DAVID RAZHIEL CERES ARROYO

TASK ALLOCATION AND SENSOR FUSION LOCALIZATION FOR AUTONOMOUS SYSTEMS

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A Multi-Tool Allocation Approach for Optimized Weed Removal in Autonomous Agriculture

June 2025 – classicthesis v4.8

Ohana means family.
Family means nobody gets left behind, or forgotten.

— Lilo & Stitch

Dedicated to the loving memory of Rudolf Miede.

1939 – 2005

ABSTRACT

Short summary of the contents in English... a great guide by Kent Beck how to write good abstracts can be found here:

https://plg.uwaterloo.ca/~migod/research/beck00PSLA.html

ZUSAMMENFASSUNG

Kurze Zusammenfassung des Inhaltes in deutscher Sprache...

PUBLICATIONS

This might come in handy for PhD theses: some ideas and figures have appeared previously in the following publications:

This is just an example.

[1] Tobias Isenberg, André Miede, and Sheelagh Carpendale. "A Buffer Framework for Supporting Responsive Interaction in Information Visualization Interfaces." In: *Proceedings of the Fourth International Conference on Creating, Connecting, and Collaborating through Computing (C^5 2006)*. IEEE, 2006, pp. 262–269. ISBN: 978-0-7695-2563-1.

[2] Ulrich Lampe, Markus Kieselmann, André Miede, Sebastian Zöller, and Ralf Steinmetz. "A Tale of Millis and Nanos: On the Accuracy of Time Measurements in Virtual Machines." In: *Proceedings of the Second European Conference on Service-Oriented and Cloud Computing (ESOCC 2013)*. Springer, 2013, pp. 172–179. ISBN: 978-3-642-40650-8.

[3] Ulrich Lampe, Qiong Wu, Ronny Hans, André Miede, and Ralf Steinmetz. "To Frag Or To Be Fragged – An Empirical Assessment of Latency in Cloud Gaming." In: *Proceedings of the Third International Conference on Cloud Computing and Services Science (CLOSER 2013)*. 2013, pp. 5–12. ISBN: 978-898-8565-52-5.

[4] André Miede. "Theses and other Beautiful Documents with `classicthesis`." In: *TUGboat – The Communications of the TEX Users Group* 31.1 (2010), pp. 18–20. ISSN: 0896-3207.

[5] André Miede, Gökhan Şimşek, Stefan Schulte, Daniel F. Abawi, Julian Eckert, and Ralf Steinmetz. "Revealing Business Relationships – Eavesdropping Cross-organizational Collaboration in the Internet of Services." In: *Proceedings of the Tenth International Conference Wirtschaftsinformatik (WI 2011)*. Vol. 2. 2011, pp. 1083–1092. ISBN: 978-1-4467-9236-0.

[6] Hsin-Yi Tsai, Melanie Siebenhaar, André Miede, Yu-Lun Huang, and Ralf Steinmetz. "Threat as a Service? Virtualization's Impact on Cloud Security." In: *IEEE IT Professional* 14.1 (2012), pp. 32–37. ISSN: 1520-9202.

Attention: This requires a separate run of `bibtex` for your `refsection`, e. g., `ClassicThesis1-blx` for this file. You might also use `biber` as the backend for `biblatex`. See also `http://tex.stackexchange.com/questions/128196/problem-with-refsection`.

We have seen that computer programming is an art,
because it applies accumulated knowledge to the world,
because it requires skill and ingenuity, and especially
because it produces objects of beauty.

— Donald E. Knuth [6]

ACKNOWLEDGMENTS

Put your acknowledgments here.

Many thanks to everybody who already sent me a postcard!

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Regarding LyX: The LyX port was intially done by *Nicholas Mariette* in March 2009 and continued by *Ivo Pletikosić* in 2011. Thank you very much for your work and for the contributions to the original style.

