They define surfaces as is and can therefore be directly used to designate VWG limits. On the other hand features that are expressed as just points or lines of connected points can not be used as VWG limits directly. Many prominent infrastructure elements such as roads and railway tracks are expressed this way as just a center line with additional information relevant to it. Additional information can include things such as the curvature between two points along the center line, cant at the current location and width of the feature. Point and line representations of features must be further defined as relevant surfaces to model three dimensional spaces.

For example, OpenBIM models railways with points noting the centerline of the railway. Figure 2.1 demonstrates railway center line position in a projected coordinate system for Finland. The points are gathered from public demonstrative BIM files from BuildingSMART Finland [9].

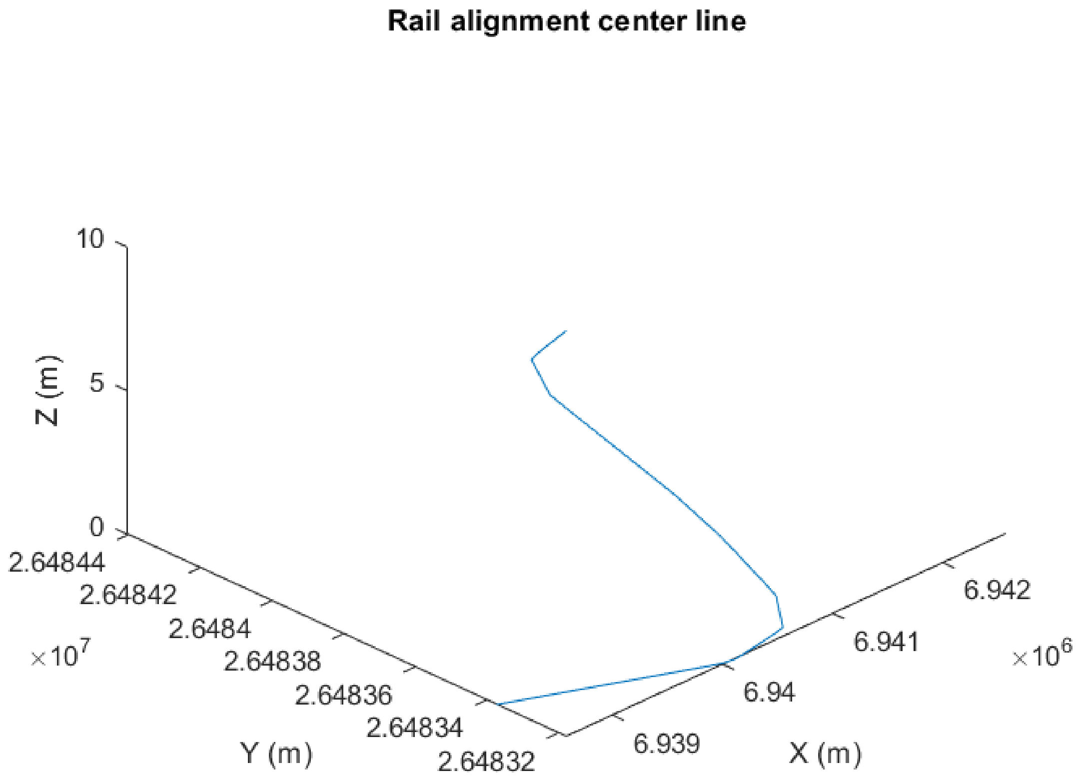
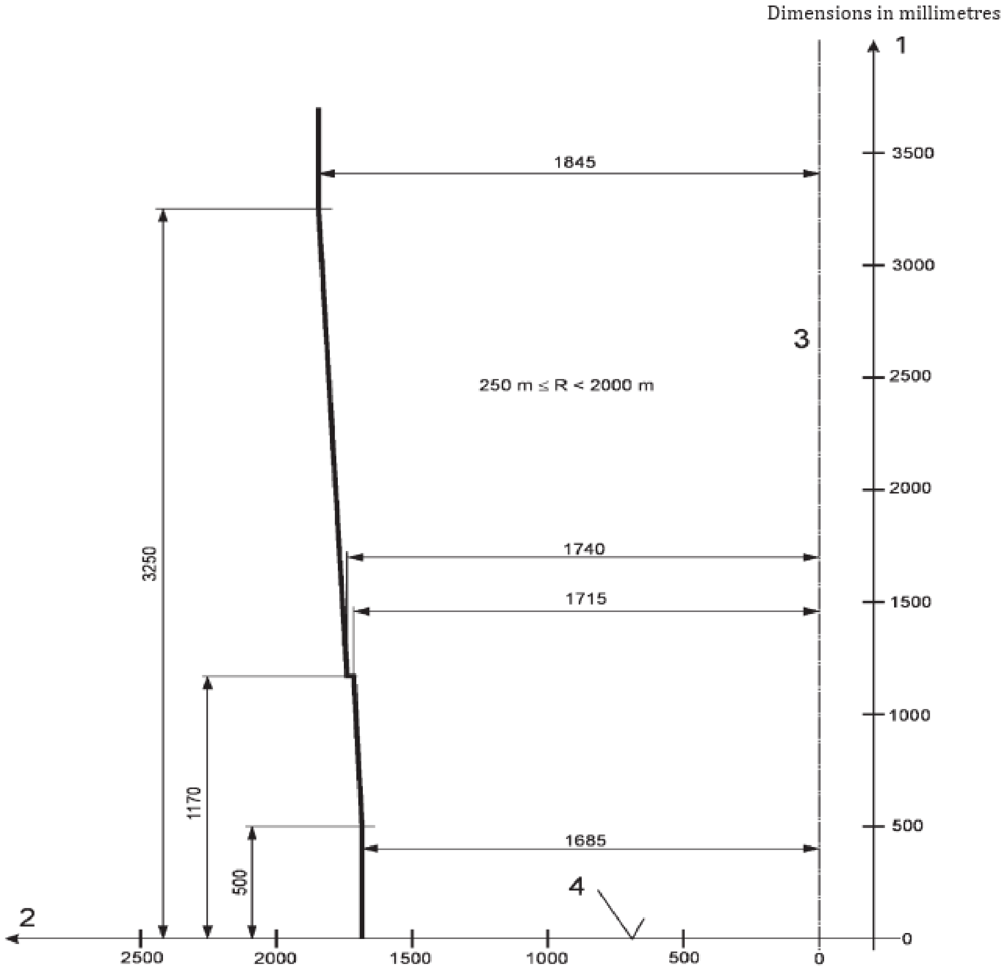


Figure 2.1. *Rail alignment representation as a line of connected points in ETRS89-GK26FIN coordinates.*

To create VWG limits around this railway, it must be represented as bounding volumes. For railways, allowed working gauge limits for tracks must comform to measurements defined in a European standard describing kinematic envelope for a railway. [1]. The kinematic envelope cross section depends on multiple factors such as the gauge of the railway as well as its curvature and cant. An examples cross section with measurements can be seen in Figure 2.2.



Key

1	height
2	width
3	axis of the operating track
4	top of the rail

Figure 2.2. *Kinematic envelope necessary for a G1 or G2 gauge vehicle on a curve of radius 250m < R < 2000m [1].*

The kinematic envelope limits shown in Figure 2.2 can be assigned as VWG limits by aligning them along the length of the BIM center line. In practical uses larger tolerances with simplified geometries are usually utilized. For example the Finnish transport infrastructure agency instructs no work to be conducted within 2500 mm from the nearest rail [2]. This is most like due to no current limiting device being available that can achieve accurate 3D limits. For this reason in this thesis the kinematic envelope limit tested is simplified as a bounding box with width defined as a straight vertical line from the furthest allowed value from the center line at current track location. For the example track shown in Figure 2.2 the vertical limit can be set at 1845 millimeters from the center line of the railway.

Simple geometries of bounding boxes can be created around the track based on the allowed kinematic envelope and chosen safety tolerances. 2 consecutive points along the center line of a feature form an axis that a bounding box can be aligned to. Multiple bounding boxes are created along the whole feature depending on its length and curvature. Use of simpler bounding box geometries reduce the required processing time which is important for a real time system.

Finnish railway network uses $25kV$ AC current running trough the overhead power lines. The Finnish Transport Infrastructure Agency requires a one meter safe distance for working below any of the electrified elements and three meters when approaching from the side [2]. Combined bounding box representation made for the rail alignment shown in Figure 2.1 featuring the bounding boxes for railway track and overhead power lines can be seen from Figure 2.3.

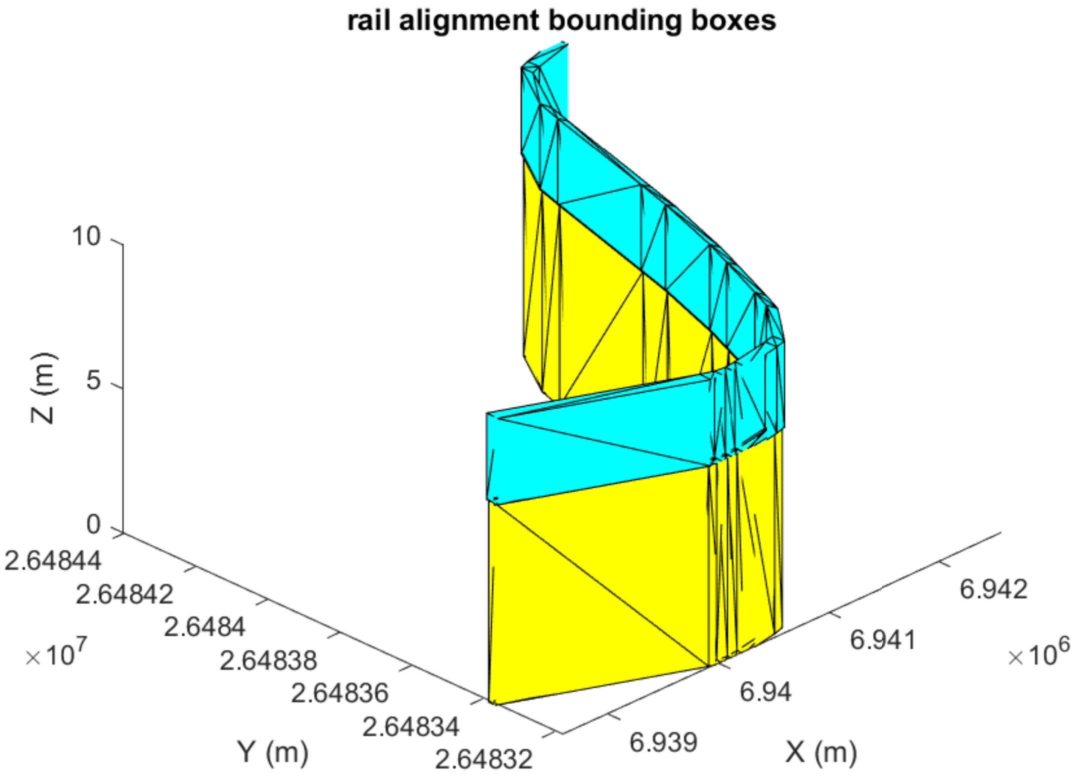


Figure 2.3. *VWG limits for a railway track (yellow) and overhead power lines (cyan).*

If RRE is working on the railway track shown in Figure 2.3, only the cyan bounding boxes marking the overhead power lines are to be considered as VWG limits. The yellow bounding boxes representing the railway track kinematic envelope would be considered as VWG limits if the railway track was open for traffic and the work was conducted near the railway track instead.

