Autonomous Navigation and 3D Scanning for Legged Robot Inspection of Offshore Structures

A Focus on Rust Detection and Prevention

Robotics Master Thesis

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Electronics and IT

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Contents

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Preface

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Aalborg University, March 24, 2023

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Chapter 1

Introduction

1.1 Corrosion

Corrosion is a major contributor to the structural failure of offshore structures like **oil and gas platforms** as well as **wind farms**.
In fact, the estimated cost of worldwide damage caused by corrosion is a staggering 2.5 trillion US dollars. However, implementing preventive measures like regular inspections can potentially reduce this cost by 15% to 30%.[5]

1.2 Inspection

Conducting inspections of offshore platforms presents a number of challenges, including **risks** to the inspector, **high costs**, and **interference** with routinely operations.
Inspectors first fly on a helicopter and look for large signs of the damages, before boarding the platform for a closer inspection, which can take several days. references from Simon
Past events, such as falls of people and objects, fires, and explosions, underscore the perilous character of offshore platforms and emphasize the necessity for solutions that decrease the personnel count necessary on the platform.[10]

1.3 Remote Inspection

Owners of offshore platforms are gradually utilizing robots for **remote visual inspection** and non-destructive testing. However, these machines are frequently controlled by humans, making them susceptible to human error. Computer vision, on the other hand, can sustain consistent performance over prolonged periods without experiencing fatigue. Nonetheless, such a system necessitates a **mobile base** capable of **autonomous navigation** around the platform with minimal disruption to workers' movements.

1.4 Problem Formulation

This study aims to develop an active vision-based navigation system, for a mobile robot to map and inspect the traversable paths on offshore platforms. The system must carry the equipment to perform an inspection independently.
The fallowing is a formulation of the research question.

How can a land robot use an active vision-based navigation system to explore and perform visual inspection of offshore platforms?

Chapter 2

Related Work

This chapter presents an heuristic view of existing robotic systems that can conduct inspections of offshore platforms. It also covers various topics, including the sensors used in these robots, the mapping representation models, and exploration algorithms.

2.1 Robots

This section shows various types of robots are used to inspect offshore platforms. Understanding the coverage limitations of these diverse types paves a way to establish coverage prerequisites for land-based robots. Moreover, examining the successful cases permits the creation of a system that builds upon prior accomplishments, instead of competing against it.

2.1.1 Legged Robots

Quadruped robots possess the ability to traverse rugged terrain, climb stairs, and maintain stability on platforms that may be swaying due to waves or strong winds. Their small size enables them to maneuver through tight spaces and narrow passages without obstructing the movement of platform workers.

ANYMal X

Swiss company **ANYbotics AG**, specialized in autonomous robotics solutions, partnered with Malaysian oil and gas company **Petronas** to develop **ANYmal X**, depicted in Figure2.1.
In March of 2022, the two companies signed an agreement to bring ANYmal X to market.[2]

ANYmal X is a robot designed for inspection of offshore oil and gas platforms. It is certified to operate in potentially explosive environments and has several capabilities, including the ability to read analog measurement instruments, determine lever positions, identify heat sources, analyze equipment vibrations, and perform gas detection.[2]
Additionally, ANYmal X is capable of 3D scanning using a **Puck** (Velodyne) LiDAR sensor and visual inspection.[2]

Figure 2.1: ANYmal X[2]

ANYbotics has not publicly disclosed the algorithm used in ANYmal X, but they have mentioned that their research partners published six papers at ICRA/RA-L 2020[1]. One of these papers details a **LiDAR Simultaneous Localization and Mapping** (LiDAR-SLAM) algorithm that leverages deep learning for loop closure. This algorithm is based on the concept of Autotuned Iterative Closest Point (AICP) and has been specifically designed for industrial environments. The researchers preferred to use LiDAR-SLAM over Visual-SLAM, because they believe it to be more resistant to variations in the light conditions[15].

