AGH UNIVERSITY OF KRAKOW

FIELD OF SCIENCE TECHNICAL SCIENCES

SCIENTIFIC DISCIPLINE AUTOMATION, ELECTRONICS, ELECTRICAL ENGINEERING AND SPACE TECHNOLOGIES

SUMMARY OF THE DOCTORAL DISSERTATION

Decision-Making and Risk-Aware Navigation in Mobile Robotics: From Path Planning to Emergency Response

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1 Introduction

Autonomous mobile robots are increasingly deployed in complex environments such as industrial facilities, warehouses, agricultural fields, disaster response missions, and planetary exploration scenarios. In such environments, navigation systems are expected not only to generate collision-free paths but also to make intelligent decisions under uncertainty.

Traditional navigation approaches generally assume that every obstacle should be avoided whenever possible. While this assumption improves safety, it may also lead to unnecessary detours, increased energy consumption, longer mission durations, and reduced operational efficiency. In many practical situations, a robot may be capable of safely traversing a minor obstacle while avoiding a more severe one. Consequently, obstacle handling should not be treated as a purely geometric problem but rather as a decision-making problem involving risk assessment.

This dissertation addresses this challenge by introducing a machine-learning-assisted navigation framework capable of estimating potential collision damage and selecting between obstacle avoidance and obstacle traversal. In addition, the dissertation proposes a generalized emergency planning framework for robotic environments operating under uncertain conditions.

The research was conducted at the Faculty of Electrical Engineering, Automatics, Computer Science, and Biomedical Engineering of AGH University of Science and Technology and contributes to the fields of autonomous robotics, path planning, machine learning, and decision support systems.

2 Research Problem

The central research problem investigated in this dissertation can be formulated as follows:

> How can an autonomous mobile robot estimate the potential consequences of interacting with obstacles and utilize this knowledge to make more efficient navigation decisions while maintaining acceptable safety levels?

The majority of existing path-planning methods focus on finding collision-free paths. Although numerous algorithms have been proposed, including A-star, Genetic Algorithms, Artificial Potential Fields, Probabilistic Road Maps, Rapidly Exploring Random Trees, and Particle Swarm Optimization, most of these methods treat obstacles as binary entities: either passable or impassable.

However, real-world obstacles differ significantly in terms of risk and potential damage. For example, traversing soft vegetation may be acceptable, whereas colliding with a concrete structure may result in severe damage. Existing approaches rarely incorporate explicit damage estimation into navigation decisions.

A second research challenge concerns emergency management in robotic environments. While emergency planning is well established in human-operated systems, comparatively limited attention has been devoted to systematic emergency response frameworks for robotic teams operating in uncertain environments.

3 Research Objectives

The primary objective of this dissertation was to develop a decision-making framework that allows autonomous robots to distinguish between obstacles that should be avoided and obstacles that may be traversed with acceptable risk.

The specific objectives were:

