Delivrable D6.1 - WP6 - BugWright2
Multi-crawler inspection planning and execution control

Olivier Simonin, Christine Solnon, Xiao Peng, Simon Ferrier, Damien Rambeau, Benoit Renault, Mina Rady, Oana Iova, Herve Rivano

December 21, 2023

Autonomous Robotic Inspection and Maintenance on Ship Hulls and Storage Tanks

Deliverable report – D6.1

Context	
Deliverable title	Multi-crawler inspection planning and execution control
Lead beneficiary	INSA Lyon
Author(s)	Olivier Simonin, Christine Solnon, Xiao Peng, Simon Ferrier, Damien Rambeau, Mina Rady, Oana Iova, Herve Rivano
Work Package	WP6
Deliverable due date	October 2023
Document status	
Version No.	1
Type	DEMONSTRATION
Dissemination level	PUBLIC
Last modified	
Status	NOT RELEASED
Date approved	
Approved by Coordinator	Prof. Cédric Pradalier (CNRS) Signature:
Declaration	Any work or result described therein is genuinely a result of the BugWright2 project. Any other source will be properly referenced where and when relevant.

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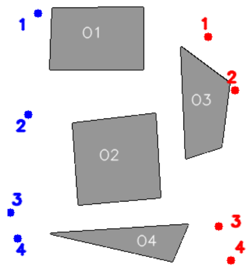
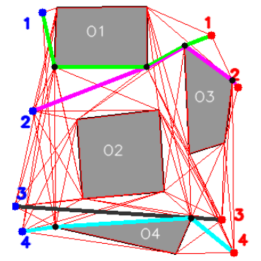
Contents

(a) Real crawler and its tether on a hull



(b) Ex. of NC-MAPF initial setting with 4 robots/target locations



(c) Visibility graph and solution (green, purple, blue and light blue lines)

Figure 1: Real crawler (a) - Modelling of the Non-Crossing Multi-Agent Path Finding problem, and illustration of the best solution with a complex environment and 4 robots (b),(c).

1 Executive summary

This document presents work and results of tasks 6.1 Multi-Robot inspection tasks modeling and 6.2 Multi-crawler inspection planning and execution control of the WP6 "Autonomous Multi-Robot Inspection". It also provide all demonstrations (videos, publications) defining the Deliverable D6.1.

This document is organized in 4 parts, corresponding to the following topics:

- Path-Planning and Coverage with Tethered Robots
- Demonstrator with Tethered Mobile Robots
- Cooperation between Crawlers and UAVs
- Performance Evaluation of Wireless Technologies for Robots Communication

2 Path-planning and coverage with tethered robots

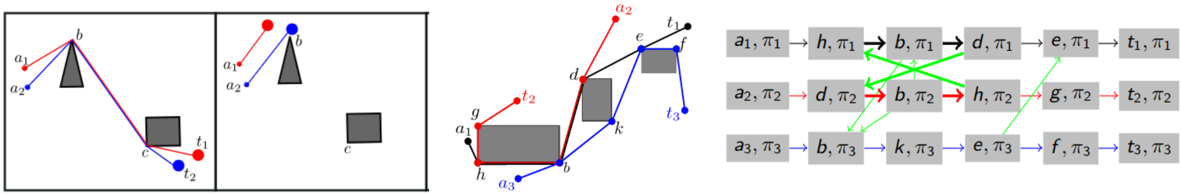
The general objective of this work is to design algorithms to plan the shortest paths for a set of crawlers that must move across the hull surface to detect corrosion. The main constraint is that each crawler is attached to a cable and it is necessary to prevent the cables from crossing or getting tangled around obstacles. To answer this complex question, we considered extensions of the MAPF (Multi-agent path finding) problem. We first considered solving the problem of finding paths for a set of robots to reach a set of target locations, then generalizing to cover the whole surface (i.e. finding a set of waypoints to follow to cover a region, see section 2.3). To deal with the first planning problem, we started by considering point-sized robots (section 2.1), then we extended the results to non-point-sized robots (section 2.2).