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LISTINGS

ACRONYMS

TA Task Allocation

SVCA Shapley Value Clustering Algorithm

CBDTA Consensus-Based Distributed Task Allocation Algorithm

VDKM Voronoi Diagram-Based, K-Means Algorithm

CBBA Consensus-Based Bundle Algorithm

CBPAEA Consensus Based Parallel Auction and Execution Algorithm

GRU Gated Recurrent Units

MLP Multi-Layer Perceptron

EDACAM Encoder Decoder Architecture with Cross Attention Mechanism

GNN Graph Neural Network

CNN Convolutional Neural Network

PSO Particle Swarm Optimization Algorithm

GTODT Group Theory and Optimization Duality Theory

MIQP Mixed-Integer Quadratic Program

GA Genetic Algorithm

COQP Constraint Optimization as Quadratic Program

DEMP Diferential Evolution for Multimodal Problems

IT Implement Tool

DOF Degrees of Freedom

URDF Unified Robot Description Format

SDF Simulation Description Format

Part I

BUILDING THE TOOLS

1 INTRODUCTION

1.1 BACKGROUND AND CONTEXT

Autonomous systems are complex agents capable of carrying out operations without human intervention. They have become more capable thanks to technological advancements and increasingly integrated into society with recent remarkable progress in artificial intelligence (AI) techniques. According to Zhang in [14], current trends indicate that the development and adoption of such systems will continue to grow in the coming years.

The agricultural sector is one of the areas where the integration of autonomous technologies has great potential. These systems could significantly benefit farmers by making their work safer and less repetitive. Autonomous systems have already been used in alternative cropping methods such as precision agriculture. Nevertheless, traditional practices are still facing challenges that autonomous systems could perfectly address. Among these challenges, the proliferation of weeds in grass fields raises as a major concern for the livestock well-being for two main reasons. First, weeds compete with grass for resources, reducing the quality of food available for grazing animals. Second, some weed species pose a direct threat to livestock health. In particular, plants like Rumex have been identified as toxic and the cause of livestock poisoning [11].

Removing these plants is a task that farmers must perform manually, as EU regulations restrict the use of pesticides and prevent farmers from combating weed proliferation through chemical means. It is evident that this task, especially in large grass fields, is highly time-consuming and extremely repetitive, making it an ideal candidate for automation. In Germany, companies like Paltech have developed solutions to address this problem using autonomous wheeled robots. Their flagship robot is a differential-drive wheeled system equipped with various sensors for localization and weed detection, as well as an onboard drilling mechanism for weed removal. Currently, if the weed removal process needs to be sped up, the only solution is to deploy a fleet of robots. While this is feasible, developing single units capable of holding more than one drilling mechanism seems like the natural next step in Paltech's solution.

1.2 PROBLEM STATEMENT

The development of systems with more than one drilling unit for weed removal comes with both hardware and software challenges. It is crucial to ensure that tools and system resources are used as efficiently as possible. We want to avoid having more capable units with unused tools, especially since the production and deployment of these improved systems are more costly. Therefore, reducing idle time is a top priority and the focus of this thesis.

Idle time refers to periods when resources, such as drilling equipment, are not actively engaged in productive work. Reducing idle time in this context means minimizing the time tools remain unused and maximizing their productivity in weed removal. To achieve this, allocating detected plants to the correct tools is essential. In the literature, this process is known as TA. Some technical challenges to consider during implementation include computational latency and multi-tool coordination. The TA algorithm and execution pipeline must be fast enough to process new detections and reassign tools in real time without causing delays, while also ensuring that multiple drilling units operate efficiently without interference or redundancy.

1.3 CURRENT SOLUTIONS

In general, a task allocation system aims to achieve an efficient assignment of tasks to robots (or tools in this case) by considering various characteristics such as the robots' capabilities, task requirements, and system efficiency. This process of task allocation involves three important factors to be consider acording to Umashankar in [4]. Robot/tool, environment and coordination as shown in Figure 1.1.