Spot

In 2020, **BP** deployed Boston Dynamics **Spot**, another quadruped robot, to the Mad Dog oil rig for evaluation as an autonomous inspector. Spot demonstrated positive interaction with platform workers, prompting BP to explore its potential for tasks such as gauge checks, abnormality scanning, and corrosion tracking. However, no information regarding the outcome of the project has been found.[9]

Spot is equipped with five **active stereo cameras** capable of producing grey and depth images with an operational range of up to 4 meters. Two of the cameras are located in front, one on each side, and another on the back. The design of the cameras is similar to the Intel RealSense models, although specific information about the cameras has not been disclosed.[7]
Spot can be seen in Figure3.1.

Figure 2.2: Spot[9]

Notice that even though ANYmal X is sold with much more sensors than Spot, but the latter is approximately 75.000 US dollars less expensive.[14]

2.1.2 Crawler Robots

Eddyfi Technologies produce the **VersaTrax 320** and **Magg 480**, shown in Figure**??**. The robots can reportedly perform visual inspection on the interior of pipes and large vertical surfaces of offshore platforms. They can reach places inaccessible to most quadruped robots, but they are limited to speeds around 0.54Km/h.[18] Therefore, it is preferred that they are only used as complementary solution.

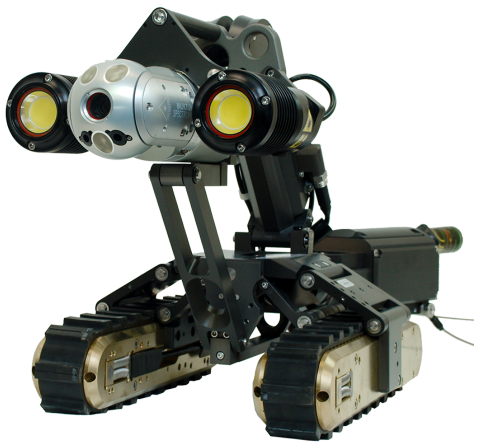

Figure 2.3: VersaTrax 320, designed to operate in pipes[18]

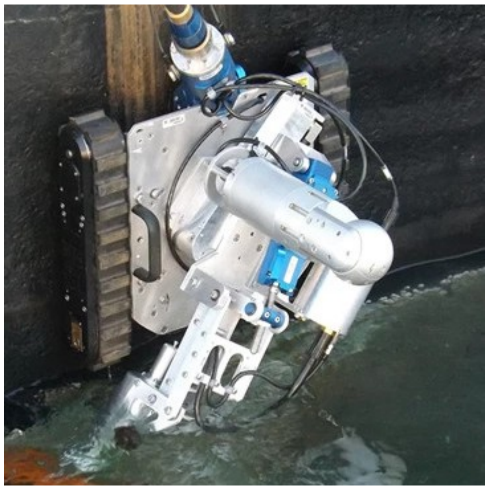

Figure 2.4: Magg 480, design to operate in vertical surfaces, by using a magnet on the base.[18]

2.1.3 Other Inspection Robots

Unmanned Aerial Vehicles (UAV) and **Underwater Unmanned Vehicles** (UUV), such has the ones shown in Figure2.5, have been used for visual inspection in offshore platforms[6][4]. However, for safety and logistic reasons, their workspace is outside of the workers traversable regions.
As the robots described in 2.1.2, these might complement the inspection performed by the other types of robot. More, UAVs remove the need for quadruped robots to inspect areas near to the edge of the platform, preventing the risk of fall.

Figure 2.5: Matrice 300 RTK [6] and Blueye X3 ROV[4]

2.1.4 Summary

A LiDAR-equipped Spot robot has the potential to conduct visual inspections in the traversable regions of offshore platforms. Such system can use LiDAR-SLAM to map and inspect traversable areas, while avoiding regions near the edges of the platform.

A multi-robot system can be implemented in future iterations of the project, to improve inspection coverage, but a single Spot would still be preferred in the traversable regions.

2.2 Sensors

This section analyses sensors that can potentially be used to perform a visual inspection with Spot. These include cameras and LiDARs.