The work carried out in this part of the project has been mainly developed through the PhD thesis of Xiao Peng (November 2020 to February 2024), funded by the BugWright2 project, and co-supervized by Olivier Simonin and Christine Solnon from INSA Lyon, Chroma team.

2.1 Non-Crossing AMAPF for point-sized robots

We first worked on the Anonymous MAPF problem (AMAPF), where the target of each agent is not known, i.e., there is a set of targets and each agent must first be assigned to a target before searching for a path. In addition, we need to find non-crossing paths from anchor points to targets so that the makespan is minimized (makespan is the longest paths among all).

After reviewing the state of the art, we called this new problem NC-AMAPF for Non-Crossing AMAPF. We showed that this problem without obstacle is a special kind of assignment problem in a



(a) Motion synchronisation : priority to the blue robot at first obstacle

(b) Resolution of deadlocks with a Precedence graph (illustration with 3 paths a_1-t_1, a_2-t_2 and a_3-t_3)

Figure 2: Planning with non point-sized robots needs to synchronise their motions when robots access the same area : this is managed with a precedence graph at the corner of obstacles.

bipartite graph, and we showed how to efficiently compute the lower and upper bounds by solving well-known assignment problems. We also introduced a Variable Neighbourhood Search (VNS) approach, to improve the upper bound, and a Constraint Programming (CP) model, to compute the optimal solution. Next, we considered the case where the workspace has obstacles (as in Fig. 1b and 1c). We have proven that optimal solutions to assignment problems still provide bounds in this case. We also showed that the optimal solution of the NC-MAPF problem may contain some paths that are not the shortest paths. Hence, we introduced an approach to enumerate all relevant paths and, finally, we introduce a CP model to calculate the optimal solution.

We have reported experiments on randomly generated instances that allow us to control the number of obstacles and the number of robots. We have considered two models for generating anchor and destination points, and we observed that the distribution of points has a strong influence on the solution process. In particular, when anchor points and destinations are constrained to belong to two opposite sides of the workspace, this increases the hardness of the problem.

- This work has been presented in an article published at CP 2021 conference (Constraint Programming) [PSS21]
- This work is presented in the first part of the Video Presentation/Demonstration: D6.1BugWright2-DEMO-PRESENTATION-NC-MAPF.mp4

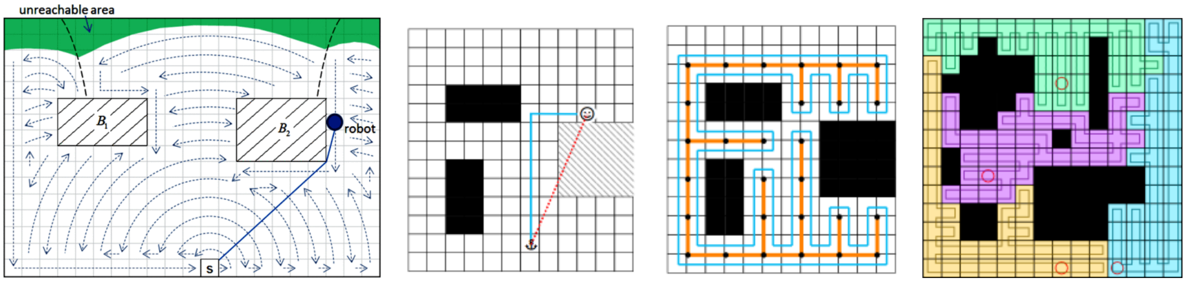
2.2 Non-Crossing AMAPF for non point-sized robots

This section presents an extension of the previous work by considering robots of non-point-size, that is to say robots with a body (to get closer to real systems). The main difference with the previous NC-AMAPF problem is that we add precedent constraints between robots that share the same subpath in order to take into account the fact that a safety distance must be maintained between them to avoid collisions and cable entanglements (see Fig. 2a). This new setting definitely changes the definition of the makespan as we may have to introduce waiting times to satisfy precedence constraints.