2.1.3 Perception system

For fully automatic operations BIM alone can't be used to create an accurate depiction of the real environment. InfraBIM is only accurate when it was created and can lack information about features that should be avoided because they were not modelled into it. Additionally there is always the possibility that the workspace has dynamic obstacles such as other machinery or human workers in it that would not be modelled into BIM.

A type of perception system would therefore needed to allow collision free automatic operations. Perception system such as Lidar and stereo cameras mounted to the manipulator could be used in combination with the BIM to get full understanding of the environment. By continuously scanning the environment, perception system can create a pointcloud representation of surfaces it sees. Image recognition can be used to determine what features these surfaces depict and whether they should be considered as VWG limits. GNSS signal can be used to position the pointcloud relative to the manipulator. It can then be compared to the infraBIM model and combined to make an accurate real time 3D representation of the VWG where the manipulator is allowed to work in.

2.2 Distance query

To prevent collisions with the modelled environment the shortest distance between the manipulator and the environment must be calculated. The shape of the manipulator can be complex based on its Computer assisted design (CAD) model. Additionally it is to be expected that accurate CAD models of the maniputator parts might not available. Therefore for collision detection purposes, it is best to simplify how the manipulator is represented. Universally applicable way to simplify the manipulator is to represent it as bounding boxes. Using bounding boxes the collision detection and distance queries can be computed much faster as the approach reduces a CAD model consisting of possibly hundreds of faces to just six faces of a box. Additionally a bounding box representation can more easily be adapted to any manipulator structure without access to accurate 3D models of the parts.

2.2.1 Manipulator representation for distance query

Manipulator such as excavator can be complex in shape. Being a complex shape, distance calculations are more resource intensive and therefore often difficult to perform in a real time system. Additionally accurate measurements and CAD models are always not available. To simplify and reduce the required calculations the excavator manipulator structure will be represented with bounding boxes.

As an example this thesis uses a standard 6 DOF excavator structure with revolute joints for demonstrative purposes. The excavator dimensions and kinematics model are based on a model demonstrated in [10]. The excavator model was modified for the purposes of this thesis by configuring it with road-rail interface. The used excavator model with its respective links naming is explained in Figure 2.4.

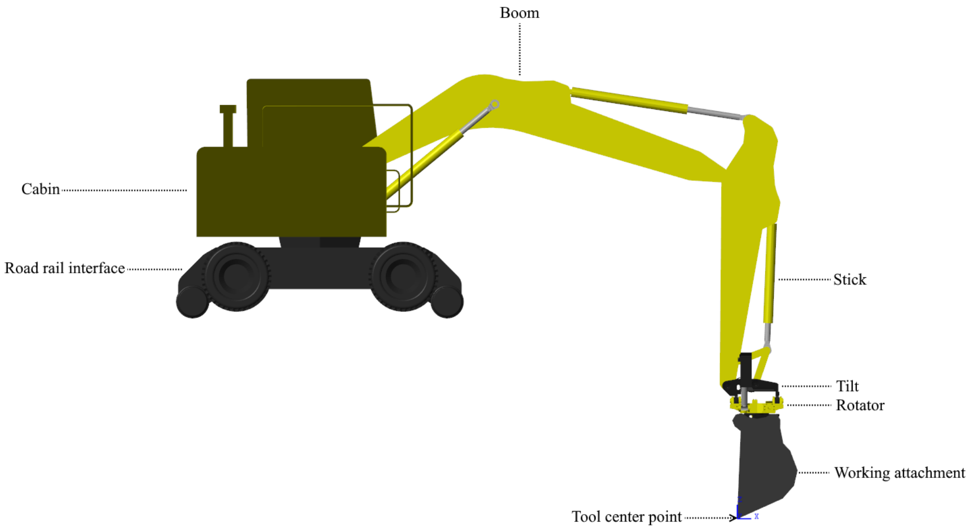


Figure 2.4. *Naming convention of the 6DOF RRE links and location of tool center point.*

So called Axis aligned bounding boxes (AABB) are created for each link in the manipulator structure [11]. Their position and orientation can be defined with the forward kinematics calculations for each link. Using object oriented bounding boxes a standard 6DOF excavator can be represented with just 7 bounding boxes simplifying the required distance calculations. For industrial 6DOF robots the last 3 joints are usually joined together with a spherical wrist. With excavators something very similar, usually called the tilt-rotator is used for the last joints to gain larger freedom of movement. With a tilt-rotator these last three joints intersect in the same point or close to the same point. This means that the last 3 bounding boxes of tilt-rotator and working attachment would often overlap. For more efficiency they can be represented with just one larger bounding box relative to the working attachment. This last bounding box encompasses the links tilt, rotator and working attachment.

Combining links this way reduces the manipulator representation of a 6DOF excavator to just 5 bounding boxes. Link objects are often not cuboids and therefore a bounding box is just an approximation of it. For most collision avoidance tasks this is often adequate but if necessary, a link can be represented with multiple bounding boxes for more accurate representation. The modified excavator model and its bounding box representation can be seen from Figure 2.5.

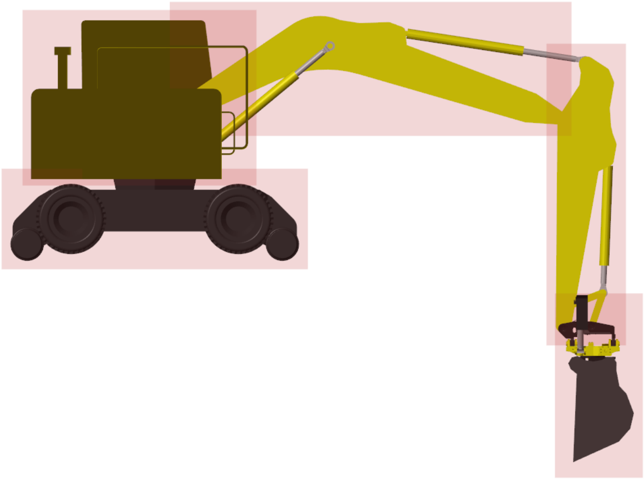


Figure 2.5. *6DOF RRE model represented by 5 bounding boxes.*

When the excavator kinematic model consists of only revolute joints $\theta^i, i = 1, ..., 6$ bounding boxes can be static with specific width, length and height. Hydraulic cylinders that control the joint movements extend and retract and can therefore affect the size of the bounding box. Therefore the AABBs are created such that they enclose the respective link when its hydraulics cylinders are fully extended. For some excavators, joints can also be prismatic in nature. In such cases the link length will vary based on the joint variable d^i. In this case a similar extended AABB is created but the parameter for bounding box length is modified based on the current link length value d^i.

2.2.2 Distance calculations

Different studies and methods for distance calculations regarding robotic manipulator collision avoidance have been conducted before. These usually simplify the calculations to simpler shapes such as oriented bounding boxes [12], [13], [14].

For collision avoidance the manipulator must be able to detect the obstacles it should avoid before such collision would occur. Collision avoidance requires that the shortest distance between two objects is known and also what is the direction of this shortest distance from the manipulator. Shortest distance calculations should return the coordinates of closest points of both the manipulator, p_m, and the obstacle, p_o. Expressing these two points as vectors, both the distance and unit vector expression for direction can be calculated. The shortest distance d_{min} between these two points can be calculated as

$$d_{min} = \sqrt{(p_{m_x} - p_{o_x})^2 + ((p_{m_y} - p_{o_y})^2 + ((p_{m_z} - (p_{o_z})^2} \tag{2.1}$$

and the unit vector between the points is

$$p_m\hat{p}_o = \frac{p_m - p_o}{d_{min}}. \tag{2.2}$$

Flexible Collision Library (FCL) is a unified interface that provides a way to perform proximity queries for different types of models [15]. For VWG purposes it enables shortest distance calculations between models such as triangle meshes, general polygons and point cloud data.

Distance queries using FCL are based on Gilbert–Johnson–Keerthi (GJK) algorithm [12]. This algorithm provides a way to compute shortest distances between convex polytopes and determine the closest points that provide this distance usually without having to calculated distances for each face of the original polytopes. The algorithm works by choosing 3 corner points for one of the shapes at random and creates a plane from them. Shortest distance from a plane to a point on the other shape can be calculated as the shortest distance along the normal of the plane. The convex polytope is reduced such that any corner points that were further away from the point on the opposing polytope than the current plane are removed and new convex shape with remaining corners is created. A new plane is created by changing one of the corner points to a new one on the reduced convex polytope. Same procedure is continued for both polytopes until both convex polytopes are reduced to a single plane that is closest to each other. The same algorithm is then continued in two dimensions. Eventually two corners remain for both planes defining two lines between which the shortest distance between the two original convex polytopes is computed as the normal distance between these two lines.

An example of the algorithm principle for a single 2-dimensional object and a point can be seen from Figure 2.6. It illustrates how the shortest distance can be computed using this method and how it can avoid having to compute the shortest distance against each of the convex shape sides. In Figure 2.6 first two corners selected are z_2 and z_3. Corner z_1 is further away from the reference point o than the line drawn between the selected corners and is therefore removed. Algorithm is continued until the shortest distance is found to be on the line between corners z_4 and z_5.