1. To investigate and compare representative path-planning algorithms commonly used in robotic navigation.

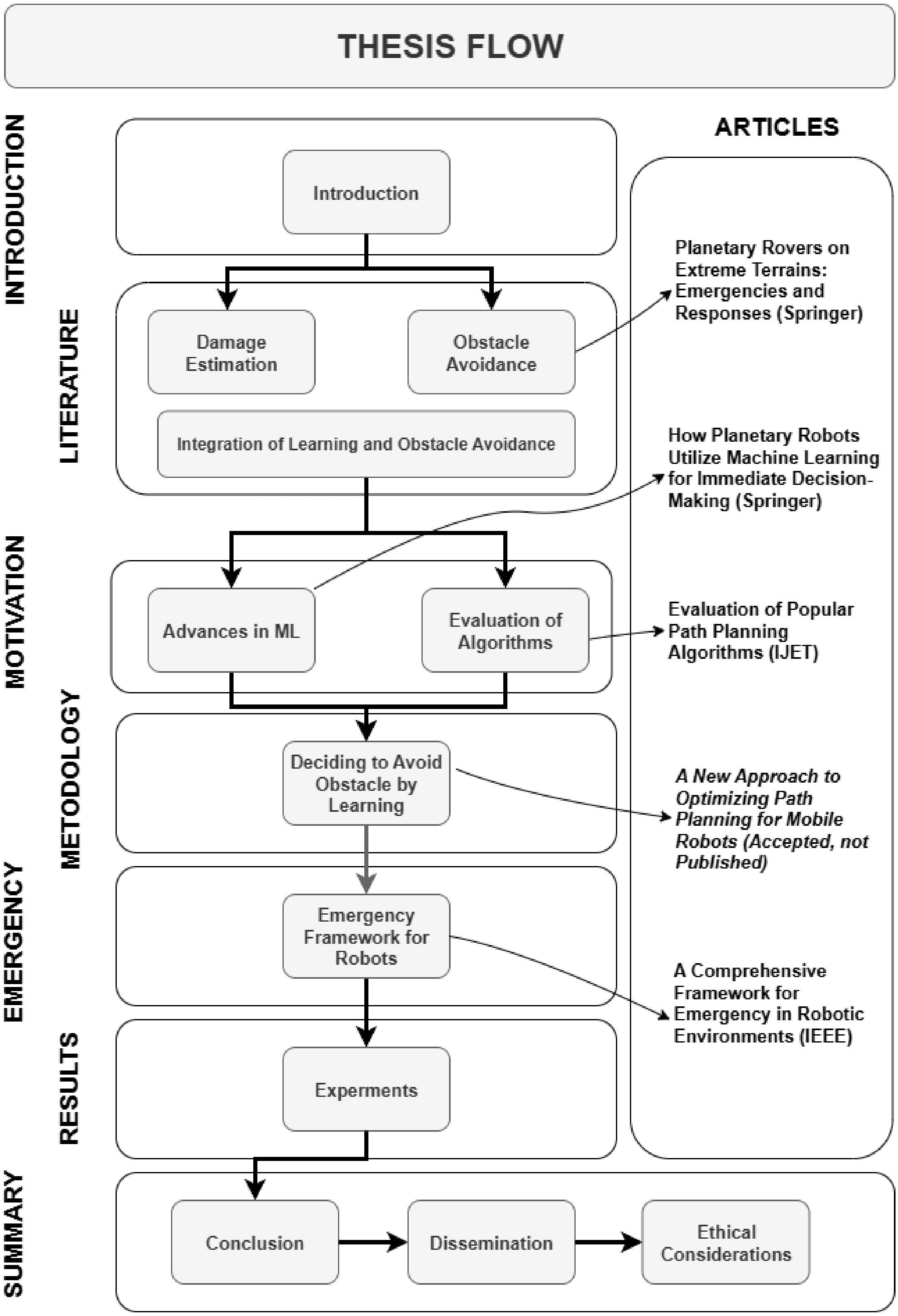

Figure 1: Thesis flow diagram.

2. To identify a suitable optimization method capable of supporting risk-aware navigation.
3. To develop a machine-learning-based mechanism for estimating expected collision damage.
4. To integrate damage prediction into robot navigation decisions.
5. To validate the proposed framework through simulation experiments.
6. To design a generalized emergency planning framework applicable to robotic environments.

The main hypothesis of this dissertation is that machine-learning-assisted damage estimation can improve autonomous navigation performance by allowing robots to distinguish between obstacles that should be avoided and those that may be safely traversed.

4 Methodology

The research methodology consists of three major components.

4.1 Evaluation of Navigation Algorithms

The first stage involved a systematic evaluation of seven representative path-planning algorithms:

- A-star
- Fuzzy Logic
- Genetic Algorithms
- Artificial Potential Fields
- Probabilistic Road Maps
- Rapidly Exploring Random Trees
- Particle Swarm Optimization

The algorithms were evaluated using multiple simulated environments with varying complexity levels. Performance was assessed primarily through path length and computational time.

Table 1: Summary of algorithm performance across all test environments

Algorithm	Success Rate	Average Length (px)	Average Time (s)
A-star	100%	815	9.6
GA	60%	1185	4.0
FL	20%	903	1.9
APF	40%	782	2.7
PRM	80%	819	3.7
RRT	100%	936	3.4
PSO	80%	752	5.8

Among all tested algorithms, PSO achieved the shortest average path length while maintaining a high success rate. Consequently, PSO was selected as the primary optimization method for integration with the proposed machine-learning-based decision framework.

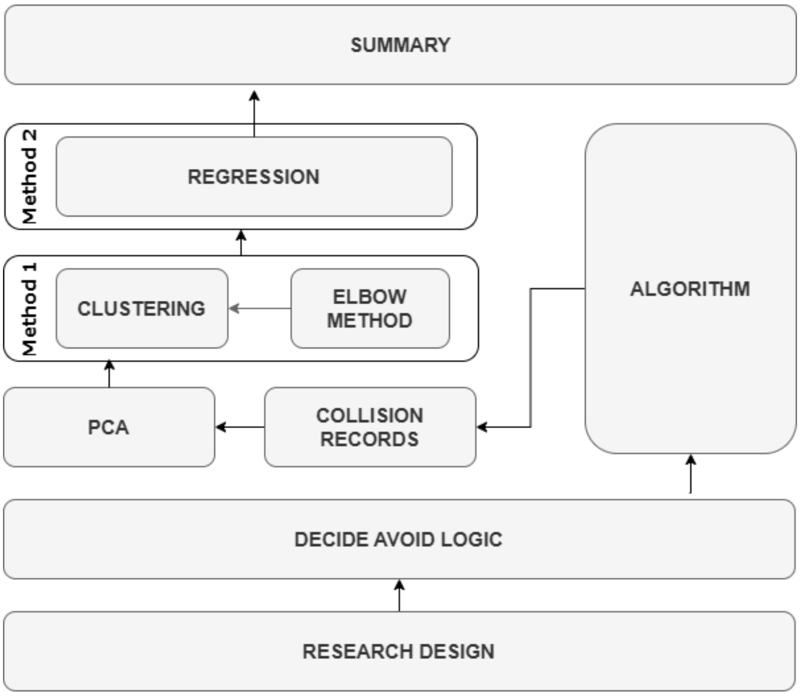

Figure 2: Methodology flow.