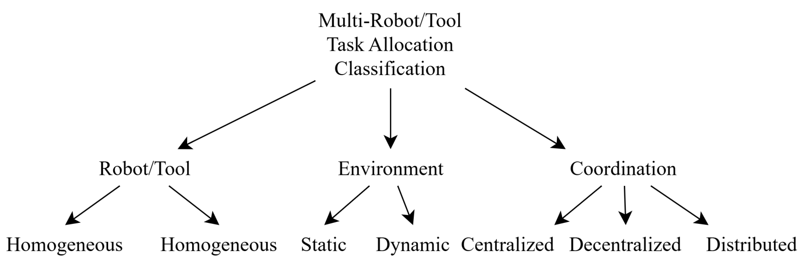


Figure 1.1: Multi-robot task allocation classification. Source [4]

An example of homogeneous tools in this context is a robot equipped with multiple tools of the same type, such as drills. In contrast, heterogeneous tools refer to robots equipped with different types of tools, such as drilling, seeding, and sensing equipment.

The multi-tool task allocation can take place in either a dynamic or static environment. In an environment that is static in nature, tasks are allocated to tools in advance before they begin to execute them. This method works well in situations when the tasks are predetermined and the environment remains unchanged. In contrast, dynamic task allocation involves the real-time assignment of tasks to tools as they carry out their activities. For the scope of this thesis, we will focus on homogeneous tools operating in a dynamic environment with centralized coordination, where the onboard computer will act as the master, assigning plants to each drilling mechanism.

There are several ways to accomplish multi-tool allocation, including heuristic, cluster-based, market-based, learning-based, and optimization-based techniques. Table 1.1 and 1.2 presents a comprehensive classification of task allocation algorithms found in the literature.

APPROACH	TECHNIQUE/ALGORITHM
Cluster Based	SVCA [10]
	Group Agent Partitioning [3]
	CBDTA [1]
	VDKM [5]
	CBBA [12]
	Cluster First Consensus-Based Strategy
	K-Means Clustering
Market Based	Auction Algorithm [7]
	Improved Auction Algorithm [13]
	Extended Auction Algorithm
	Distributed Auction Algorithm
	Sequential Single-Item Auctions
	Auction-Based Algorithm
	Multihop-Based auction Algorithm
	Based on Sequential Single Item Auctions
	CBPAEA
	Extended Sequential Single Item Auction
	Distributed Auction-Based Algorithm
	The Consensus-Based Bundle Algorithm
	Linear Integer Programming
	Contract Net Protocol

Table 1.1: Comparative overview of cluster-based and market-based approaches to multi-agent TA. [4]

In cluster-based approaches, the goal is to group tasks into a predefined number of clusters. Instead of assigning a single task to each tool, the clustering approach allocates entire groups of tasks to them, reducing the number of individual task assignments and computational

APPROACH	TECHNIQUE / ALGORITHM
Learning Based	GRU, MLP [9]
	Deep Reinforcement Learning [2]
	Heterogeneous Graph Attention Network
	Capsule Attention-Based Mechanism
	EDACAM
	Graph Neural Network (GNN)
	Q-Learning, CNN and a GRU
	Graph Convolutional Neural Networks
Optimization Based	Mixed-Integer Quadratic Program
	Centralized Hungarian Method [8]
	Bin Maximum Item Doubled Packing
	PSO
	GTODT
	Integer Programming
	MIQP
	Genetic Algorithm (GA), A* Algorithm
	COQP
	Heuristic Based
	DEMP
	Fuzzy Optimization

Table 1.2: Comparative overview of learning-based and optimization-based approaches to multi-agent TA. [4]

complexity. Clustering approaches aim to minimize travel distance and maximize task coverage by grouping tasks effectively. However, the optimal clustering of tasks still needs further exploration. Although these approaches simplify task allocation, they struggle to handle dynamic changes in the environment.