2.2.1 Cameras

Cameras can be used for both visual inspection and SLAM, but [15] do not recommend the use for the latter.

3D cameras

Active stereo cameras project light patterns onto the surfaces, then estimate depth by identifying the pixel disparity between the features found in the images of two cameras, with known positions relative to each other. These are the type of cameras found on Spot.
Time-of-flight (ToF) cameras are capable of estimating depth, by measuring the time that light takes to travel from the camera to the object and back.

Visible Light Cameras

Both **Grey-scale** and **RGB** cameras can be used for visual inspection, object recognition, and **visual-SLAM**. However, their usefulness is limited in low-light conditions or when dealing with transparent or reflective surfaces.[15]

Non-Visible Light Cameras

Infra Red(IR) cameras are useful to detect temperature variations, normally found in faulty electrical equipment, as well as gas leaks. Ultraviolet (UV) cameras are commonly used for inspecting cracks and corrosion on metal structures.**??**

2.2.2 Light Detection and Ranging (LiDAR)

A LiDAR employs rotating lasers to measure distances. Multi-channel LiDARs use an array of lasers displayed along the axis of rotation, producing a radial 3-dimensional representation of the environment.

get the price difference

Figure2.6 shows the 16 channels **Velodyne Puck**, used in the ANYmal and the the 32 channels **Ouster OS1**.

Figure 2.6: Ouster OS1 and Velodyne Puck

2.2.3 Summary

A **Ouster OS1** can be mounted on Spot to perform SLAM. Spot's cameras can feed depth data, but the LiDAR must be the main source of depth information.

In a future version of the project, a camera capable of capturing colors beyond the visible light spectrum may be considered. However, since the project's main focus is on navigation, Spot's gray-scale cameras are deemed adequate for conducting visual inspections.

2.3 Active Simultaneous Localization and Mapping (ASLAM)

ASLAM provides robots with the ability to explore unfamiliar environments and generate a map in real-time. To ensure the system operates efficiently in real-time, depth information must be effectively managed in a compact map of the environment.
The upcoming section will outline various map representations suitable for mapping offshore platforms. It will then delve into exploration algorithms that could be well-suited for this undertaking.

2.3.1 Map Representation

The following section provides a sample of commonly used map types, with a focus on their relevance for Spot's navigation capabilities in a multi-floor environment.

Grids and Voxel Maps

Grids maps are 2D maps composed of labeled cells. The simples ones are **occupancy grids**, where each cell indicating whether an area is unexplored; occupied or not. **Voxel grids**, apply the same principle to the 3D space, where each cell is volumetric structure called **voxel**. These concepts are depicted in Figure2.7.[13]

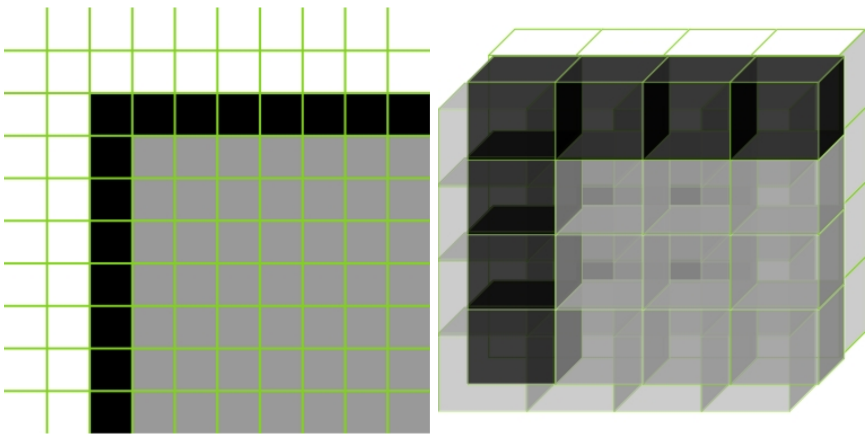

Figure 2.7: Occupancy grid (2D) and voxel map (3D). White: unexplored; black: occupied; grey: free

OctoMaps

Building on the concepts of grid and voxel maps, **adaptive cell decomposition** is a technique conserves resources by optimizing the number of representative cells cells.
Figure**??** shows an example in 2D. Here the image is divided into four equal cells. Then, any partially occupied cell is further divided into four smaller cells, and so on.[13]
OctoMaps apply this principle to 3D. Voxels are incrementally divided into eight smaller cells, until a pre-defined resolution. By reducing the number of cells in the map, this technique increases computational efficiency of 3D search algorithms and reduced memory usage.
According to [11] octoMaps are among the most widely used map representations for **ASLAM**.