Then, we introduce an algorithm that exploits a precedence graph to suppress deadlocks by reassigning targets (illustrated in Fig. 2b). We also introduce a VNS approach to improve the identified upper bounds. This algorithm is similar to the VNS approach introduced in section 2.1, but it enlarges the neighborhood by taking into account non-shortest paths, because the optimal solution may contain non-shortest paths in order to avoid crossings.

Finally, we extended the CP model mentioned in section 2.1 to include waiting times due to interactions between pairs of robots when computing the makespan. This CP model relaxes constraints due to interactions of more than two robots, and we show how to lazily generate constraints to compute the optimal solution. The experimental results make it possible to show the efficiency of the different approaches (e.g. based on VNS, CP) on different environments/scenarios.

- This work has been published as an article in the Journal JAIR in 2023 (Journal of Artificial Intelligence Research) [PSS23]
- This work is presented in the second part of the Video Presentation/Demonstration: D6.1BugWright2-DEMO-PRESENTATION-NC-MAPF.mp4



(a) Coverage path [SR14] (b) (c) (d)

Figure 3: Coverage problem with a single robot (a), extended with forbidden areas (b), solved with our Spanning Tree approach (c) and extended to multi-area coverage planning with a set of robots (d)

2.3 Robot Coverage path planning

This last section presents how the multi-robot planning with tethered robots has been extended to the coverage task. The problem is illustrated in Fig. 3a with a single robot: what is the shortest path the robot must follow to inspect (visit) the whole surface? Inspection of the hull surfaces led us to specify a set of constraints associated with the robot's cable: 1) the cable has a limited length, 2) the cable should be fully retracted at the end, 3) the space for work contains obstacles and 4) the space for work contains forbidden areas. This last constraints is illustrated in Fig. 3b.

Before considering coverage with multiple robots we tackled the single robot case. To this aim, we proposed a Spanning tree coverage based planning (STC), illustrated in Fig. 3c. In a meshed representation of the environment, it consists in calculating a Spanning tree in G4 (the 2x2 cells graph) and deducing an hamiltonian path in the grid (blue path in Fig. 3c). This gives a lower bound of the coverage solution.

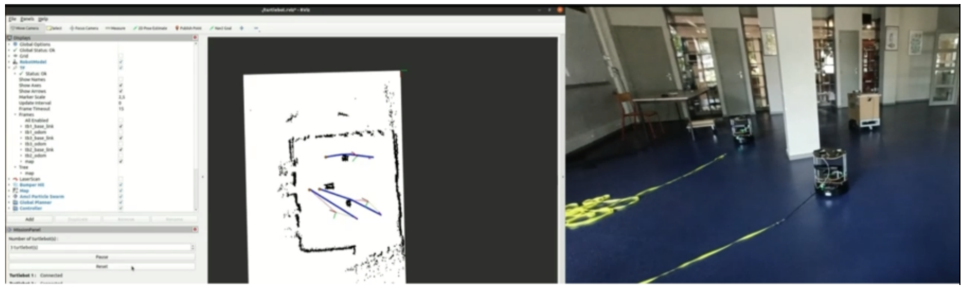
The last part concerns the problem of optimal division for multiple tethered robots. To distribute coverage, the computed areas must include the robot anchor locations and must be approximately the same size. We adapted and compared different existing approaches for the division of complex area (DARP, HST, Voronoi). We trained these methods with tethered robots constraints and obtained valid solutions, such as the one in Fig. 3d. We also compared the quality of solutions with the different methods.