An optimization-based strategy aims to select the best solution from a set of available options. These solutions are constrained by specific conditions, and the optimal one is determined based on the objective function. The objective function represents the system's ultimate goal. Some of the optimization algorithms have poor robustness to uncertainties therefore this approach is more suitable for solving well-defined and static problems focusing on theoretically optimal or near-optimal solutions. Additionally, optimization-based approaches require more computational power and are less adaptable to changing environments.

Market-based approaches effectively handle highly combinatorial optimization problems. In this method, an auctioneer informs agents about available tasks and requests bids. Each agent evaluates its capacity to complete the tasks and submits a bid accordingly. The auctioneer then assigns tasks to the agent with the most favorable bid. Generally, task allocation using this approach minimizes travel time. While these methods are flexible and scalable, they may not always achieve a globally optimal solution.

Recent approaches to task allocation incorporate deep learning techniques such as graph neural networks and graph convolutional networks. These types of task allocation methods are commonly referred as learning-based approaches. Most learning-based approaches struggle to generalize to larger-scale problem scenarios beyond those used during training. This characteristic is especially important because real-world task allocation problems frequently require modeling scenarios whose costs increase with the number of tasks and robots. Table 1.3 gives a comparison between all the approaches.

	Clustering	**Optimization**	**Market-Based**	**Learning-Based**
Advantage	Simplifies task allocation and reduces complexity	Provides optimal solutions, well suited for static problems	Flexible, scalable, decentralized	Adaptable, learns, and improves over time
Limitation	May not account for dynamics well	Computationally intensive, less adaptable	May not yield global optima, and needs effective bidding	Requires training time, initially sub-optimal
Best case	Logical tasks	Well-defined, static problems	Dynamic environments with varying tasks	Complex and uncertain environments
Future work	Dynamic clustering, online adaptation	Hybrid models, real-time optimization	Adaptive market mechanisms, incentive models	Transfer learning, meta-learning

Table 1.3: A Comparison of different approaches to TA, Source [4]

1.4 PROPOSED SOLUTION

As Table 1.3 illustrates, algorithm selection must be carefully considered based on the application's nature to achieve optimal performance. In a grass field clearing application, the environment is highly dynamic, especially since weed detections occur while the system is in motion. Therefore, market-based approaches are well-suited to ensuring the system adapts effectively to such conditions. However, since weeds often spread in clustered areas, a cluster-based approach could help reduce the algorithm's computational load and improve real-time responsiveness.

A hybrid algorithm is proposed to tackle the dynamics of the environment and leverage the benefits of both market-based and cluster-based approaches. By combining real-time adaptability with efficient task grouping, the system can dynamically allocate tasks while minimizing computational overhead. This approach ensures that weed removal remains efficient even as new detections occur, ultimately improving performance in large-scale and rapidly changing field conditions.

2

SIMULATION

2.1 THE ROBOT

Nuga is Paltech's solution for speeding up the weed removal process. Nuga is a mobile platform equipped with two drilling mechanisms, also called IT, one main camera at the front for plant detection, two internal cameras for fine adjustment during tools' placement, an IMU, and two GNSS antennas for GPS localization. Each IT is mounted on a structure with three Degrees of Freedom (DOF) using prismatic joints, allowing movement in X, Y, and Z directions.

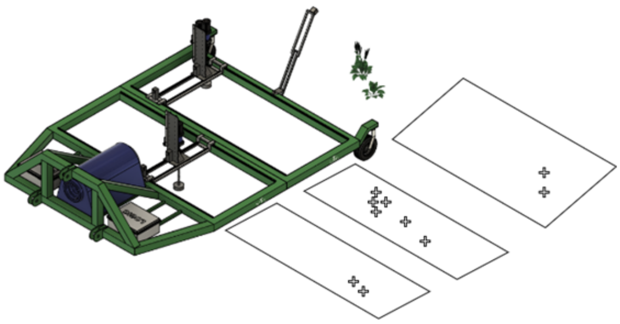


Figure 2.1: Nuga Platform

2.2 SIMULATION

A representative simulation of reality is crucial for developing new algorithms and analyzing robot behavior before real-world implementation. Therefore, building a simulation of the project was a foundational step for this work, ensuring a controlled environment for validation and testing. Gazebo[1] was the selected tool because it provides a physics engine, supports sensor and actuator modeling, and integrates well with ROS[2], making it ideal for testing robotic systems.