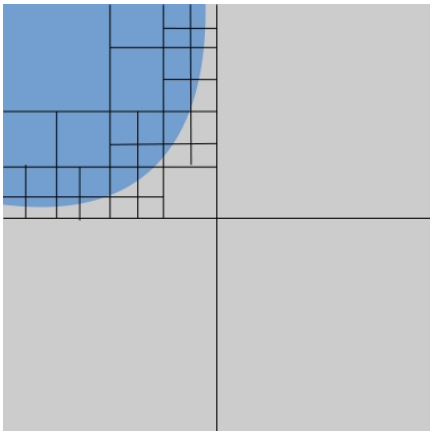

Figure 2.8: Adaptive cell decomposition

Signed Distance Fields (SDF)

Euclidean Signed Distance Fields (ESDF) label grid cells with the minimum distance between the cell and the nearest occupied surface. The sign has a positive or negative value in respect to whether or not it is inside the structure. ESDFs can be either 2D or 3D.
Truncated Signed Distance Fields (TSDF) are ESDFs that do not label cells about a given threshold. When compared to octomaps, TSDFs demonstrate superior suitability for ASLAM by effectively reducing noise and computational demands. In addition to these benefits, TSDFs can also produce meshes with a resolution that surpasses the voxel[12].

Depth Maps

Depth maps are 2D images where each pixel or cell is assigned a depth value. They are commonly obtained as the output of stereo cameras.
Height maps are similar to depth maps, but the cell value is the height of a portion of the surface, as shown in Figure2.9.

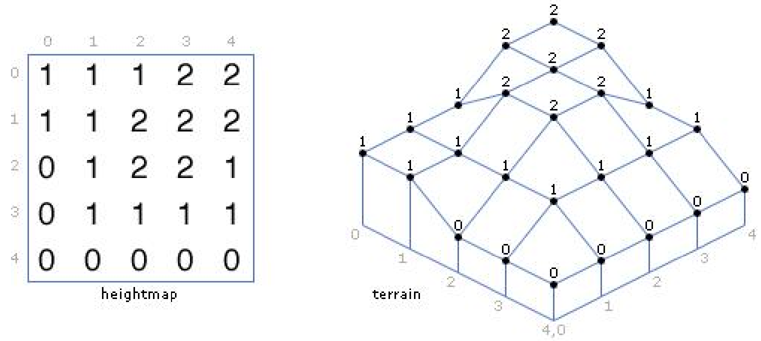

Figure 2.9: Height map[16]

maybe get a image from the project

Multi-Level Surface (MSL) Maps

MSL Maps are used to model multi-floor environments. These maps consist of a set of 2D floor plans stacked on top of each other to form a 3D model of the building. Each floor plan represents the layout of a particular floor and contains information about the location and dimensions of walls, doors, and other obstacles.

MSL maps also include information about the vertical connections between floors, such as stairs and elevators. This allows the robot to plan and execute multi-floor navigation tasks, such as traveling between floors and locating objects on different levels.

In addition, MSL maps can be used to represent dynamic environments by updating the map in real-time as the robot navigates through the space and detects changes. This enables the robot to adapt to changes in the environment and continue navigating effectively.

Topological Map

Topological maps represent the environment as a graph, where nodes represent locations, and topics represent the connections between them. **Topological metric maps** also include the length of the topics[13]. This representation is suitable for environments with clear landmarks and structured connectivity. However, it may not perform well in unstructured environments or when accurate positioning is required.