5 Machine Learning-Based Decision Framework

The central contribution of this dissertation is a machine-learning-assisted decision framework that enables an autonomous mobile robot to evaluate potential obstacle interactions before executing a navigation action. Unlike conventional path planning approaches, where obstacles are generally treated as binary entities to be avoided, the proposed framework introduces an intermediate reasoning layer that estimates the expected consequences of a collision and supports informed decision making.

The framework combines dimensionality reduction, clustering, predictive modeling, and path planning into a unified decision pipeline. First, collision-related observations are collected and transformed into a structured dataset. Subsequently, Principal Component Analysis (PCA) is applied to identify dominant patterns and reduce redundancy in the feature space. The resulting low-dimensional representation is then processed through clustering algorithms to identify groups of obstacles exhibiting similar behavioral characteristics.

Based on these groups, a regression model is trained to estimate the expected damage associated with potential obstacle interactions. The predicted damage is subsequently integrated into a navigation decision module that determines whether an obstacle should be avoided or traversed.

The overall framework transforms path planning from a purely geometric optimization problem into a risk-aware decision-making problem. As a result, the robot is able to distinguish between obstacles that pose an acceptable level of risk and those that require avoidance.

The proposed architecture is intentionally modular. Individual components such as clustering algorithms, regression models, or optimization algorithms can be replaced without modifying the overall structure. This flexibility facilitates future extensions and adaptation to different robotic platforms and application domains.

6 Collision Dataset and Feature Engineering

Since publicly available datasets containing detailed robot collision records are extremely limited, a synthetic dataset was generated to support the development and evaluation of the proposed framework.

The dataset was designed to emulate realistic interactions between autonomous robots and environmental obstacles. Rather than focusing solely on obstacle properties, the dataset captures both environmental and robot-related factors that influence collision severity.

Examples of recorded features include:

- Robot velocity,
- Impact angle,
- Estimated impact force,
- Post-impact vibration,
- Obstacle characteristics,
- Obstacle dimensions,
- Obstacle category,
- Additional environmental descriptors.

The target variable associated with each record is a continuous damage score representing the expected severity of a collision event.

Feature engineering played an important role in improving the quality of the subsequent learning stages. Raw variables were transformed into a representation that better captures the relationships between robot behavior and obstacle characteristics. This process also reduced noise and improved the interpretability of the resulting models.

An important design choice was the inclusion of both robot-dependent and obstacle-dependent variables. Collision severity is rarely determined by obstacle properties alone. For example, a collision with the same obstacle may result in significantly different outcomes depending on robot speed, impact angle, or kinetic energy at the moment of contact. Consequently, the generated dataset reflects the interaction between the robot and its environment rather than considering obstacles in isolation.

The resulting dataset serves as the foundation for the clustering and predictive modeling stages developed in later sections.

Figure 3: Obstacle types visualized after dimensionality reduction via PCA

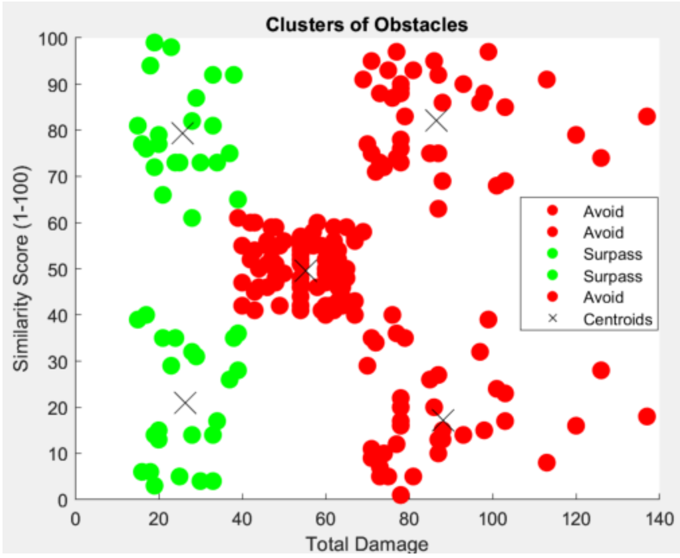

Figure 4: Clustering of obstacles using PCA reduced features.

7 Dimensionality Reduction and Clustering

The generated collision dataset contains numerous variables that may exhibit redundancy and correlation. Directly processing all features can increase computational complexity and obscure meaningful relationships within the data. To address this challenge, Principal Component Analysis (PCA) was employed as a dimensionality reduction technique.

PCA transforms the original feature space into a smaller set of orthogonal components that preserve most of the variance present in the data. This transformation enables a more compact representation while retaining the most informative characteristics of collision events.

In the context of this dissertation, PCA serves two complementary purposes. First, it reduces the dimensionality of the learning problem, thereby improving computational efficiency. Second, it facilitates visualization and interpretation of collision patterns by revealing dominant structures within the dataset.

After dimensionality reduction, clustering techniques were applied to identify naturally occurring groups within the collision records. Both K-means and Hierarchical Clustering approaches were investigated during the experimental phase.

The clustering process revealed distinct categories of obstacle interactions that exhibited similar damage-related characteristics. These categories corresponded to obstacle types such as liquid surfaces, terrain elevations, and mound-like structures. While the exact physical interpretation depends on the application domain, the clustering results demonstrated that meaningful obstacle groups can be extracted directly from data.