- This work will be submitted to a Journal at the end of 2023, and also constitutes a chapter of Xiao Peng's doctoral thesis, which will be defended at the beginning of 2024 [Pen24].
- This work is presented in the last part of the video Presentation/Demonstration: D6.1BugWright2-DEMO-PRESENTATION-NC-MAPF.mp4

2.4 Outcomes

- NC-AMAPF and Coverage planning implementation's source code, available on internal repository.
- Xiao Peng's PhD thesis, INSA Lyon, CITI Lab. [Pen24].
- Article in the journal JAIR 2023 (Journal of Artificial Intelligence Research): [PSS23]
- Article in the CP conference 2021 (Constraint Programming): [PSS21]
- Presentation/Demonstration video: D6.1BugWright2-DEMO-PRESENTATION-NC-MAPF.mp4

(a)



(b)

Figure 4: Experiment with 3 tethered turtlebot robots

3 Demonstrator with Tethered Mobile Robots

The objective was to design a demonstrator of Xiao Peng's PhD thesis results, that is to test the NC-AMAPF [PSS23] and the coverage planning algorithms with real mobile robots attached by a cable to an anchor. To this end, we decided to adapt a fleet of Turtlebot robots (available at INSA Lyon/Chroma team, see Fig. 4a). To enable the construction of a permanent demonstrator in Lyon, we decided to consider that the ground emulated the vertical surface of a hull (cables are kept taut to avoid considering gravity effects). The main challenge was to develop an application including a graphical interface and capable of managing the robots connection, the selection of parameters (initial and target locations), the call to planning functions, and the execution control of robots to follow their paths.

3.1 Milestones

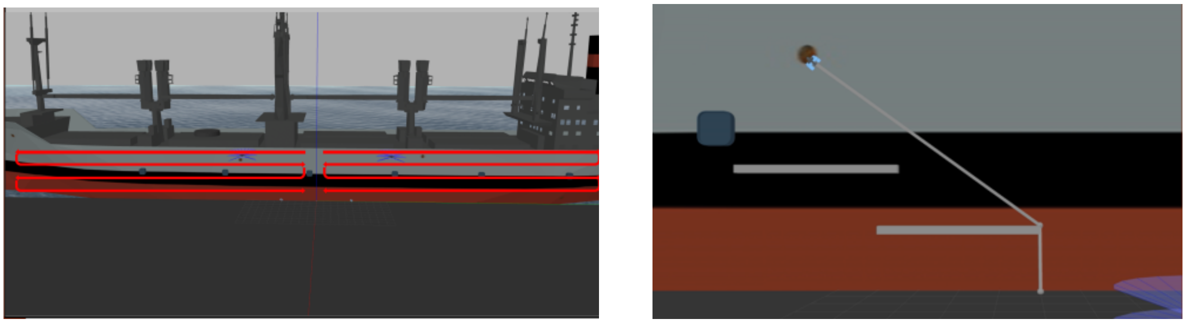
The work has been divided into the following milestones:

- Extension of Turlebot2 with NanoJetson, RPLidar, and cables to emulate tethered crawlers.
- Development of an interface to manage multi-robot inspection tasks, able to call the NC-AMAPF planning software. [PSS23, Pen24].
- Implementation of an experimental area and mapping of the environment.
- Experiments of planning and visit of target locations with several robots.
- Experiments of planning for coverage of the environment with several robots (work in progress)

These developments and the first experiments with 3 mobiles robots are presented in the Video-Demonstration D6.1BugWright2-DEMO-Robot-Demonstrator.mp4 and also illustrated in Fig. 4b.

3.2 Outcomes

- Source code of the demonstrator application and embedded robot controllers are available on an internal repository github.
- Presentation/Demonstration video: D6.1BugWright2-DEMO-Robot-Demonstrator.mp4



(a) Paths of UAVs visual inspection

(b) Displacement of a crawler and its cable

Figure 5: Illustration of cooperation between two UAVs and two tethered crawlers to detect corrosion areas - design of a simulator in Gazebo with a modeling of unwinding cables.

4 Cooperation between Crawlers and UAVs

The objective is to extend previous planning tasks to more complex scenarios in particular by allowing cooperation between UAVs (drones) and Crawlers. The general scenario we are developing and testing in simulation consists in a set of UAVs carrying out a visual inspection of a hull surface while sending to tethered crawlers the mission of inspecting locations where corrosion is suspected.