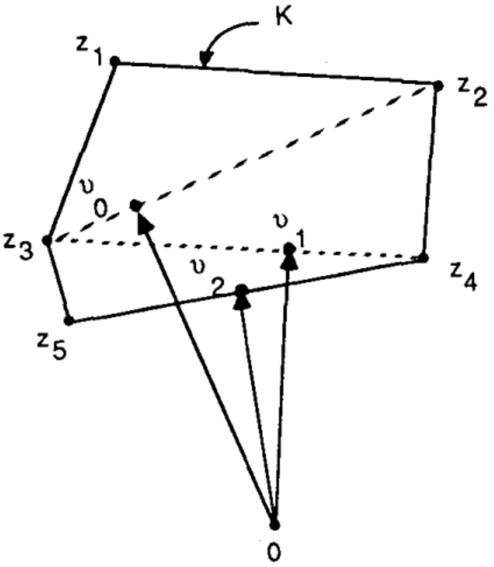


Figure 2.6. *An example in two dimensions illustrating the steps of GJK algorithm [12].*

CAD models, meshes and point clouds can be used as an input for FCL. For VWG limits each infrastructure element is inputted separately as separate submodels to form one model designating the VWG. When calculating distances FCL can first determine which of the submodels are closest to the manipulator. This helps the calculations further as computing time can be reduced by avoiding having to check for shortest distance against every submodel.

Using the FCL, shortest collision distances are calculated for the manipulator defining bounding boxes of cabin, boom, stick and working attachment. Distances are calculated between these bounding boxes and the environment. To prevent self collisions from happening shortest distances are also calculated between bounding boxes of stick and working attachment respect to bounding boxes of road-rail interface and cabin.

3. MANIPULATOR REAL-TIME CONTROL

Distance calculations between the manipulator and the VWG limits is used to accomplish different control functions for the manipulator. The main functions are collision avoidance and collision free path planning. With collision avoidance the manipulator joint velocities will be controlled as a function based on the shortest distance to VWG limit. This will stop the manipulator in such a way to prevent collisions. The same distance calculations can also be leveraged to accomplish more complicated collision free path planning. There instead of just limiting or stopping the manipulator joint speeds, it's trajectory is changed so that it can move to the desired location without collisions. In addition to control methods that are based on obstacles a limiting factor is required based on the physical limitations of the manipulator itself. In an excavator, joints are actuated using hydraulic cylinders that limit the joint movements. An end cushion control is designed to cushion the joint movements before the joint limits are reached.

3.1 Manipulator kinematics

A manipulator can be schematically represented from a mechanical viewpoint as a kinematic chain of rigid bodies (links) connected by means of revolute or prismatic joints. One end of the chain is constrained to a base, while an end-effector is mounted to the other end. The resulting motion of the structure is obtained by composition of the elementary motions of each link with respect to the previous one. [16]

To move a manipulator in space, its end-effector position and orientation must be expressed as a function of individual joint variables with respect to a reference frame. Such function is called the direct kinematics equation or forward kinematics. Understanding the forward kinematics structure is necessary in representing the kinematic model of the manipulator. Forward kinematics can then be used to determine the position and orientation of each of the links. Bounding boxes for links can then be positioned and aligned accordingly for performing distance queries.

The Denavit-Hartenberg convention was used for determining the relative position and orientation between consecutive links in the manipulator structure. A coordinate frame is attached to each joint on the manipulator chain of links. These frames are positioned such that the joint variable is constrained to the relative z axis of the frame. Position and orientation between two consecutive links are parametricised with 4 values, two distances and two angles. One of these parameters is variable based on whether the joint is revolute or prismatic in nature.

Parameter a_i is the length of the link i along the normal of axes z_i and z_{i-1}. The second parameter d_i is the distance between the links along the axis z_{i-1}. The third parameter is α_i which denotes the angle between the two frames about axis x_i. The value of α_i is positive when rotation is counter-clockwise. Lastly the fourth parameter is θ_i which is calculated as the angle between axes x_{i-1} and x_i about the axis z_{i-1} being positive when going counter-clockwise. [16]

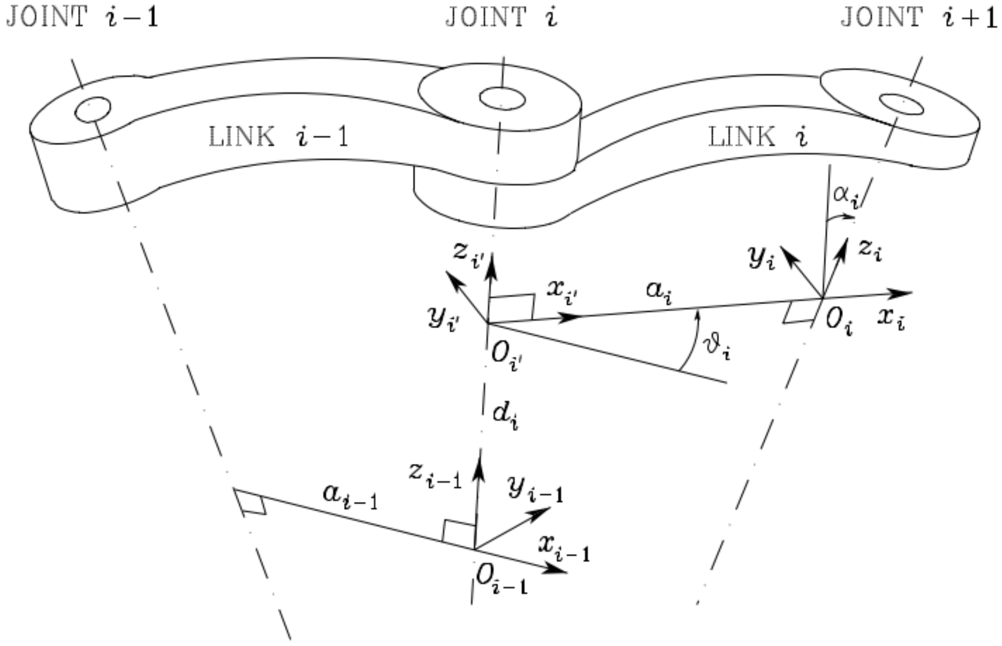


Figure 3.1. *Denavit-Hartenberg kinematic parameters [16].*

The frames for each of the links can be placed arbitarily attached to the respective link. Generally it is better to place them in in a way such that the DH-parameters for the link would be zero. The parameters for the RRE used in this thesis can be seen from Table 3.1 and follow the convention set for a 6DOF excavator in [10].

Table 3.1. *Denavit-Hartenberg parameters for a RRE*

Joint	α_i	a_i	d_i	θ_i
1	$\pi/2$	a_1	d_1	θ_1
2	0	a_2	d_2	θ_2
3	0	a_3	0	θ_3
4	$-\pi/2$	0	0	θ_4
5	$\pi/2$	0	d_5	θ_5
6	0	0	0	θ_6
7	0	a_7	d_7	0

The coordinate transformations between two consecutive links $i-1$ and i can be expressed by combining two homogeneous transformation matrices. First the frame is translated by d_i along axis z_{i-1} and rotated by θ_i. The operation will align the frame $i-1$ with the frame i. Homogeneous transformation matrix for the operation is

$$A_{i'}^{i-1} = \begin{bmatrix} cos(\theta_i) & -sin(\theta_i) & 0 & 0 \\ sin(\theta_i) & cos(\theta_i) & 0 & 0 \\ 0 & 0 & 1 & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{3.1}$$

After this as a second operation the frame is translated by a_i along axis x_i and rotated by α_i about axis x_i. For this operation the homogeneous transformation matrix is

$$A_i^{i'} = \begin{bmatrix} 1 & 0 & 0 & a_i \\ 0 & cos(\alpha_i) & -sin(\alpha_i) & 0 \\ 0 & sin(\alpha_i) & cos(\alpha_i) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{3.2}$$

Multiplying these two transformations together the coordinate transform between the two frames can be shown to be

$$A_i^{i-1} = A_{i'}^{i-1} A_i^{i'} = \begin{bmatrix} cos(\theta_i) & -sin(\theta_i)cos(\alpha_i) & sin(\theta_i)sin(\alpha_i) & a_i cos(\theta_i) \\ sin(\theta_i) & cos(\theta_i)cos(\alpha_i) & -cos(\theta_i)sin(\alpha_i) & a_i sin(\theta_i) \\ 0 & sin(\alpha_i) & cos(\alpha_i) & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}. \tag{3.3}$$

Using Equation 3.3 the transformation matrix from the base frame to any of the link frames can be calculated by multiplying each of the homogeneous transformations between these two frames. For calculating the Tool Center Point (TCP) transformation matrix the multiplication is

$$T_7^0(q) = A_1^0 A_2^1 A_3^2 A_4^3 A_5^4 A_6^5 A_7^6 \tag{3.4}$$

Similar to Equation 3.4 transformation matrices for all the previous frames in the chain can be calculated. Transformations for all the frames that define manipulator bounding boxes are needed to be calculated. For the RRE used these are frames for the base, cabin boom, stick and working attachment.These correspond to frames 1, 2, 3, 4 and 6 in the link chain and are calculated as:

$$\begin{aligned}
T_1^0(q) &= A_1^0 \\
T_2^0(q) &= A_1^0 A_2^1 \\
T_3^0(q) &= A_1^0 A_2^1 A_3^2 \\
T_4^0(q) &= A_1^0 A_2^1 A_3^2 A_4^3 \\
T_6^0(q) &= A_1^0 A_2^1 A_3^2 A_4^3 A_5^4 A_6^5.
\end{aligned}$$

3.2 Inverse kinematics

It is possible to express the given position and orientation of the manipulator in terms of the given joint values. This is called inverse kinematics. Inverse kinematics is the basis for many control algorithms used to dictate manipulator movements. The manipulator in this thesis is controlled on a velocity level from which the desired joint values can be integrated. The general equation for solving the desired TCP pose velocity ẋ is described as

$$\dot{x} = \begin{bmatrix} \dot{p} \\ \dot{\omega} \end{bmatrix} = J_G(q)\dot{q}, \tag{3.5}$$

where $\dot{p}$ and $\dot{\omega}$ refer to the vector of desired TCP linear and angular velocities, J_G is the geometric Jacobian matrix of the TCP and q̇ the desired joint velocities. Solving this for q̇ requires the inverse Jacobian matrix

$$\dot{q} = J_G^{-1}(q)\dot{x}. \tag{3.6}$$

For redundant manipulators where the manipulator joint space is larger than its operational space, a direct inverse of Jacobian matrix does not exist. A pseudo-inverse solution can be used instead [17]:

$$\dot{q} = J_G^{\dagger}(q)\dot{x}, \tag{3.7}$$

where the matrix

$$J_G^{\dagger} = J_G^T(J_G J_G^T)^{-1} \tag{3.8}$$

is the right pseudo inverse of J_G. Near kinematic singularities the pseudo-inverse solution can have stability problems. To address this, the damped least squares method can be used to calculate desired $\dot{q}$ values [16]

$$\tilde{J_G^T} = J_G^T(J_G J_G^T + \lambda^2 I)^{-1}, \tag{3.9}$$

where in λ is a non-zero damping factor that makes the Jacobian inverse better for numerical operations. [16].