A notable aspect of the proposed approach is that PCA was not used solely for mathematical compression. The resulting clusters also provided a semantic interpretation of obstacle categories that could subsequently be exploited by the navigation decision module. This link between dimensionality reduction and navigation semantics represents one of the distinguishing characteristics of the proposed framework.

The clustering stage, therefore, acts as an intermediate layer between raw sensory information and high-level decision making, transforming numerical observations into structured knowledge suitable for autonomous navigation.

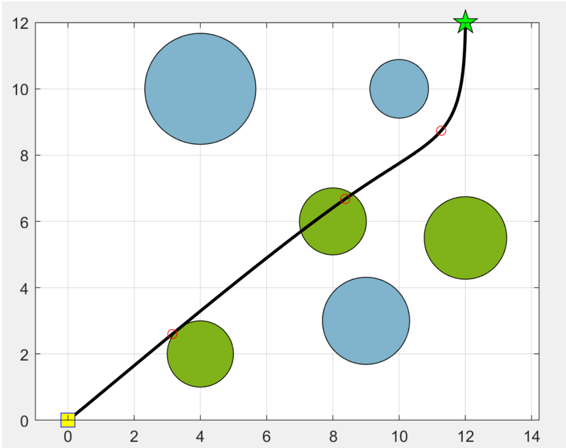

Figure 5: Regression model predictions.

8 Damage Prediction Using Multiple Linear Regression

Following clustering, the next step consists of estimating the severity of potential collisions. To achieve this objective, a Multiple Linear Regression (MLR) model was developed and trained using the generated collision dataset.

The purpose of the regression model is to predict the expected damage associated with a particular obstacle interaction before the collision occurs. This prediction serves as the key input to the navigation decision mechanism.

The model utilizes the engineered features described previously and produces a continuous damage score representing the anticipated impact severity. Unlike traditional navigation systems that rely exclusively on obstacle geometry, the proposed approach explicitly incorporates predicted consequences into the planning process.

The regression model was trained using standard least-squares optimization and evaluated on a separate test subset. Experimental results demonstrated strong predictive performance, achieving low prediction error and high explanatory power.

The obtained performance indicators were:

- RMSE = 0.52,
- $R^2 = 0.91$.

These values indicate that the model successfully captures the relationship between collision characteristics and the resulting damage within the simulation environment.

The predicted damage score becomes the principal criterion used by the decision module. If the estimated damage remains below a predefined safety threshold, the obstacle may be traversed. Otherwise, the robot initiates a replanning procedure to avoid the obstacle.

By introducing quantitative damage estimation into the navigation process, the proposed framework extends conventional path planning beyond geometric feasibility and incorporates an explicit assessment of operational risk. This capability enables more context-aware and mission-oriented navigation behavior, particularly in environments where obstacle traversal may sometimes be preferable to strict avoidance.

9 Risk-Aware Navigation Strategy

Traditional path planning algorithms typically aim to generate collision-free trajectories while minimizing a predefined objective such as path length or travel time. Although effective in many situations, such approaches implicitly assume that all obstacles should be treated equally and avoided whenever possible. In practical robotic deployments, however, obstacles may differ substantially in terms of the risk they pose to the robot and the potential consequences of interaction.

To address this limitation, this dissertation introduces a risk-aware navigation strategy that integrates predictive damage estimation into the path planning process. Rather than making decisions solely on geometric grounds, the proposed method evaluates the expected consequences of a collision and incorporates this information into the navigation decision.

The proposed decision mechanism operates after obstacle classification and damage estimation have been completed. For each obstacle encountered during navigation, the system evaluates two alternative actions:

- Avoid the obstacle by replanning the path.
- Traverse the obstacle while accepting the associated risk.

A weighted decision function is then used to compare these alternatives. The decision process considers three principal factors:

- Expected travel time,
- Estimated energy consumption,
- Predicted collision damage.

These criteria are normalized and combined into a unified decision score that reflects mission priorities. Depending on operational requirements, different weights may be assigned to emphasize safety, efficiency, or energy conservation.