The simulation consists of six key components: URDF files define the robot's structure and properties, SDF files describe the virtual environment, and Gazebo plugins provide additional functionality, such as simulating custom sensors, actuators, or control interfaces.

1 Gazebo is a physics-based robotics simulation tool that allows testing and validation of robot models before real-world deployment. https://gazebosim.org/home

2 ROS (Robot Operating System) is an open-source framework that provides tools, libraries, and conventions for developing, managing, and simulating robotic applications. https://www.ros.org/

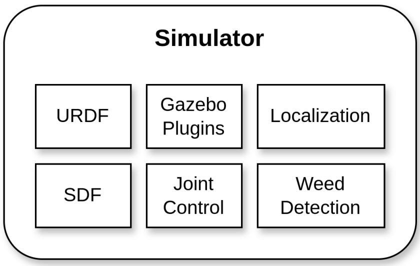


Figure 2.2: Simulator Components

Additionally, core system operations include joint control for managing the movement of the IT, localization for tracking the robot's position, and weed detection, which relies on an AI model for Rumex recognition. Figure 2.2 illustrates these components as building blocks for the simulation.

2.2.1 *URDF*

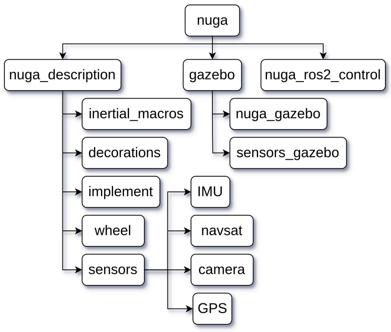
Unified Robot Description Format (URDF) is an XML file used to describe multibody systems for robot simulation. It defines the visual, collision, and inertial properties of rigid body objects, as well as their connections (*joints*). This establishes a spatial relationship between frames, which ROS and Gazebo can later interpret for control and visualization. This file also allows modeling different types of sensors and incorporating Gazebo plugins to link it with ROS control actions. We exploit these capabilities to define camera intrinsics, IMU behavior, GPS properties, and control the IT using `ros2_control`[3].

Figure 2.3a displays the structure of the URDF files, being nuga the highest level entity that joins the robot description, gazebo sensor modeling and plugins, as well as `ros2_control` configuration. Nuga description defines the robot's physical structure, including its links (e.g., chassis, wheels, camera support), joints (fixed, continuous, prismatic connections), sensors (cameras, IMU, GPS), and inertial properties. It organizes these components into a kinematic tree (e.g., base_link -> chassis_link -> wheels/sensors) using macros for modularity, and resulting in the model displayed in Figure 2.3b.

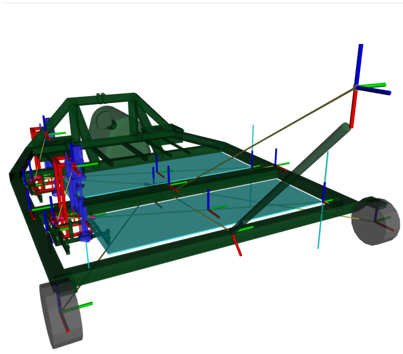
2.2.2 *SDF*

Simulation Description Format (SDF) also written in XML, describes the properties of the virtual world. Gazebo uses this file to define the terrain, obstacles, lighting conditions, physics parameters, and other

3 `ros2_control` is a ROS 2 framework that provides a standardized interface for managing hardware, enabling modular and reusable control systems for robots. https://control.ros.org/rolling/doc/getting_started/getting_started.html



(a) URDF files structure.