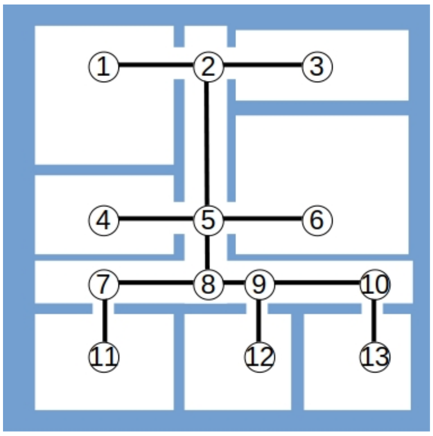

Figure 2.10: Topological map. Nodes are represented by numbered circles and topics are represented by black lines

2.3.2 Exploration algorithms

Coverage Path Planning (CPP) is a type of algorithms design to navigate a robot and perform field exploration in an optimal way. Chee Sheng Tan et al.[17] enumerates 5 problems that CPP aims to solve: coverage completeness; path overlap rate; number of turns; travel time and energy consumption.

The corrosion inspection task prioritizes **completeness**, fallowed by path length, as a longer path potentially increases the number of encounters with platform workers. The same reason can be used to argue against a multi-robot system, even though the task could be completed in a shorter period of time. Hence, a **single robot** is preferred.[17]

As the robot must search for previously absent corrosion, the task requires an **online** CPP algorithm.

According to Chee Sheng Tan et al. [17], reinforcement learning (RL) algorithms are still too immature for dynamic environments.

In this method, the environment is divided into a grid and the robot systematically explores each cell. It is more efficient than random exploration but may not be suitable for environments with complex and irregular shapes.

search for exploration with a spot

2.4 Final Problem Formulation

While visual inspection is still a significant part of offshore inspection, current robotic methods either lack autonomy or focus on traversing the map with no greater regards for what might be behind the objects of interest.
Corrosion tends to propagate on the surface, therefore it is imperative to com-

pletely assert the full extent of the problem once it is detected.
In this line of thought, the project will attempt to answer the question.

How to combine active vision with ASLAM to enable continuous inspection of corrosion in the traversable path of an offshore platform?

Chapter 3

Methodology

Methodology: This section should describe the research design, data collection and analysis methods, and any ethical considerations.

3.1 System Overview

This chapter presents an overview of the development of an active vision-based navigation system which employs a Spot robot, coupled with a Ouster-OS1 LiDAR, to autonomously explore offshore environments. The system building up on the various algorithms presented on 2.3, in an attempt to perform the fallowing:

- Switch between autonomous and manual navigation mode
- ASLAM: frontier exploration while mapping
- Active-vision: attempt to fully scan a corrosion affected surface
- Exploit map: load a previously defined map and navigate to targets
- Test fake rust target: using AprilTags
- Identify and localize corrosion (optional): use a instance segmentation algorithm (possibly yolact)