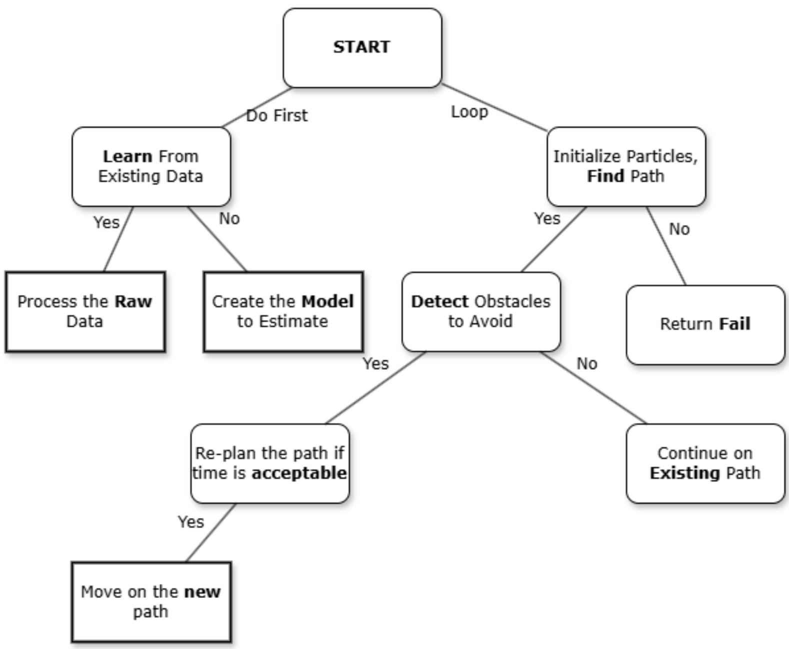

Figure 6: Flow of the integrated PSO and damage-aware decision model.

A central element of the framework is the predicted damage threshold. If the expected damage remains below the acceptable threshold, the robot may continue through the obstacle. Conversely, if the estimated damage exceeds the admissible level, the system initiates a replanning procedure to avoid the obstacle.

This mechanism transforms navigation from a purely shortest-path problem into a decision-making problem involving risk assessment and mission objectives.

An important characteristic of the proposed framework is its suitability for autonomous robots operating in remote or communication-constrained environments. In such scenarios, immediate human intervention may be unavailable or impractical. Consequently, the robot must independently determine whether obstacle traversal is acceptable. The binary decision structure adopted in this dissertation was therefore intentionally designed to support fully autonomous operation while maintaining computational simplicity.

The resulting navigation strategy enables robots to make context-aware decisions rather than applying a rigid obstacle avoidance policy. This capability constitutes one of the principal scientific contributions of the dissertation.

10 Emergency Planning Framework

While the previous chapters focus primarily on local navigation and obstacle management, autonomous robotic systems operating in real environments must also be prepared to respond to unexpected events and emergency situations.

Emergency planning has traditionally been associated with human-operated systems, industrial facilities, and disaster management procedures. Comparatively little attention has been devoted to establishing systematic emergency response frameworks specifically designed for robotic environments.

To address this gap, this dissertation proposes a generalized emergency planning framework intended for autonomous robotic systems operating in dynamic and uncertain environments.

The framework was developed by adapting concepts from conventional emergency management methodologies and extending them to robotic applications. The proposed approach is not restricted to a particular robot type and can be applied across multiple domains, including:

- Agricultural robotics,
- Warehouse automation,
- Service robotics,
- Disaster-response systems,
- Planetary exploration missions.

The framework organizes emergency management into several stages:

1. Hazard identification,
2. Risk assessment,
3. Preventive planning,
4. Emergency response,
5. Recovery and mission continuation,
6. Knowledge acquisition and future adaptation.

Particular attention is given to environments characterized by uncertainty and limited predictability. Examples include unexpected terrain changes, equipment malfunctions, environmental hazards, communication interruptions, and sensor failures.