Applying the damped least squares method to Equation (3.7) a general form for the solution of q̇ can be shown to be [17]

$$\dot{q} = J_G^{\dagger}\dot{x} + \left(I - J_G^{\dagger}J_G\right)z, \tag{3.10}$$

in which z denotes an arbitrary vector in $\dot{q}$-space.

3.3 Collision avoidance

Collision avoidance sets out to improve the safety of operations by modifying manipulator joint speeds $\dot{q}$ in a way to prevent collisions. In this thesis two methods for achieving collision free movements is described. They both use the shortest distance calculations described in Section 2.2.2 but use them in different ways. The control systems consider shortest distances to obstacles equally and therefore achieve both environmental obstacle avoidance and self collision avoidance.

Linear velocity scaling is the first control method. It is simple and designed to linearily slow down and stop the manipulator movements before collisions can occur. It is mainly used as a safety feature in manual operating modes where the operator has full control of the manipulator movements. The second method is dynamic obstacle avoidance and uses Artificial potential field (APF) to perform desired manipulator movements. It is geared towards automatic operations where the manipulator tries to complete the desired motions while avoiding collisions.

3.3.1 Linear velocity scaling near obstacles

Collision avoidance is achieved by limiting the allowed joint velocities as a function of the distance to the obstacle. Chapter 2.2.2 describes a method for how the closest points between a manipulator link and obstacles are calculated. Using Equation (2.1) the distances from each of the manipulator links to an obstacle can be calculated. Shortest of these distances is used to determine a scale factor for joint speeds.

Collision avoidance scales the allowed joint velocity references linearly when the shortest distance is between two threshold distances. At or below the lower threshold the scale-factor is 0 and above the upper threshold it is set to 1 meaning it does not affect the joint speeds. Upper and lower thresholds are chosen such that joints can decelerate to a stop regardless of the initial velocity. The scale factor s_{fac} is calculated as

$$s_{fac} = \begin{cases} \dfrac{p_i - p_l}{p_u - p_l}, & \text{if } p_i < p_l \\ 1, & \text{otherwise,} \end{cases} \tag{3.11}$$

where p_i is the shortest distance to an obstacle and p_u and p_l the upper and lower thresholds for applying scale factor. Combining Equations (3.10) and (3.11) the joint speeds can be scaled near obstacles as

$$\dot{q} = \left(J_G^{\dagger} \dot{x} + \left(I - J_G^{\dagger} J_G \right) z \right) s_{fac}. \tag{3.12}$$

Shortest distance to an obstacle can be calculated using forward kinematics of a desired position before moving the manipulator to that position. This can be achieved also when the calculations are done on a small scale with the desired pose being the the next time step of the control system. Comparing shortest distances between the current and next time step it is possible to determine whether the manipulator is moving closer to or away from an obstacle. Collision avoidance can then be designed such that moving away from an obstacle does not limit the joint speeds. This makes the operations faster and also more user friendly when an operator is controlling the manipulator manually.

3.3.2 Dynamic obstacle avoidance

Unlike linear velocity scaling which allows movements until an obstacle is too close, dynamic obstacle avoidance aims to control the manipulator such that it can avoid that obstacle and still reach its desired pose. Collision free path planning is usually required for autonomous operations. The excavator TCP will be commanded to travel trough n number of points with set position and orientation. The path planning algorithm will create a path through these points. If the path would travel such that the manipulator would reach outside the VWG limits, the control system modifies the path and keep the manipulator withing the VWG.

Path planning can be achieved with either global or local approaches. Global methods calculate a suitable path without collisions for the whole path from starting pose to the desired end pose before moving the manipulator. This can be computationally heavy and requires that the environment is static for the duration of the movements. Therefore global strategies are not suitable for real time dynamic operations. Local strategies use sensor data to determine if a collision would happen and modify the trajectory based on the information gathered. Local methods are easier to compute but come with drawbacks. With local methods the control system reacts only to the immediate sensor information, in our case the calculated closest points. Control system can't therefore form an optimal path and in some cases might get stuck on a local minimums. For larger movements a combination of local and global approaches might be preferred.

Artificial potential field methods are a well studied local control approach to accomplish collision free path planning. Artificial potential fields were first coined in the 1980s [18]. Generally APF can be described as a sum of attractive and repulsive forces affecting the manipulator. Manipulator TCP is attracted to the desired end position while the manipulator will be repelled by obstacles.

Maciejewski and Klein showcased a method for determining APF at velocity level using the closest point of the manipulator to an obstacle called the obstacle avoidance point [19]. Their method considered only one obstacle avoidance point and was further improved by [11]. to take into account multiple obstacle avoidance points.

Obstacle avoidance points velocity $\dot{x}_{O_i}$ can be defined by using the artificial potential field using previously calculated shortest distance to an obstacle as [11]

$$\dot{x}_{O_i} = -\bigtriangledown U_{O_i} = \begin{cases} \mu \left(\frac{1}{p_i} - \frac{1}{p_u} \right) \frac{1}{p_i^2} \frac{\delta p_i}{\delta \dot{x}_{O_i}}, & \text{if } p_i \leq p_u \\ 0, & \text{if } p_i > p_u. \end{cases} \tag{3.13}$$

In it μ denotes a scalar coefficient, term p_i is the shortest distance for current link i calculated with Equation 2.1 and term $\frac{\delta p_i}{\delta \dot{x}_{O_i}}$ is the direction of the collision line calculated with Equation 2.2. Increasing the value of μ changes how aggressively the artificial potential field tries to avoid collisions. Using n_o-amount of collision avoidance points the equation 3.10 can be combined with 3.13 to form a solution for path generation with multiple collision avoidance points [11]

$$\dot{q} = J_G^{\dagger}\dot{x} + \sum_{i=1}^{n_o} \left[(I - J_G^{\dagger} J_G) J_{O_i}^{\dagger} \dot{x}_{O_i} \right]. \tag{3.14}$$

In it $J_{O_i}^{\dagger}$ denotes the pseudo inverse Jacobian of the obstacle avoidance point. Knowing which link i bounding box the obstacle avoidance point is in, $J_{O_i}^{\dagger}$ can be calculated from the Jacobian matrix of that links joint with

$$J_{O_i}^{\dagger} = (J_{v_i} - \tilde{r} J_{\omega_i}). \tag{3.15}$$

where J_{v_i} and J_{ω_i} are the translational and rotational parts of the joints Jacobian. While $\tilde{r}$ is the skew symmetric matrix representing the obstacle avoidance point in local coordinates relative to the joint Jacobian [20].

Equation 3.14 can be used to find a collision free path to the desired pose but faces problems for non-redundant manipulators. When the manipulator is not redundant in nature, meaning it does not have more degrees of freedom than than is needed to execute a task, equation can modify the TCP orientation in undesired ways. For a 6DOF manipulator use case, artificial potential field was applied to modify the joint velocities of only the first three joints.

$$\dot{q}_{1\ldots6} = J_G^{\dagger}\dot{x} + \begin{cases} \sum_{i=1}^{n_o} \left[(I - J_G^{\dagger} J_G) J_{O_i}^{\dagger} \dot{x}_{O_i} \right], & \text{if } \dot{q}_{1\ldots3} \\ 0, & \dot{q}_{4\ldots6} \end{cases} \tag{3.16}$$

Using Equation 3.16 prevents undesired orientation changes of the TCP for a 6DOF manipulator but can cause the manipulator to get stuck in more local minimums. For VWG purposes the trade-off is neglectable as the manipulator is not expected to fit trough small spaces. Equation 3.14 can be used if the desired use case does not involve handling the manipulator in a specific orientation.

3.4 Virtual working gauge architecture

VWG architecture consists of three main subsystems achieving collision free movements for the manipulator. These subsystems are the manipulator control system, collision server and the robotic manipulator itself. In addition to these main subsystems additional inputs such are required. Signals relaying the desired goal pose of the manipulator, the GNSS signal and possible information given by the perception system are processed and utilized in other systems of the architecture. A simplified version of the architecture noting the information flow between the different subsystems is shown in Figure 3.2.