This work is developed inside the Gazebo simulator, which is exploited more generally in WP6 and the BugWright2 project. Figure 5 illustrates this work which is also presented in the video : D6.1BugWright2-DEMO-Cooperation-UAV-Crawlers.mp4

4.1 Milestones

The work has been divided into the following milestones:

- Modelling in Gazebo the motion of a crawler and its cable attached to an anchor
- Simulating UAVs visual detection in Gazebo
- Designing and simulating cooperation scenarios with UAVs and crawlers.
- Designing a strategy to distribute target locations between crawlers which are sent by UAVs.
- Experimenting and analysing results

4.2 Outcomes

- Source code of the developed simulator (plugin in Gazebo) is available on an internal repository github.
- Presentation/Demonstration video : D6.1BugWright2-DEMO-Cooperation-UAV-Crawlers.mp4

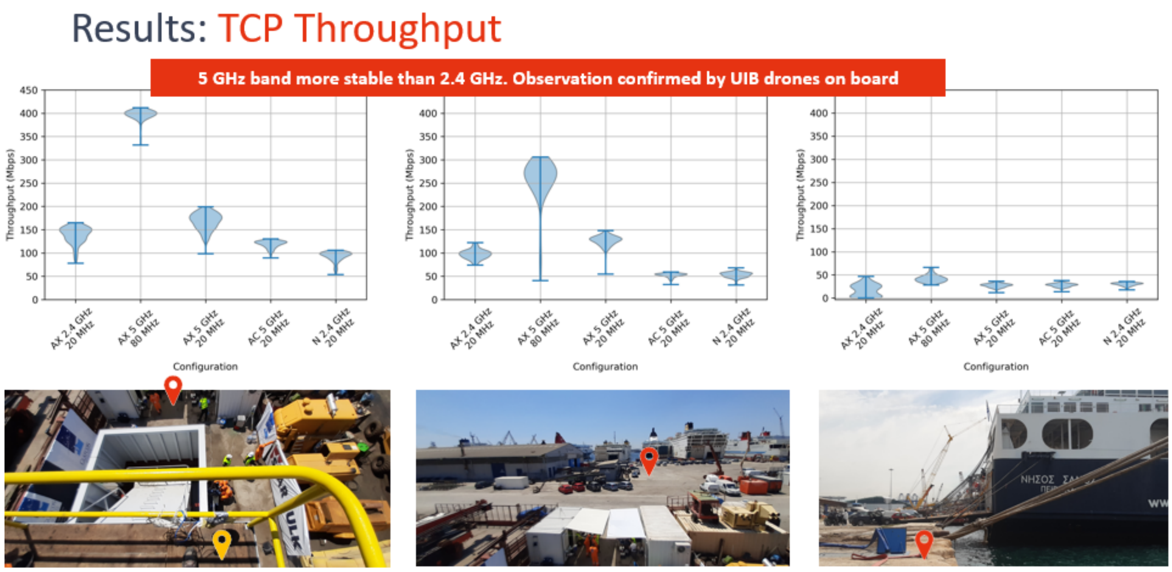


Figure 6: Perama Shipyard - results from first experimental setup

5 Performance Evaluation of Wireless Technologies for Robots Communication

The work presented here has been developed in WP6 with connections to other WPs and partners. The work carried out in this part of the project has been mainly developed by Mina Rady, post-doc from 19/04/2022 to 22/9/2023, funded by the BugWright2 project and co-supervized by Oana Iova and Herve Rivano from INSA Lyon Agora team.

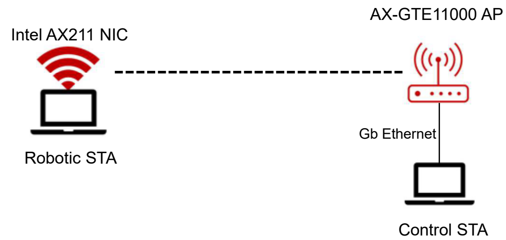
Here we focused on studying the performance of a Wi-Fi for industrial robotics. Ensuring a wireless communication QoS was considered from the beginning of the project as a prerequisite to allow a set of heterogeneous robots (at least crawlers and aerial robots) to communicate and cooperate. This question interested all partners of BugWright2 that deploy robots, so the work involved a lot of interaction with partners during several integration meetings. We present the timeline of the achieved milestones in Section 5.1. The outcomes are presented in Section 5.2.