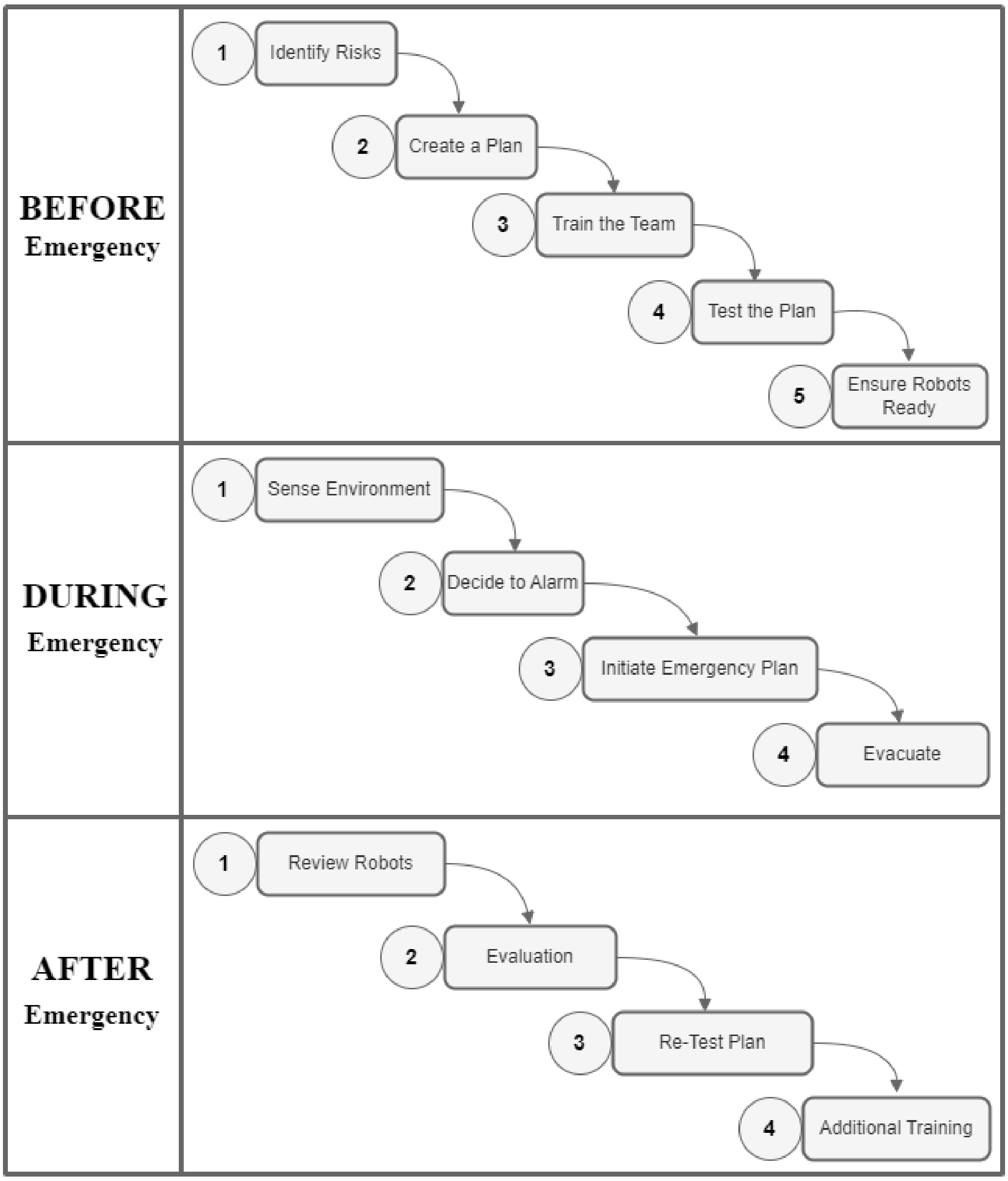

Figure 7: The story of an emergency plan

The proposed framework emphasizes proactive preparation rather than purely reactive behavior. By maintaining predefined emergency procedures and decision protocols, robotic systems can respond more effectively to unforeseen events while minimizing operational disruption.

Another important contribution of the framework is its compatibility with autonomous robotic teams. Emergency procedures can be coordinated across multiple robots, enabling collaborative responses to hazards and mission-critical situations.

Although the framework remains conceptual in nature and was not implemented as a complete operational system, it establishes a foundation for future research into resilient robotic operations and autonomous emergency management.

11 Experimental Validation

The proposed methods were validated through a comprehensive set of simulation experiments designed to evaluate both algorithmic performance and decision-making capabilities.

The validation process was conducted in several stages corresponding to the major components of the dissertation.

The first stage focused on the comparative evaluation of representative path-planning algorithms. Seven widely used navigation methods were implemented and tested under multiple environmental conditions of varying complexity. The objective of this analysis was to identify an optimization algorithm suitable for integration with the proposed decision-making framework.

The experimental results demonstrated that Particle Swarm Optimization (PSO) provided the most balanced performance when considering path quality, computational efficiency, and adaptability. Consequently, PSO was selected as the primary optimization engine for subsequent experiments.

Table 2: Path length statistics obtained from the benchmark environments

Algorithm	**Mean Path Length ± Std. Dev. (px)**
A-star	814.6 ± 84.6
RRT	935.6 ± 117.9
PSO	752.0 ± 56.4

The second stage evaluated the machine-learning components of the framework. Principal Component Analysis successfully reduced feature dimensionality while preserving the dominant variance within the collision dataset. Clustering techniques identified meaningful obstacle categories exhibiting distinct interaction characteristics.

Subsequently, the Multiple Linear Regression model was trained to estimate collision damage. Experimental evaluation demonstrated strong predictive performance, achieving a coefficient of determination of approximately $R^2 = 0.91$ and a low prediction error. These results indicate that the selected features effectively capture the factors influencing collision severity.

The final validation stage examined the complete decision-making pipeline. In these experiments, robots encountered obstacles exhibiting different characteristics and risk levels. The proposed framework successfully differentiated between obstacles that could be traversed and those that required avoidance.

The experiments demonstrated several important observations:

- Not all obstacles should be treated equally.
- Damage-aware decision making can reduce unnecessary detours.
- Machine-learning-based prediction improves navigation flexibility.
- The framework remains computationally feasible for real-time deployment.

- Risk-aware navigation provides more informative decisions than purely geometric approaches.