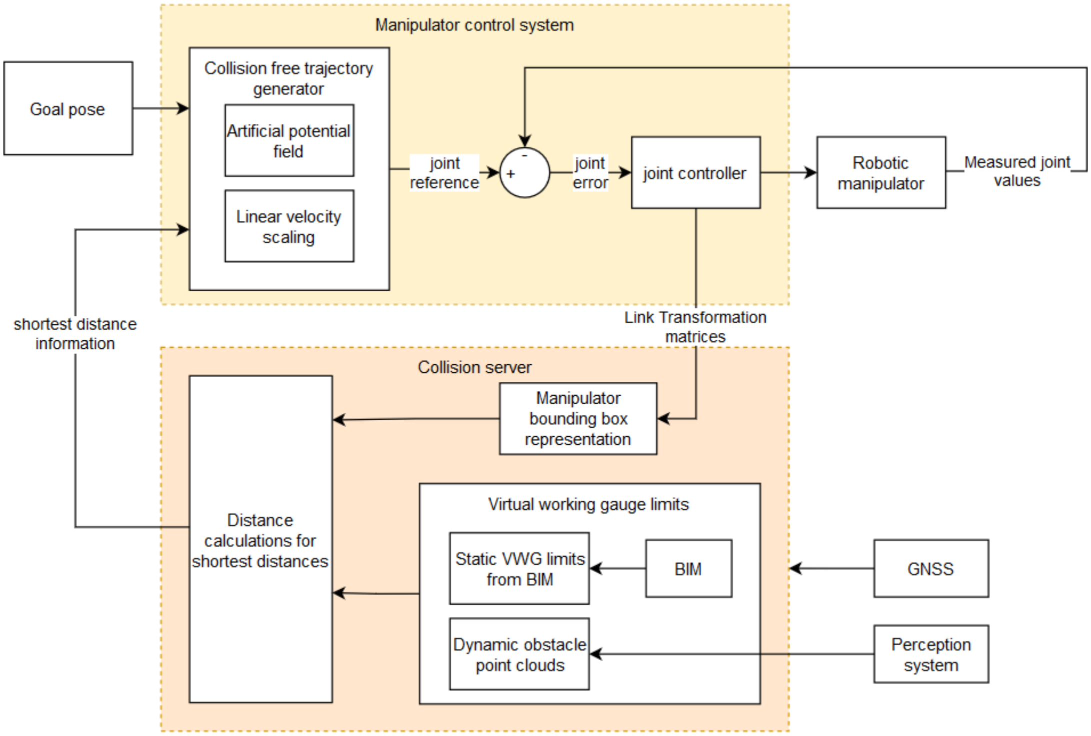


Figure 3.2. *Simplified VWG architecture.*

3.4.1 Manipulator control system

Manipulator control system is responsible for controlling the robotic manipulators movements. A desired goal pose for the manipulator TCP is given to the control system. The control system controls the joint movements such that the goal pose is reached without collisions with VWG limits or the manipulator itself. The manipulator control system was programmed using MATLAB and can be later converted into C-code for use in an real machine.

The control system uses both Equations 3.12 and 3.16 to control the joint speeds of the manipulator depending on application. Equation 3.12 is mainly used when the manipulator is driven manually. In manual operations the goal pose is received directly from the operator joystick input. Artificial potential field method with Equation 3.16 is used when performing automated motions between different poses of the TCP. With more elaborate motions simple point to point movement is usually not enough but rather multiple intermediate points define a full path motion. Here series of goal poses are created that define the motion as a function of time in the joint space.

Current angle of the manipulator joints is measured by the Internal measurement unit (IMU)s at each links joint from the robotic manipulator. Measured joint angles are fed back to the manipulator control system. Using forward kinematics described in Section 3.1 the current pose of the manipulator is realised as transformation matrices and the respective Jacobian matrices for each link frames can be calculated with the given measurements. New joint reference velocities are calculated based on the difference between the current pose and the goal pose. The Equations 3.12 and 3.16 calculate the desired joint velocities that are then integrated to give reference joint angles for the robotic manipulator.

3.4.2 Collision server

Collision server is a subsystem in the architecture that's function is to calculate the shortest distances between the manipulator and the VWG limits as well as self collision distances between the different links of the manipulator. Calculating distances is the most computing time demanding operation in the system and therefore separated into its own server entity. The FCL library is used to process different data types that form the VWG limits. FCL has a C++ interface and therefore the collision server is also programmed using C++ programming language. Collision server is run on a different machine that would communicate with manipulator control system programmed with MATLAB trough a Robot operating system (ROS) interface. Figure 3.3 explains the workings of the collisions server in slightly more detail.

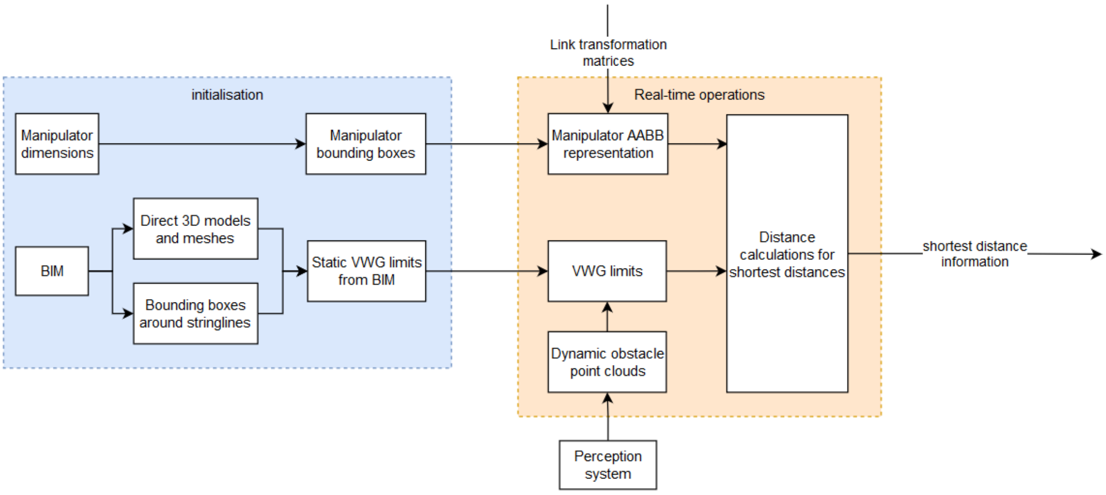


Figure 3.3. *Collision server architecture.*

The collision server performs some of its operations during so called initialisation phase. The data for BIM and manipulator dimensions stay constant during operations and therefore they can be evaluated during an initialisation phase before real time operations start. The less operations the collision server has to perform during real time operations improves the server response time. In Chapter 2.1 different ways on how BIM portrays the environment is discussed. During initialisation relevant mesh information of infrastructure elements is directly translated into VWG limits for the collision server. For elements noted as a line of points, necessary bounding boxes are created and resulting bounding boxes are fed into the collision server. These form the static VWG limits for the collision server and they do not need to be altered during real time operation.

During initialisation bounding boxes can be created for all the manipulator parts based on their dimensions. At this time, the collision server does not yet have information from the IMUs to determine the current position and orientation of the respective manipulator bounding boxes. Therefore the bounding boxes are created with the correct dimensions centered around ground reference point of the manipulator and with identity matrix as the orientation.

During real time operations as an input the collision server receives the Denavit-Hartenberg transformation matrices for each of the manipulator links. These are calculated from the robotic manipulator data from IMUs attached to each of the manipulator joints using forward kinematics discussed in Chapter 3.1. Using the transformation matrices all the manipulator bounding boxes current position and orientation are aligned with the relevant links axis to form the AABBs for each of the links.

At the start of real time operations accurate location of the robotic manipulator is measured with GNSS and the VWG limits are positioned relative to the manipulator. If the manipulator moves during operations the GNSS will track this and move the VWG limits accordingly. FCL can also process point cloud data and with it the collision server can also gather point clouds from a separate perception system to detect dynamic obstacles and obstacles not modelled into BIM. These introduce dynamic limits for the VWG that can change during operations.

Shortest distances are calculated from the manipulator AABBs respect to all the obstacles. The FCL calculates the distances using same method regardless if the obstacle is a VWG limit or another part of the manipulator. It then saves the coordinates for the closest points for each of the manipulator bounding boxes and the obstacles and sends all the closest points back to the manipulator control system using ROS to send the information.

4. RESULTS

In order to test the functionality of the control modes presented representative use cases were designed. These use cases were tested in an simulation setting using MATLAB. The results gathered from these tests were used to evaluate the effectiveness of the VWG.

4.1 Control system test cases

A simulation environment and practical use case was designed to test the VWG in a railway maintenance application. Simulations were tested in a MATLAB Simulink environment. In the simulation environment two train tracks are situated parallel to each other. Manual selection was required to choose what features of a BIM should be used create the VWG limits. No automatic method for selection was created for this thesis. A bounding box is created around the adjacent track based on the Building information model (BIM) model of the area detailing the tracks location and shape. Additionally a bounding box representing a pole next to the railway was included in the model to represent a feature that the perception system would recognize. The adjacent track and the pole define the VWG limits for the environment. RRE is situated on the track and could be moved to different locations on the track to change the relative locations between it and the VWG limits.

Visualization was done using an excavator model designed in [10]. It was modified for the purposes of this thesis. Differences include for example a road-rail interface instead of the initial tracks the excavator had. The model was imported to MATLAB Simulink and a 10 by 10 meter square area around the excavator was visualised with Simulink Simscape. The simulation environment can be seen from Figure 4.1

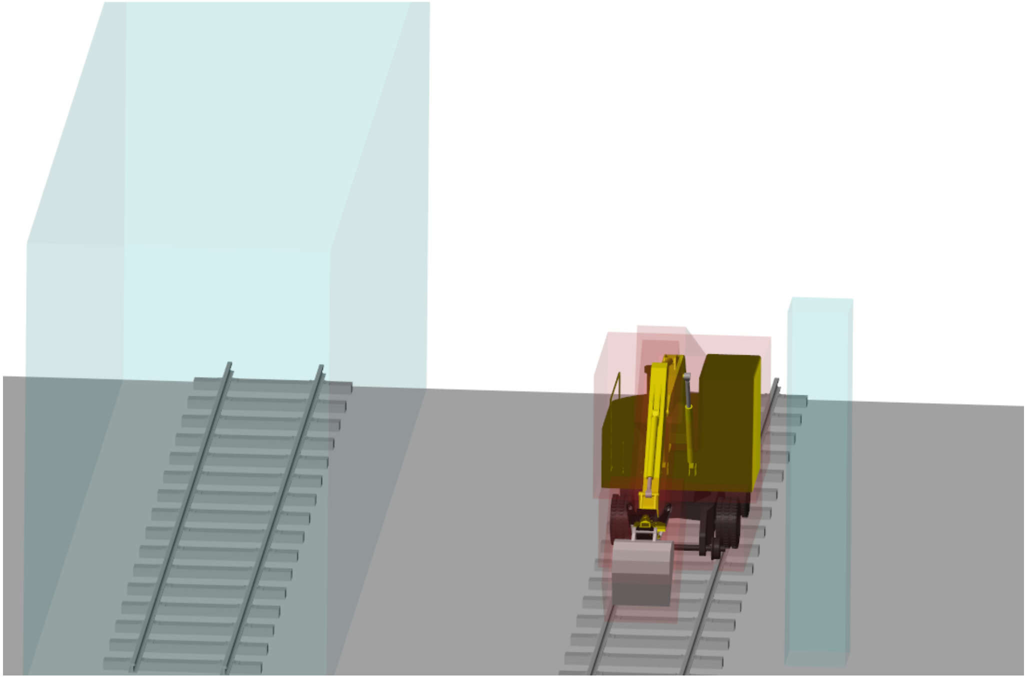


Figure 4.1. *Simulation environment with bounding boxes noting VWG limits.*

4.2 Manual operation test for linear velocity scaling

Linear velocity scaling control system was designed to be used in manual operations. To test collision avoidance, the RRE was deliberately moved towards a VWG limit. This was done by moving the RRE TCP on a linear path towards the nearby pole. After sufficient time had passed the path was reversed and the RRE moves back towards its starting position. Positions of the sequence can be seen from Figure 4.2. For readability, only the RRE and the poles bounding box is visible.