(b) RViz visualization of Nuga description.

Figure 2.3: Robot definition using URDF

environmental elements that affect the robot's interaction with the simulation. Having repeatability in a simulated world is important for debuging and testing purposes, for this reason a Python script was used to generate easy to configure worlds from a YAML configuration file. An example of the config file is shown in Listing A.1. For reproducibility, a seed value is configured in the simulation settings, the weed infestation pattern is defined within quadrants of specified dimensions (`quadrant_size`) and each quadrant is individually configured with:

- Spatial distribution:
  - *uniform*: Random uniform distribution
  - *clustered*: Random normal distribution with definable standard deviations (σ_x, σ_y)
- Weed density: Weeds per square meter (weeds/m^2)
- Direction: Propagation axis for adjacent quadrants ($\pm x, \pm y$)
- Workspace expansion: If `outside_workspace` is true, the infestation area extends 10% beyond the quadrant boundaries.

A visual result of the generated world using such configuration file is shown in Figure 2.4.

2.2.3 *Gazebo Plugins*

The files `nuga_gazebo` and `sensors_gazebo` from Figure 2.3a instantiate and configure Gazebo plugins to define sensor behavior, including optical properties for the camera, as well as update rates and noise models for the IMU and GPS. The file `nuga_ros2_control` on the other hand, establishes an interface between the IT 's joints and

Figure 2.4: Weed Infestation Example

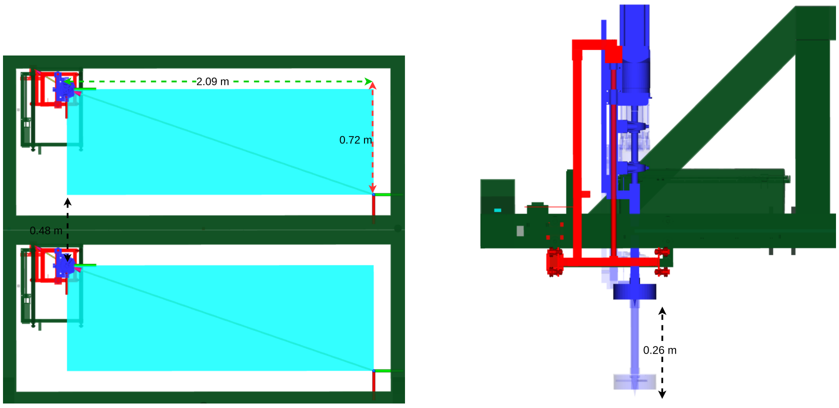
`ros2_control` framework, specifying the command interface (position), controller type (forward position controller), and movement limits, enabling 3-DOF prismatic motion for each tool. Regarding movement control of the Nuga vehicle, the `ros_planar_move` plugin satisfied all control requirements given the platform's kinematic constraints, eliminating the need for additional configuration.

2.2.4 *Joint Control*

The control of both IT units was handled using the `ros2_control` framework (configuration example shown in Listing A.2), as previously described. This framework provides a seamless transition between simulation and real hardware control. In this context, the `forward_command_controller` was used, which is recommended for simulation because it bypasses PID computations by directly sending commands to simulated joints. These joints already track positions perfectly, without the disturbances or error correction needed in real-world scenarios. Simulators like Gazebo inherently handle ideal position tracking, making closed-loop control redundant. However, when switching to real hardware, replacing it with a `position_controller` is needed but straightforward thanks to the flexibility of the framework.

Nuga's workspace layout and dimensions are shown in Figure 2.5. The gantry carrying the IT operates within a zone of 2.09 m in the Y direction, 0.72 m in X, and 0.26 m in Z. An extraction cycle begins with the gantry moving in X and Y to position the tool above the plant, followed by a downward movement in Z to lower the drill and perform the extraction. The gantry has a maximum speed of $1\frac{m}{s}$ in the XY plane, and each extraction can take up to 45 seconds per plant.