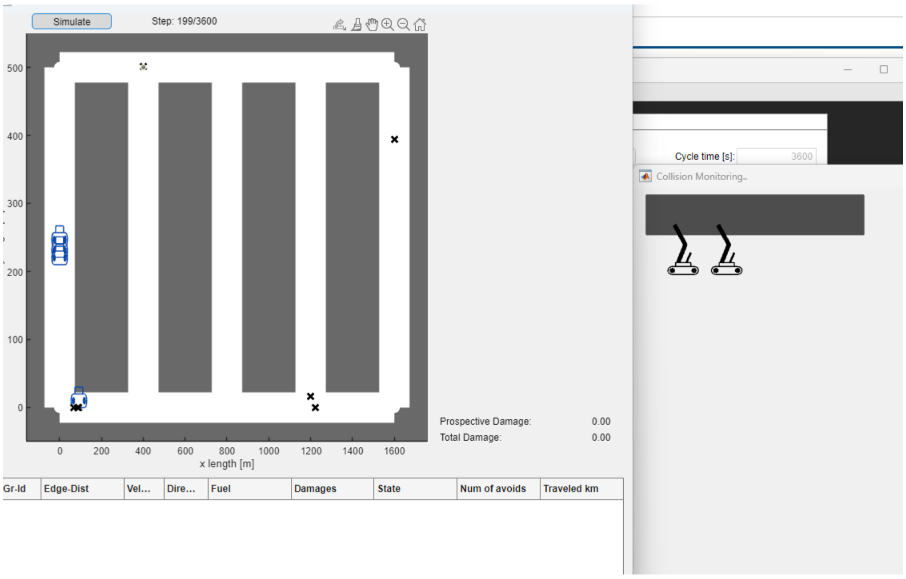

Figure 8: Third level tests - 5 corridor result.

The experimental findings support the central hypothesis of the dissertation: navigation performance can be improved when robots are capable of estimating and incorporating expected damage into their planning decisions.

At the same time, the experiments also revealed several limitations. The proposed framework was evaluated primarily in simulation environments and relies on synthetic collision datasets. Real-world deployment would require additional validation using physical robotic platforms and experimentally collected collision records.

Nevertheless, the obtained results demonstrate the feasibility of integrating machine learning, predictive modeling, and navigation planning into a unified risk-aware decision framework. The validation studies therefore provide strong evidence supporting the scientific contributions presented throughout the dissertation.

12 Scientific Contributions

The dissertation contributes to the fields of autonomous robotics, path planning, machine learning, and decision support systems. The principal scientific contributions can be summarized as follows.

12.1 Scientific Contribution 1: Comparative Evaluation of Path Planning Algorithms

A systematic evaluation of seven representative path-planning algorithms was conducted under multiple simulated environments of varying complexity. The study provided a unified experimental framework for comparing classical and heuristic navigation approaches using consistent evaluation criteria.

The comparative analysis identified the strengths and limitations of each method and demonstrated that Particle Swarm Optimization provides a favorable balance between solution quality and computational efficiency. The results establish a foundation for selecting optimization techniques in subsequent risk-aware navigation systems.

12.2 Scientific Contribution 2: Integration of Machine Learning into Navigation Decisions

The central contribution of the dissertation is the introduction of a machine-learning-assisted decision framework that extends conventional path planning beyond purely geometric considerations.

Unlike traditional navigation systems that treat all obstacles as equivalent obstacles to be avoided, the proposed framework estimates the expected consequences of obstacle interaction and incorporates this information directly into the navigation process.

This transforms navigation from a shortest-path optimization problem into a risk-aware decision-making problem, enabling robots to select actions according to predicted consequences rather than obstacle presence alone.

12.3 Scientific Contribution 3: Data-Driven Obstacle Characterization

A methodology was developed for representing obstacle interactions using collision records that combine robot-related and obstacle-related characteristics.

Principal Component Analysis and clustering techniques were employed to identify meaningful patterns within the collision dataset. The obtained clusters revealed obstacle categories with distinct behavioral characteristics and enabled the construction of a structured representation suitable for autonomous decision making.

An important aspect of this contribution is the use of dimensionality reduction not only for computational purposes but also for extracting navigation-relevant obstacle semantics from collision data.

12.4 Scientific Contribution 4: Predictive Damage Estimation Framework

A predictive damage estimation model was developed using Multiple Linear Regression.

The model estimates expected collision damage from multiple physical interaction variables and provides quantitative information that can be directly integrated into navigation decisions.

The experimental results demonstrate that reliable damage estimation can be achieved using data-driven methods, thereby enabling autonomous robots to evaluate the consequences of their actions before executing them.

12.5 Scientific Contribution 5: Risk-Aware Navigation Strategy

A decision-making mechanism was proposed that allows autonomous robots to choose between obstacle avoidance and obstacle traversal according to estimated damage levels.

The proposed strategy introduces explicit risk evaluation into the navigation process and provides a practical mechanism for balancing safety, efficiency, and mission objectives.

This contribution represents a departure from traditional obstacle avoidance approaches by incorporating predictive reasoning into path planning.

12.6 Scientific Contribution 6: Emergency Planning Framework for Robotic Environments

The dissertation proposes a generalized emergency planning framework applicable to autonomous robotic systems operating in uncertain environments.

The framework extends concepts from traditional emergency management to robotic domains and provides a structured methodology for hazard identification, risk assessment, emergency response, and recovery planning.

This contribution broadens the scope of robotic decision making beyond navigation and addresses resilience in long-duration autonomous missions.

12.7 Summary of Contributions

In summary, the dissertation demonstrates that machine learning can be effectively integrated with navigation algorithms to support damage-aware and risk-aware decision making. The proposed framework combines path planning, predictive modeling, clustering, and emergency planning into a unified methodology for autonomous robotic systems.

13 Publications Related to the Dissertation

The research presented in this dissertation has been progressively developed through a series of scientific publications addressing autonomous robotics, path planning, machine learning, decision support systems, and emergency planning. These publications document the evolution of the proposed concepts and provide intermediate validation of the methods developed during the doctoral research.