The upper limit p_u for modifying the velocities was set at 0.8 meters and the shortest allowed distance p_i between the manipulator and the VWG limits was 0.2 meters. Movements were achieved by manually controlling the RRE using a joystick input.

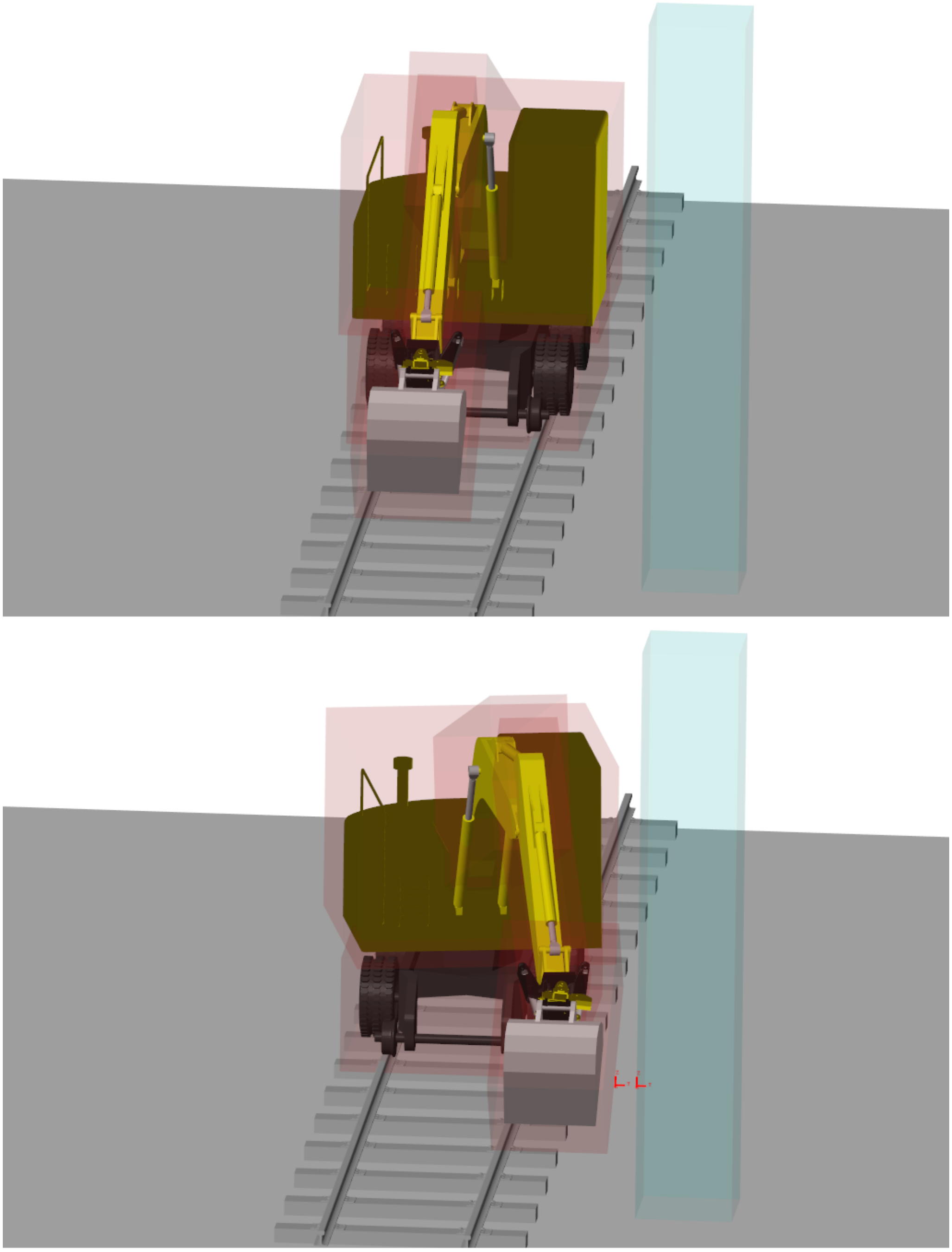


Figure 4.2. *Linear velocity scaling sequence initial position and position near collision.*

4.3 Linear velocity scaling simulation results

Collision avoidance was achieved using Equation 3.12 to control the RRE joint velocities. Joint velocities and the shortest distance to the pole during the sequence can be seen from Figures 4.3 and 4.4.

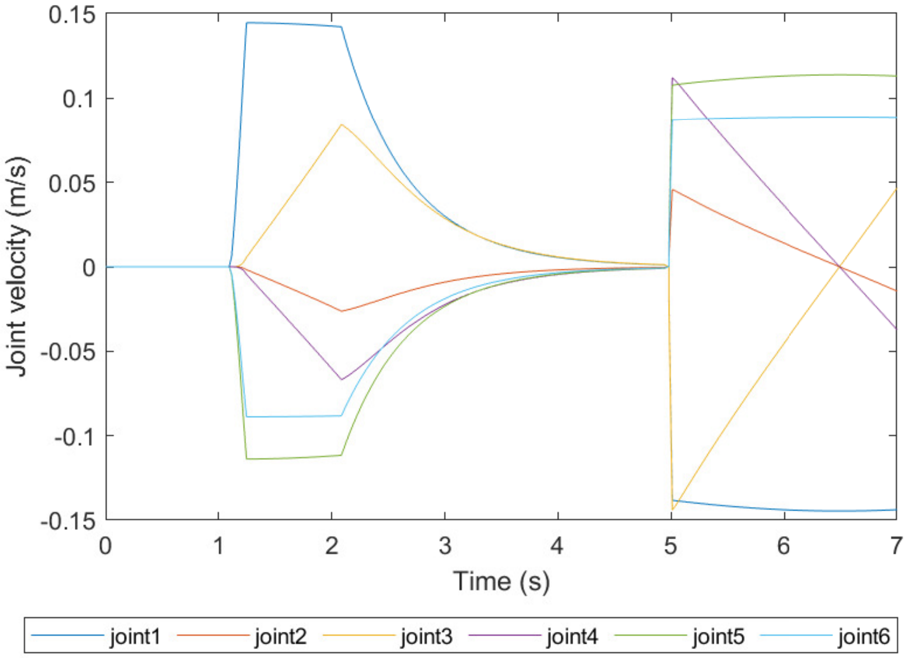


Figure 4.3. *Joint velocities during the linear velocity scale test sequence.*

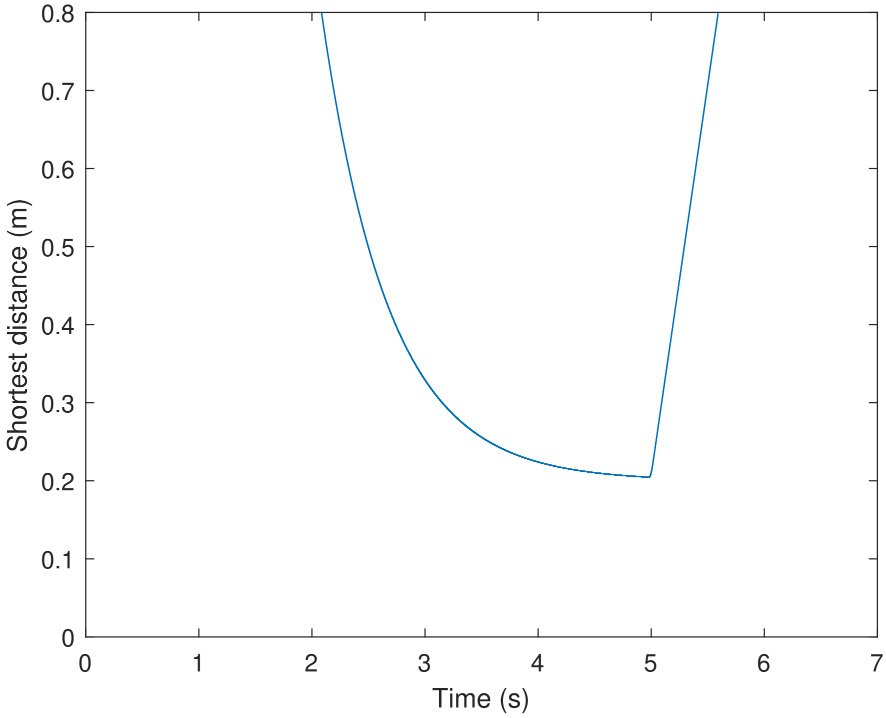


Figure 4.4. *Shortest distance for collision detection during the linear velocity scale test sequence.*

Starting at one second into the sequence the RRE was instructed to move towards the pole. Once the shortest distance reaches below 0.8 meters at around two seconds, the scale factor linearly modifies the joint velocities gradually bringing the velocities to zero when the distance to the VWG limit reaches lower threshold. At five seconds the RRE is operated to return back to its starting position. This movement causes the shortest distance to increase and therefore joint velocities are not reduced during this movement.

Linear velocity scaling performs as expected. It decreases the joint velocities when approaching a VWG limit but does not hinder operations by making the movements slow when shortest distance increases. This can speed up operations when it is necessary to work near VWG limits. Manual operation test is successful in a simulation setting. Further testing is needed though when implementing the system to a real excavator. Different excavator models can move their joints at different speeds. Values for p_u and p_l might therefore need to be adjusted to ensure suitable breaking procedure is possible at maximum joint velocities.