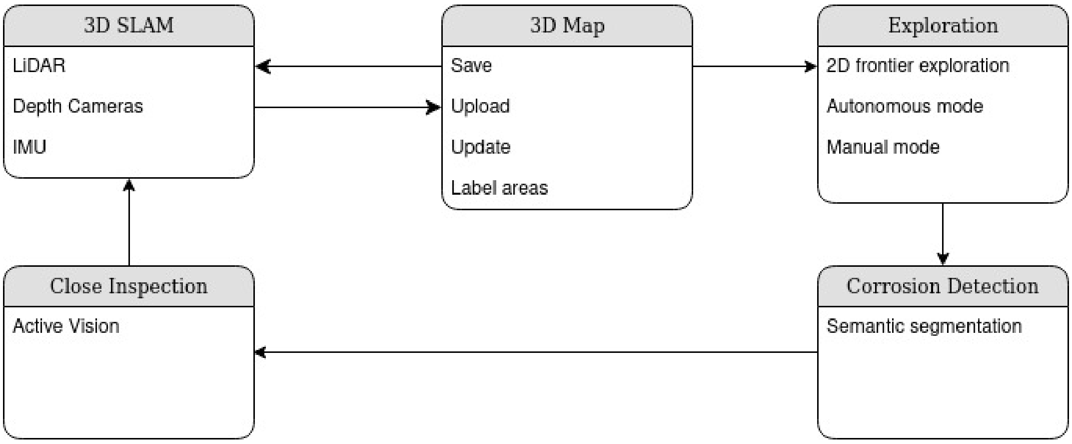

Figure 3.1: System flow chart

3.1.1 Delimitations

v This section discusses the delimitations of the system, doing so will help narrow the scope of the project and manage expectations. Notice that the system is intended to showcase a set of features aimed to integrate a larger system.

Will not identity corrosion

The project focus on navigation, as such, corrosion detection can be replaced by other type of visual detection, as long as the target location can be identified.

The system will not be tested in an offshore environment

The system will be tested in a onshore structures.

The tests will be done in favorable weather conditions

not sure about this one yet

3.1.2 System requirements

Must be able to save a 3D map with complete coverage of the walk-able path

make it quantitative

Must be able to change between manual and autonomous exploration

make it quantitative

Must be able to stop with the emergency button

make it quantitative

Must not fall of the edges or bump into obstacles

make it quantitative

Must be able to navigate a given map

make it quantitative

Must be able to detect targets location accurately

make it quantitative

Must be able to perform active vision on target

make it quantitative

3.2 Software

3.2.1 Framework

ROS2 is an open-source robotics framework that provides a standardized way for different software modules to communicate with each other. The use of ROS2 allows for modular development and simplifies the integration of different hardware components into the system.

ANYmal X has undergone rigorous field trials with ROS [3]. Despite Boston Dynamics' lack of official support for ROS2[8], several ROS2 packages have been developed for Spot by some of the parties involved in its creation. ref

As this project uses both a Spot and a LiDAR, ROS2 is the elected framework. Furthermore, future iterations of the project may use other sensors or even, a multi-robot integration. As such ROS2 paves the way for a multi-field inspection endeavor.

3.2.2 Simulation

Isaac Sim is a robot simulation tool developed by NVIDIA. In comparison to Gazebo, V-REP, Unity and Webots, Isaac Sim provides a more advanced physics engine, advanced rendering capabilities.

One of the key benefits of Isaac Sim is its tight integration with NVIDIA platform and deep learning frameworks such as PyTorch and TensorFlow. This integration allows developers to test and optimize machine learning algorithms in a simulated environment before deploying them to the real world.

Overall, Isaac Sim offers a powerful and flexible simulation environment for robotics development. Its advanced features and tight integration with deep learning frameworks make it an excellent choice for developing and testing complex robotics systems.

One major advantage of Isaac Sim is its physics engine, which is based on NVIDIA's PhysX technology. This engine provides highly realistic physics simulations, allowing developers to test their algorithms in complex and dynamic environments.

Another key feature of Isaac Sim is its support for advanced rendering techniques, including ray tracing and global illumination. This allows for highly realistic visual simulations, which can be useful for tasks such as training machine learning models.

Additionally, Isaac Sim provides support for a variety of sensors commonly used in robotics applications, including cameras, LIDAR, and IMUs. This makes it easy to test and develop algorithms that rely on sensor data.

Overall, while there are many simulation engines available for robotics development, Isaac Sim stands out for its advanced physics and rendering capabilities, as well as its support for a wide range of sensors.

3.2.3 AprilTag

Chapter 4

Results

Results: This section should present the results of your research, including any statistical analyses or visualizations.

4.1 Testing

Chapter 5

Discussion

Discussion: This section should interpret your results, explain their significance, and relate them to your research question and objectives.

Chapter 6

Conclusion

Conclusion: This section should summarize your main findings, draw conclusions, and suggest directions for future research.

Bibliography

[1] Anybotics. *ANYmal, a Cutting-Edge Legged Robot Platform to Advance Robotics Research*. URL: https://www.anybotics.com/advancing-legged-robotics-research/. (accessed: 15.02.2023).