The IT is controlled using ROS2 actions, which provide a structured way to handle asynchronous tasks with feedback and result reporting. For the XY movement of the gantry, the `AxisPosition` action is used, allowing the specification of target coordinates (x, y) and speed, while providing feedback on the current position and confirming whether



(a) X, Y Workspace (b) Z Workspace

Figure 2.5: IT Workspace Layout

the target was reached. The `Extraction` action manages the vertical movement of the tool along the Z axis, reporting the depth reached, total time taken, and success status, along with real-time feedback on the current depth. Finally, the `ExtractionCycle` action coordinates the execution of multiple extractions by accepting an array of target poses and their corresponding IDs, providing feedback on the current status and reporting the results of the extraction process for each pose. These actions enable precise and modular control of the gantry system, ensuring efficient and reliable operation. A diagram summarizing this process is shown in Figure 2.6.

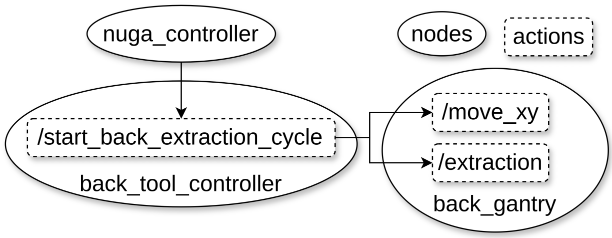


Figure 2.6: ROS Interface for back gantry control

2.2.5 *Localization*

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2.2.6 *Weed Detection*

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Part II

THE SHOWCASE

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3 TASK ALLOCATION AND OPTIMIZATION

Solving the TA problem in this context means assigning weed detections to removal tools in the most efficient way. The idea is to find the best allocation of resources and the optimal sequence of stops, that will maximize the number of plants removed, and minimize the tools' idle time. The solution has to consider the constraints of the problem such as:

GEOMETRIC CONSTRAINTS: A stop is considered valid only if the weeds lie within the workspaces of the tools (observe Figure 3.1).

MOVEMENT CONSTRAINTS: The robot can only move forward in a straight line at a max speed of $0.3\frac{m}{s}$.

TASK PROCESSING: Each plant removal takes approximately 45 seconds, during which the robot must remain stationary to ensure a successful extraction. Movement during this process is not allowed as it could compromise the tool operation.

DYNAMIC ENVIRONMENT: Weed positions are initially unknown and are discovered dynamically during operation by the camera in front of the vehicle.

PROCESSING TIME: The solution must run online because the robot discovers new weeds during operation, and decisions about stopping and TA must adapt in real-time.

We define a '*good*' stop as the next robot position that maximizes plant coverage while keeps a balance on the number of tasks assigned to each implement (aiming to minimize idle time). The problem can be approached in two ways: one option is to first determine the optimal stop location, after which task allocation becomes trivial by simply assigning tasks based on whether they fall within the front or back workspace. Alternatively, we can first allocate tasks to the implements and then compute the stop position that satisfies the corresponding geometric constraints. Both approaches are similar, differing mainly in the order of operations, but each perspective opens the door to different methods and algorithms to try.