For clarity, the publications are grouped according to the principal research themes addressed in the dissertation.

13.1 Group I: Path Planning and Autonomous Navigation

This group of publications focuses on autonomous navigation, optimization techniques, and path-planning algorithms. The results obtained in these studies formed the basis of the comparative investigations presented in Chapter 4.

1. *A Novel Software Architecture of Anticipatory Harvesting Robot Teams*, 25th International Conference on Methods and Models in Automation and Robotics (MMAR), pp. 47–52, 2021.

2. *Evaluation of Popular Path Planning Algorithms*, International Journal of Electronics and Telecommunications (IJET), 2024.

3. *A New Approach to Optimizing Path Planning for Mobile Robots*, Industrial, Engineering & Other Applications of Applied Intelligent Systems (IEA/AIE), accepted for publication, 2024.

13.2 Group II: Machine Learning and Intelligent Decision Support

The second group investigates machine learning methods and intelligent decision-support mechanisms for autonomous robotic systems. These publications contributed directly to the predictive and decision-making components presented in Chapters 5 and 7.

4. *Nowe metody analizy i wspomagania decyzji oraz ich zastosowania w inteligentnych systemach autonomicznych*, AGH Scientific Publishers, 2022.

5. *How Planetary Robots Utilize Machine Learning for Immediate Decision Making*, Proceedings of the 7th Space Resources Conference, Springer Nature, 2025.

13.3 Group III: Emergency Planning and Resilient Robotic Systems

The third research stream concerns emergency management, resilience, and autonomous operation in uncertain environments. These works provide the conceptual foundation for the framework proposed in Chapter 6.

6. *A Comprehensive Framework for Emergency Planning in Robotic Environments*, IEEE, 2023.

7. *Planetary Rovers on Extreme Terrains: Emergencies and Responses*, Proceedings of the 6th Space Resources Conference, Springer Nature, 2024.

13.4 Related Earlier Work

Prior to commencing the doctoral research, the author published:

- *An Adaptive Framework for Mobile Robot Navigation*, Journal of Adaptive Behavior, Vol. 25(1), pp. 30–39, 2017.

Although this publication predates the doctoral studies, it is thematically related to autonomous navigation and has contributed to the author's early research experience in mobile robotics.

13.5 Relationship Between Publications and the Dissertation

While individual publications addressed specific aspects of autonomous robotics, the dissertation substantially extends these contributions by integrating path planning, machine learning, predictive damage estimation, risk-aware navigation, obstacle classification, and emergency planning into a unified framework for autonomous robotic decision-making.

Table 3: Chronological overview of publications related to the dissertation

No.	Publication Title	Status / Year
1	A Novel Software Architecture of Anticipatory Harvesting Robot Teams	Published (2021)
2	Nowe metody analizy i wspomagania decyzji oraz ich zastosowania w inteligentnych systemach autonomicznych	Published (2022)
3	A Comprehensive Framework for Emergency Planning in Robotic Environments	Published (2023)
4	Evaluation of Popular Path Planning Algorithms	Published (2024)
5	A New Approach to Optimizing Path Planning for Mobile Robots	Accepted (2024)
6	Planetary Rovers on Extreme Terrains: Emergencies and Responses	Published (2024)
7	How Planetary Robots Utilize Machine Learning for Immediate Decision Making	Published (2025)

14 Conclusions and Future Research

This dissertation investigates the problem of autonomous navigation in environments containing obstacles with varying levels of risk and potential damage.

Traditional path-planning methods generally focus on collision avoidance and shortest-path optimization. While effective in many situations, such approaches often neglect the consequences associated with obstacle interaction. The central premise of this dissertation is that navigation decisions should account not only for geometric feasibility but also for expected operational consequences.

To address this challenge, a machine-learning-assisted decision framework was developed. The proposed methodology combines dimensionality reduction, clustering, predictive damage estimation, and optimization-based path planning into a unified decision-making architecture.

The experimental results demonstrate that:

- collision records can be effectively used to characterize obstacle interactions,
- machine learning can provide reliable estimates of expected collision damage,
- damage-aware navigation enables more informed decisions than purely geometric planning,
- predictive decision making can improve navigation flexibility while maintaining acceptable safety levels.

In addition, the dissertation introduced a generalized emergency planning framework that extends autonomous decision making beyond navigation and addresses resilience in robotic operations.

Although the results are promising, several limitations remain. The proposed framework was evaluated primarily through simulation studies and relies on synthetic collision datasets. Consequently, further validation using physical robotic platforms is required before deployment in operational environments.

Future research directions include:

- collection of real-world collision datasets,
- validation on physical robotic platforms,
- incorporation of sensor uncertainty and communication delays,
- extension from binary decisions to multi-action decision frameworks,
- integration of reinforcement learning techniques,
- adaptation to heterogeneous multi-robot systems,
- implementation of the emergency planning framework in real robotic missions.

The overall findings suggest that future autonomous robots will increasingly benefit from predictive and risk-aware decision mechanisms. By combining machine learning with navigation planning, robotic systems can move beyond reactive obstacle avoidance and toward more intelligent, context-aware behavior capable of supporting complex missions in uncertain environments.