5.1 Milestones

The work has been divided to the following milestones:

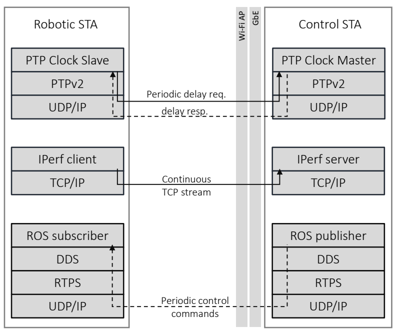
- Developed version 1 of experimental setup for Wi-Fi performance evaluation. It was tested at the Perama Shipyard (Athens, Greece) during an integration week in May 2022 (Fig. 6).
- Processing and presented results at the NTNU Integration week (Trondheim, Norway) in June 2022.
- Built version 2 of the experimental setup, including collection of physical layer information used from access point. The Wi-Fi network throughput has been tested in an RF-shielded environment, cf. Fig. 7a and 7b.
- The results from this first series of experiments were published in an Inria research report. This experiment allowed us to learn about the technical challenges of Wi-Fi experimental evaluations due to hardware limitations, as the available Wi-Fi6 hardware did not have any open source linux compatible drivers. This limited the measurements we could take to understand the performance (such as RSSI, or TCP round trip time). We decided to build a third version of the experimental setup using more open and recent hardware to account for the limitations encountered in version 2.

(a) Wi-Fi performance evaluation in RF-shielded environment

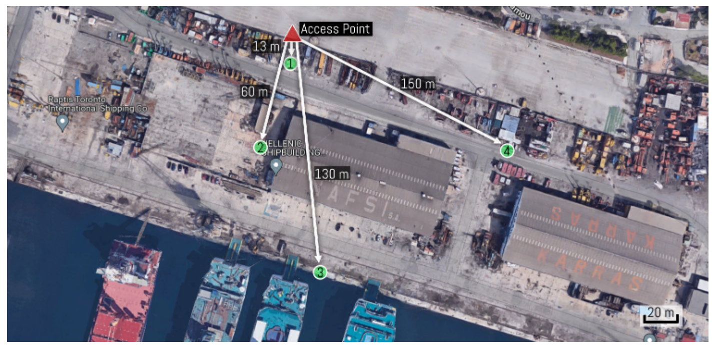


(b) Layout of the second experimental setup

Figure 7: Wi-Fi performance evaluation in RF-shielded environment CortexLab (CITI lab/INSA Lyon)



(a) Third experimental setup



(b) Perama Shipyard - second round of experiments

Figure 8: Wi-Fi performance evaluation in an industrial robotic scenario

- A version 3 of experimental setup over new hardware and 6 GHz band was developed. The setup made it possible to imitate the robotic scenario as seen in Fig. 8a. The configuration measures ROS control packet delay, PTP delay and synchronization reports, PHY layer information from the network interface card, achieved TCP throughput information using iPerf, and scans of surrounding access points for interference evaluation.
- Version 3 is run in 4 different scenarios using 9 different Wi-Fi configurations in the Perama Shipyard on 18 November 2022 (Fig. 8b).
- The same week, we extended the CNRS' magnetic crawler with wireless connectivity and we demonstrated a decently functioning streaming/control link using Wi-Fi up to 113m distance in the Perama shipyard as seen in Fig. 9. Demo is recorded and was presented during the European Commission Review Meeting on 30 November 2022.
- The experimental results are compiled and a journal paper is submitted in collaboration with Glafcos Marine to Elsevier Ad Hoc Networks Journal (summer 2023).

(a) CNRS magnetic crawler

(b) Controller streaming view

(c) Distant controller view (113m)

Figure 9: Testing Wi-Fi connectivity with the CNRS magnetic crawler

- Prepared an overview of Rate Adaptation Algorithms in IEEE 802.11 networks and identified open research questions.