[2] Anybotics. *ANYmal X — The World's First Ex-Proof Legged Robot*. URL: https://www.anybotics.com/anymal-x-the-worlds-first-ex-proof-legged-robot/. (accessed: 15.02.2023).

[3] Anybotics. *Meet ANYmal, your new inspector*. URL: https://www.anybotics.com/anymal-autonomous-legged-robot/. (accessed: 15.02.2023).

[4] Blueye. *Offshore oil & gas*. URL: https://www.blueyerobotics.com/industries/offshore-oil-and-gas. (accessed: 22.02.2023).

[5] Robert Brijder et al. "Review of corrosion monitoring and prognostics in offshore wind turbine structures: Current status and feasible approaches". In: *Frontiers in Energy Research* 10 (2022). ISSN: 2296-598X. DOI: 10.3389/fenrg.2022.991343. URL: https://www.frontiersin.org/articles/10.3389/fenrg.2022.991343.

[6] DKI. *MATRICE 300 RTK*. URL: https://www.dji.com/matrice-300. (accessed: 24.02.2023).

[7] Boston Dynamics. *About Spot*. URL: https://dev.bostondynamics.com/docs/concepts/about_spot.html?highlight=cameras. (accessed: 15.02.2023).

[8] Boston Dynamics. *FAQ: Does Spot run ROS (Robot Operating System)?* URL: https://support.bostondynamics.com/s/article/Does-Spot-run-ROS. (accessed: 22.02.2023).

[9] Boston Dynamics. *The vision*. URL: https://www.bostondynamics.com/resources/case-study/bp. (accessed: 15.02.2023).

[10] Maritime Injury Guide. *The Dangers of Offshore Oil Rigs*. URL: https://www.maritimeinjuryguide.org/blog/dangers-offshore-oil-rigs/. (accessed: 10.02.2023).

[11] Andréa Macario Barros et al. "A Comprehensive Survey of Visual SLAM Algorithms". In: *Robotics* (2022). URL: https://www.mdpi.com/2218-6581/11/1/24.

[12] Helen Oleynikova et al. "Voxblox: Incremental 3D Euclidean Signed Distance Fields for on-board MAV planning". In: (2017).

[13] Terry Payne. *Robotics and Autonomous Systems - Lecture 7: Maps and mapping (2017)*. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwifn_WRzcz9AhWwZ_EDHRjLBMgQFnoECAwQAQ&url=https%3A%2F%2Fwww.csc.liv.ac.uk%2F~trp%2FCOMP329_files%2FCOMP329%2520Maps%2520and%2520Mapping%2520%25287%2529%25202018.pdf.pdf&usg=AOvVaw0yHnspp1VFumcn3jtAUXwC. 2017.

[14] Magdalena Petrova. *Where four-legged robot dogs are finding work in a tight labor market*. URL: https://www.cnbc.com/2021/12/26/robotic-dogs-taking-on-jobs-in-security-inspection-and-public-safety-.html. (accessed: 15.02.2023).

[15] Milad Ramezani et al. "Online LiDAR-SLAM for Legged Robots with Robust Registration and Deep-Learned Loop Closure". In: (2020), pp. 4158–4164. DOI: 10.1109/ICRA40945.2020.9196769.

[16] Robot-Frog. *Terrain Generation Tutorial: Heightmaps*. URL: https://www.stuffwithstuff.com/robot-frog/3d/hills/heightmaps.html. (accessed: 10.03.2023).

[17] Chee Sheng Tan, Rosmiwati Mohd-Mokhtar, and Mohd Rizal Arshad. "A Comprehensive Review of Coverage Path Planning in Robotics Using Classical and Heuristic Algorithms". In: *IEEE Access* (2021). DOI: 10.1109/ACCESS.2021.3108177.

[18] Eddyfi Technologies. *Eddyfi Technologies*. URL: https://www.eddyfi.com. (accessed: 22.02.2023).

Appendix A

Appendix A name

Here is the first appendix