4.4 Ballast removal use case

To test the artificial potential field a use case for a more representative task was created. In it the RRE in this simulation environment is used for railway maintenance work to do ballast removal. The RRE moves old ballast gravel from between the two tracks to be replaced with new ballast. The RRE uses a bucket as a working attachment to lift old ballast from the side and move it behind onto a train cart that would transport the ballast rock material away. A simple trajectory with intermediate points is created to perform this operation. This desired trajectory was set up such that the excavator would reach outside its VWG limits without control system interference in operations. Additionally when lifting the bucket, up it reaches near the road-rail interface triggering the control system to avoid self collisions. Artificial potential field modifies RRE movements to allow the desired ballast removal to take place.

The modelled environment during the sequence can be seen in Figures 4.5, 4.6 and 4.7. In these visualizations the pole is removed for better readability.

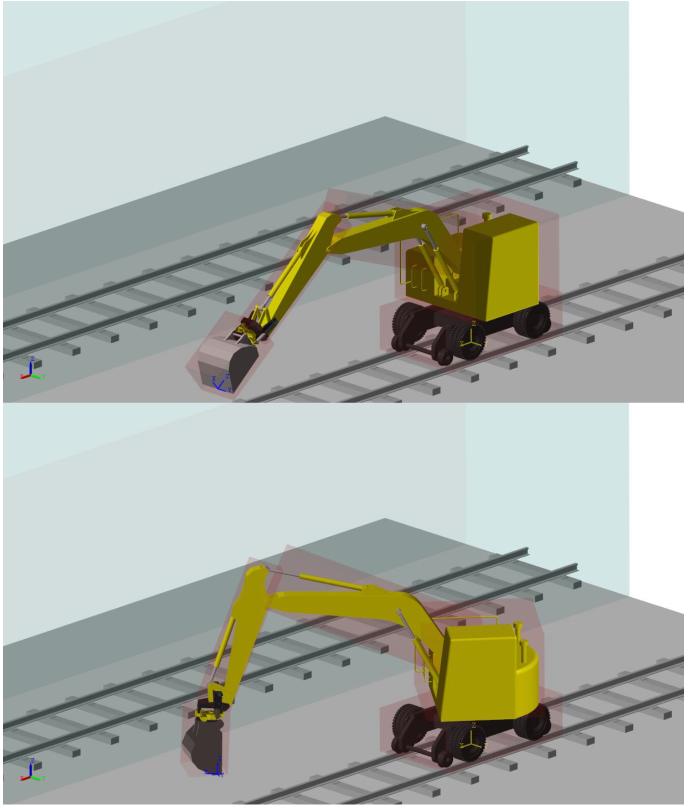


Figure 4.5. *Ballast removal initial pose and start of digging.*

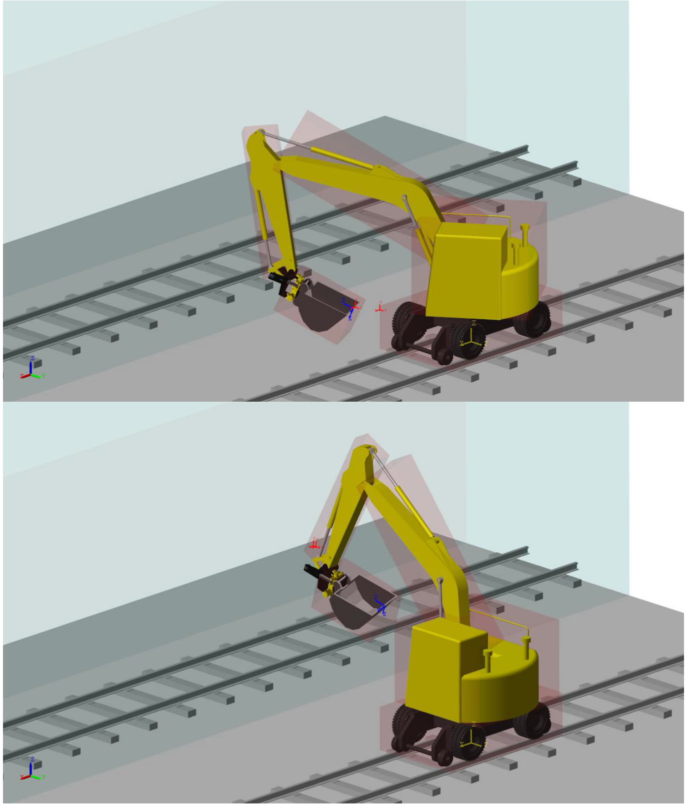


Figure 4.6. *Manipulator near self collision and adjacent track.*

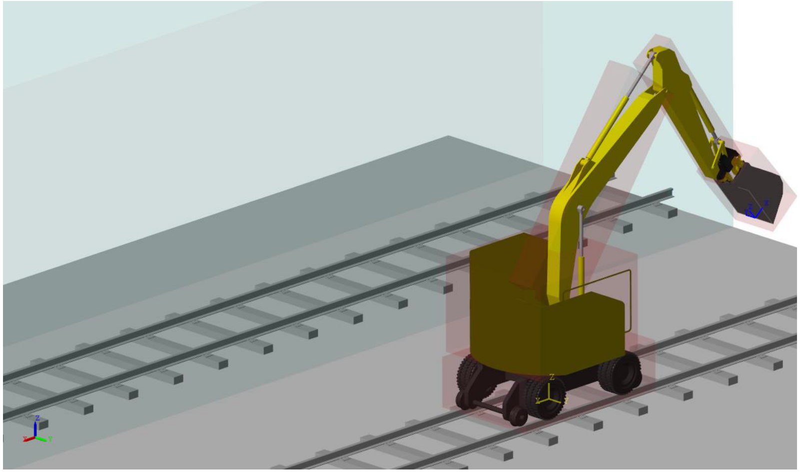


Figure 4.7. *Ballast removal sequence end pose.*

4.5 Artificial potential field simulation results

adjacent track is located in the negative Y-direction. For comparison the TCP position and orientation was plotted for both designed path and the path using artificial potential field. Artificial potential field was accomplished by modifying the RRE joint velocities with Equation 3.16. The behaviour differences during the ballast removal sequence can be seen from Figure 4.8.

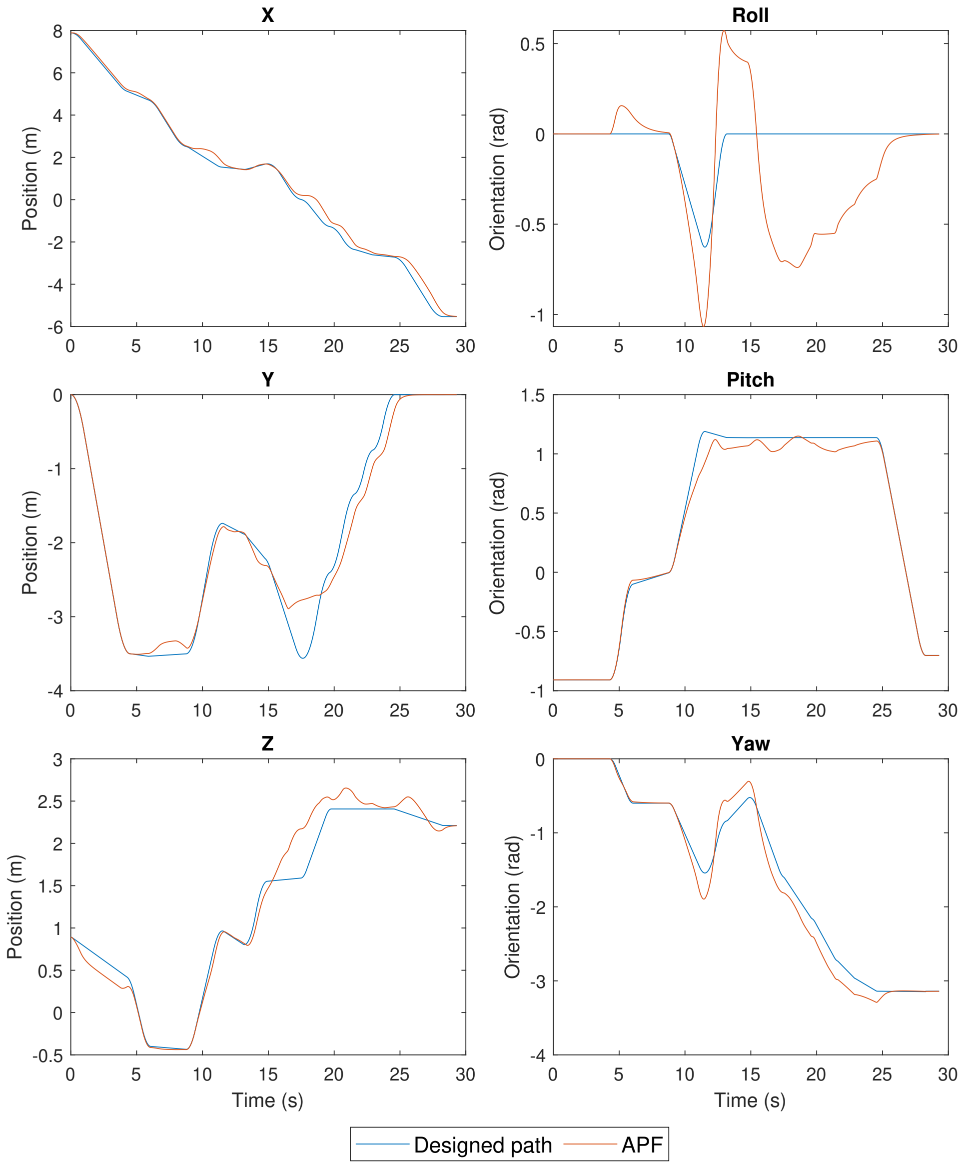


Figure 4.8. *Ballast removal sequence position and orientation using different control modes.*

Figure 4.8 shows how artificial potential field changes the manipulator movements to prevent collisions. The desired ballast removal task is achieved with slight alterations to the RRE movements. Generally the movements follow the desired path but are modified when nearing VWG limits.

When lifting the working bucket, it reaches near the road-rail interface and the artificial potential field prevents an self collision between the bounding boxes from happening. This can be seen from Figure 4.8 as slight deviations in X and Y-coordinates as well as roll and pitch orientations at around 10 seconds into the sequence.