5.2 Outcomes

Publications and invited talks

- Mina Rady, Oana Iova, Hérvé Rivano. *Faster is not Always Better: Cost of High Bit-Rates in Wi-Fi Networks.*. RR-9519, INSA Lyon - CITI; Inria Agora. 2023. ⟨hal-04219738⟩ [RIR23]
- Mina Rady, Oana Iova, Hérvé Rivano, Angeliki Deligianni, and Leonidas Drikos. *How does Wi-Fi 6 Fare? An Industrial Outdoor Robotic Scenario.* Submitted to Elsevier Ad Hoc Networks.
- Integration week briefing and Wi-Fi testing observations in Greece - May, 2022. *NTNU Integration Week.* 30 June 2022. Trondheim, Norway (online).
- Demonstrating a Wireless Robot Link Up to 113m. *NTNU Integration Week.* 30 November 2022. European Commission review meeting (online).
- Characterizing the Performance of Wi-Fi for Industrial Robotics. *AIO research team, Inria.* 12 July 2023. Paris, France.

Recorded Demo

- Mina Rady, Simon Ferrier, Cédric Paradalier, Oana Iova, Hervé Rivano , Olivier Simonin. Wireless Control of Magnetic Crawler. Perama, Greece : D6.1BugWright2-DEMO-WirelessControlofMagneticCrawler.mp4

Source code and open data

- Source code of automation scripts for the experiment setup in Fig. 8 in Perama Shipyard is available on internal repository github.
- The collected performance data for 9 PHY configurations of Wi-Fi in 4 different scenarios is available in open data (same repository).

6 Conclusion

As a synthesis, the Deliverable 6.1 presented the work, from theory to experimentation, which was carried out in tasks 6.1 and 6.2. It can be summarised as follows:

- A major result of WP6 is the design of algorithms for multi-robot tethered robot path-planning, ensuring their cables do not cross. The PhD thesis produced the NC-AMAPF algorithm which allows to find optimal paths (minimum makespan) in limited-time calculation even with large instances. This is the first algorithm providing such an optimal planning for robots with cables and in complex environments (obstacles, forbidden areas) [PSS21, PSS23, Pen24].
- The PhD thesis also provided a coverage path-planing algorithm for a tethered robot, built from a spanning tree computation. We also designed algorithms to divide the multi-robot coverage problem into a set of single-robot coverage ensuring no cables will cross [Pen24].
- We then designed a demonstrator of the NC-AMAPF algorithm with real mobile robots. We modified Turtlebot robots and attached them to cables to emulate tethered crawlers. We also developed an interface to manage the fleet, to deal with delays in robots motion, and to design complex scenarios.
- We designed a simulator to study cooperation between tethered crawlers and UAVs (aerial robots) in hull corrosion detection scenarios. This tool is built with Gazebo/ROS. We have proposed an original model of cables, that stretch with the robot's movements and deform around obstacles. Here again, the NC-AMAPF algorithm is exploited and tested to plan crawlers' paths.

- All along the project, we identified constraints and requirements from real experiments during the integration weeks. In this context we evaluated the wireless technologies which are used by partners deploying UAVs and crawlers. We designed an experimental setup, allowing us and partners to test different Wifi configurations and optimize communications in real-world experiments.

Perspectives:

- Path-planning with tethered robots is a complex problem when taking into account several real world/applications constraints. The proposed algorithms could be extended by considering more realistic environments, e.g. non-flat environments, 3D environments, and cables could be modelled with gravity effects. Same extensions could be done in the simulator designed with Gazebo/ROS.
- We plan to extend the robot demonstrator to test coverage scenarios with a growing number of robots and obstacles, in order to test the limits of the approach.
- Concerning cooperation between crawlers and UAVs, we plan to test more complex scenarios and strategies. We think that cooperation could be improved by allowing direct interactions while they work simultaneously. Also, it could be interesting to exploit and test UAVs strategies designed in Task 6.3 (see D6.2 Multi-Robot visual inspection and execution monitoring).

References

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