3.1 METRICS

Defining a good set of metrics is crucial to establish a good point of comparison between solutions and easily determine the flaws of each

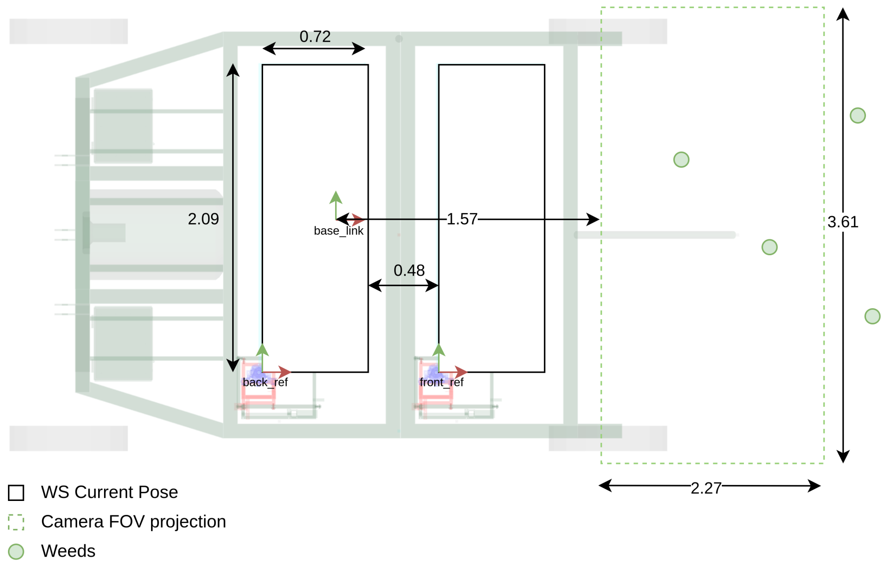

Figure 3.1: Problem Layout Dimentions

method and determine the best solution. Building a dashboard for the summary of each mission was one of the acitivities

3.2 HEURISTICS

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3.3 GRAPH SEARCH

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3.4 OPTIMIZATION

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Part III

APPENDIX

A APPENDIX TEST

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More dummy text.

A.1 CONFIGURATION FILES

YAML files are the standard method for setting up configuration variables in the Nuga project. A collection of configuration examples is provided in this appendix.

Listing A.1: Weed Infestation World config example

```yaml
seed: 2
quadrant_size: [2.0, 2.0]
quadrants:
  1:
    direction: x
    weed_density: 0.4   # weeds/m2
    spatial_distribution: clustered
    std_dev: [0.5, 0.5]
    outside_workspace: false

  2:
    direction: x
    weed_density: 1.2   # weeds/m2
    spatial_distribution: uniform
    outside_workspace: false
```

Listing A.2: ROS2 config example

```yaml
# ROS2 Control
controller_manager:
  ros__parameters:
    use_sim_time: True
    update_rate: 20 # Hz

    joint_state_broadcaster:
      type: joint_state_broadcaster/JointStateBroadcaster

    forward_position_controller_front:
      type: forward_command_controller/ForwardCommandController

    forward_position_controller_back:
      type: forward_command_controller/ForwardCommandController

forward_position_controller_front:
  ros__parameters:
    joints:
      - front_x_axis_joint
      - front_y_axis_joint
      - front_implement_tool_joint
    interface_name: position

forward_position_controller_back:
  ros__parameters:
    joints:
      - back_x_axis_joint
      - back_y_axis_joint
      - back_implement_tool_joint
    interface_name: position
```

A.2 APPENDIX SECTION TEST

Test: Table A.1 (This reference should have a lowercase, small caps A if the option `floatperchapter` is activated, just as in the table itself → however, this does not work at the moment.)

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Table A.1: Autem usu id.

A.3 ANOTHER APPENDIX SECTION TEST

Equidem detraxit cu nam, vix eu delenit periculis. Eos ut vero constituto, no vidit propriae complectitur sea. Diceret nonummy in has, no qui eligendi recteque consetetur. Mel eu dictas suscipiantur, et sed placerat oporteat. At ipsum electram mei, ad aeque atomorum mea. There is also a useless Pascal listing below: Listing A.3.

Listing A.3: A floating example (`listings` manual)

```
for i:=maxint downto 0 do
begin
{ do nothing }
end;
```

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DECLARATION

Put your declaration here.

Zagreb, Croatia, June 2025

David Razhiel Ceres Arroyo

COLOPHON

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