Between 15 and 20 seconds the RRE is travelling along the bounding box of the adjacent track. During this time the stick is the closest link to the VWG limits. The adjacent track is in the negative Y-direction. The artificial potential field prevents the manipulator from reaching in that direction by mainly lifting the boom up which can be seen as positive Z-direction movement. It takes a while before the control system is able to start following the designed path again. Figure 4.9 shows the joint angles during this sequence when using artificial potential field.

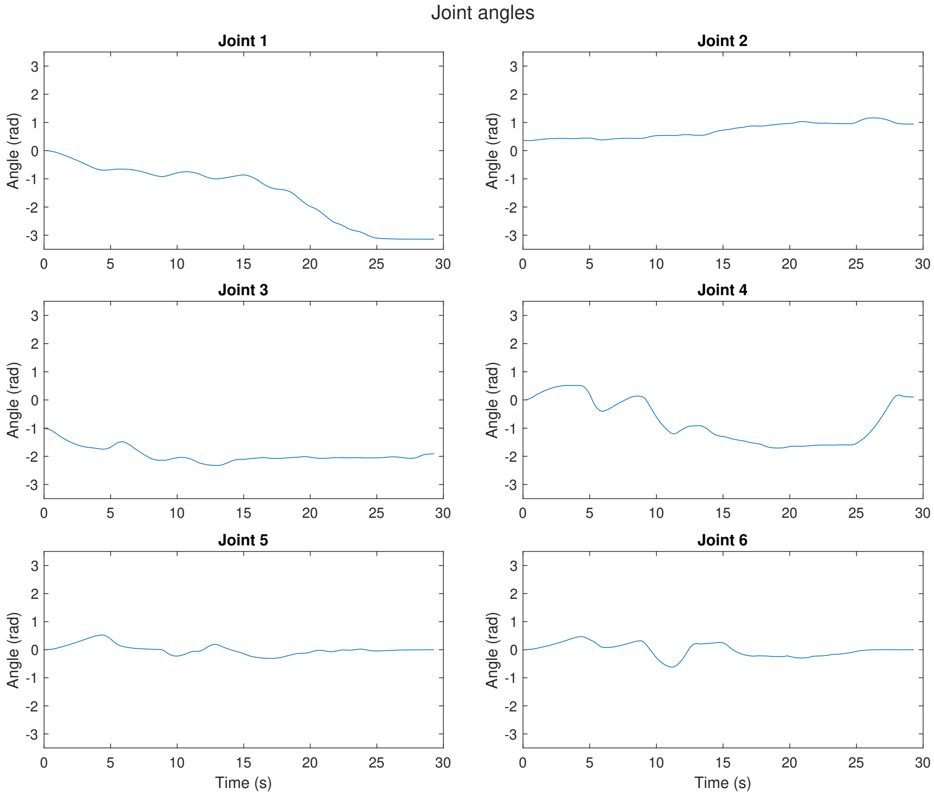


Figure 4.9. *Joint values during ballast removal when using artificial potential field.*

During testing the artificial potential field method experienced slight vibrations in certain circumstances caused by sudden changes in the calculated shortest distance. Sudden changes in the location of the shortest distance affects the shortest distance direction and can cause vibrations that way. Gilbert–Johnson–Keerthi algorithm used for detecting shortest distances in a default case can only calculate a single shortest distance between two bounding boxes even if multiple shortest distances could exists. For example this can happen when joint velocities are changed when the shortest distance is between two bounding box faces that are near parallel to each other or when 2 bounding boxes in different directions are the same distance from the manipulator. Examples of these are depicted in Figure 4.10

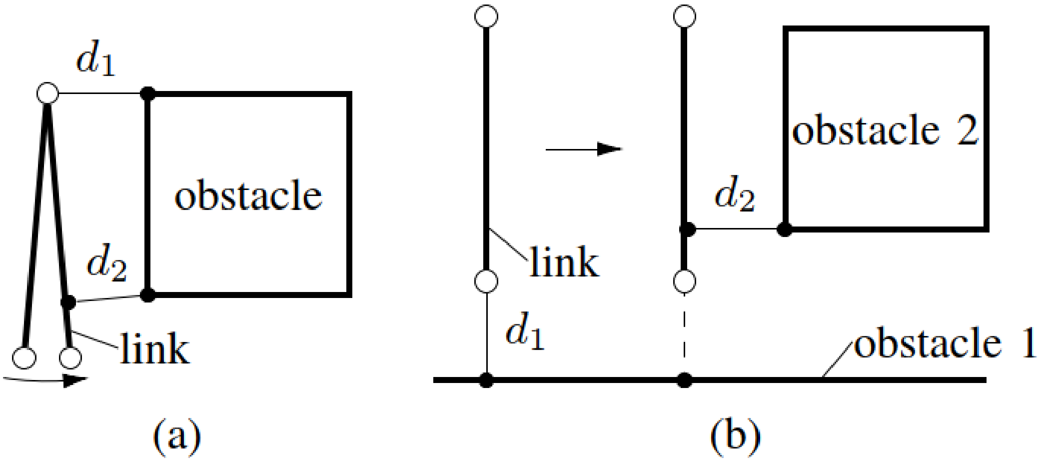


Figure 4.10. *Situations with sudden changes in the shortest distance, (a) link rotation with near parallel sides, (b) shortest distance between multiple obstacles [20].*

During the ballast removal sequence using artificial potential field, situation similar to the one shown in Figure 4.10a happens a few times where the shortest distance changes location on the working attachment when the working attachment and the road-rail interface are near self collision. The sudden changes in shortest distance is small and don't majorly affect the operations but showcases how such changes can occur with current methods. Figure 4.11 shows the calculated shortest distance during the use case. Shortest distance upper bound p_u in the figure is 0.8 meters as this is was the set threshold for artificial potential field to function.

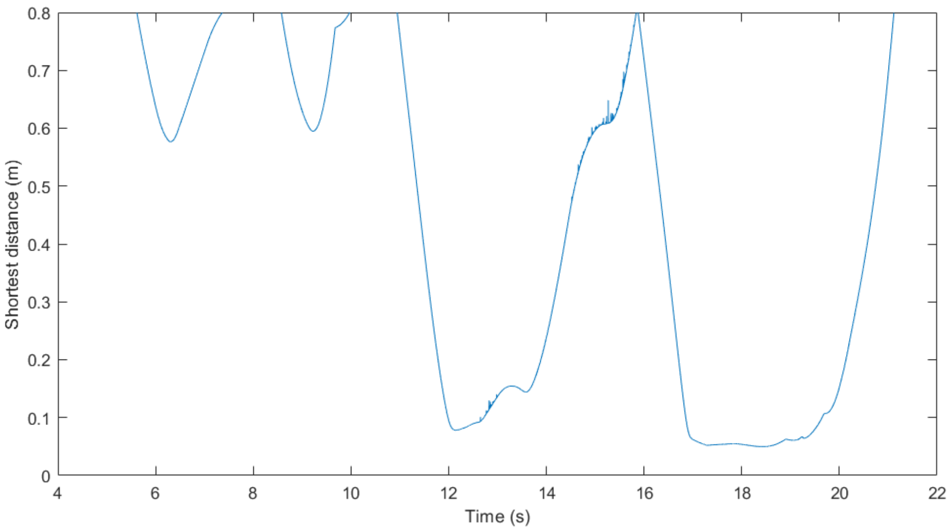


Figure 4.11. *Shortest distance for collision detection during ballast removal sequence.*

Possible mitigation method for these vibrations have been presented in literature and they rely on calculating multiple shortest distances per manipulator link. For situations similar to shown in Figure 4.10a, the link could be sectioned into multiple regions and such shortest distances calculated from multiple locations on the link bounding box [21]. Without sectioning the link into smaller parts, additional points could be projected along the link length from the calculated shortest distance [20]. Distances from these additional points could be calculated and added to the artificial potential field calculations. Alternative method for mitigating the issues would be to represent the manipulator as a point cloud and calculate shortest distances for n number of shortest points in the point cloud [11]. Figure 4.10b type situations with multiple closest obstacles can already be handled with FCL by calculating shortest distances to different obstacles separately.

5. CONCLUSION

In this thesis a control system that could limit robot manipulators reach when its global position was know was developed. The reach was limited to a VWG using GNSS data on the manipulators position and a BIM of the environment. The control system was designed such that these limits would not be violated. Functionality of the control system was simulated in MATLAB Simulink environment.

BIM and satellite positioning can be used to infer different infrastructure elements exact location in relation to the manipulator. If the manipulator was to move, the GNSS can sense that and update its relative position in regards to the BIM. Utilising BIM is also especially useful in defining virtual limits for features for which their exact location is hard to define using traditional perception methods. To maintain manipulator movements inside these defined limits, the control system will calculate the shortest distance from the manipulator to the limits. Defining exact distances between complex shapes is resource intensive and therefore the manipulator representation was simplified to each of its links bounding boxes. This way the distance calculations could be ensured to work in a real time system. Two control methods were implemented for modifying the manipulator joint speeds based on the distance information. Manipulator movements could be slowed down linearly when approaching a limit or alternatively using an artificial potential field function to generate a path towards the target while repelling the manipulator away from the limits.

As an case study the thesis researched defining VWG limits for an RRE that operates close to an train track open for traffic. In this situation the RRE reach should be limited such that no part of it crosses the working gauge limits of the nearby train track. BIM is suitable in this context as defining the exact location of the train track using perception methods is difficult.

Creating and maintaining VWG using the control system developed was deemed possible. For infrastructure elements that are normally expressed as just lines of connected points in current BIMs need to be adjusted by creating bounding volumes around them to be usable in a VWG application. The ways in which the control system modifies the manipulator movements work as desired in the simulation environment. However the manipulator representation as bounding boxes can lead to singularities, where there are multiple options for the location of the shortest distance. Ways of calculating multiple shortest distances along the manipulator bounding boxes need to be utilised to eliminate slight vibrations in the controller desired velocity signal that are caused by singularities when calculating only single shortest distance per bounding box.

Methods for calculating multiple shortest distances per link in the manipulator structure was showcased. One of these methods needs to be implemented to reduce the effect of calculating only one shortest distance has on velocity signal vibrations. Before conclusive analysis the VWG should also be tested on a real excavator to determine how accurate the simulation results were and whether a real system introduces other complications to consider.

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