DR 4.3: Communication and knowledge flow gluing the multi-robot collaborative framework

Luigi Freda[*], Mario Gianni[*], Fiora Pirri[*]

[*]*Alcor Laboratory, Department of Computer, Control, and Management Engineering "Antonio Ruberti" - Sapienza University of Rome.*

⟨pirri@dis.uniroma1.it⟩

Project, project Id:	EU FP7 TRADR / ICT-60963
Project start date:	Nov 1 2013 (50 months)
Due date of deliverable:	M38
Actual submission date:	February 2016
Lead partner:	ROMA
Revision:	final
Dissemination level:	PU

This document describes the progress status of the research work of WP4 in Year 3 of TRADR project.

WP4 developed a framework for both multi-robot path planning and patrolling. The underlying inter-robot communication flow is leveraged by a distributed hybrid communication model.

Persistence has also been taken into account within the functional architecture of the framework, in terms of access and reuse of both maps and robot trajectories of previous sorties.

The document reports both the research and engineering work that has been performed, in collaboration with other project partners, to effectively deploy a team of UGVs in real scenarios under the control of the developed framework.

Moreover, a virtual simulated environment of the TRADR system is described. It has been used during testing and validation, before real deployment.

The document is organized as follows. Planned work is introduced and the actual work is discussed, highlighting the relevant achievements, how these contribute to the current state of the art and to the aims of the project.

Executive Summary

This report describes the research work of WP4 toward the development of the formal methods needed in TRADR to model knowledge exchange, knowledge maintenance, information sharing, common and individual decision structures in order to enable collaborative planning.

In Year 3 we developed a functional architecture allowing for the deployment of a team of TRADR UGVs in real scenarios. This architecture manages the communication, the coordination and the collaboration among the UGVs in both multi-robot path planning and patrolling tasks (see Subsection 1.3.1, Section 1.3).

More precisely, the architecture integrates two levels of coordination to handle with both interferences and spatial conflicts among the UGVs, namely, the *topological* and the *metric* level.

At the topological level, each robot selects its target node on a topological map, relying on a shared heuristic criterion as well as on a coordination mechanism so as to prevent topological conflicts (e.g., such as same target node selection).

At the metric level, each robot path planner manages and minimizes the occurrences of spatial conflicts according to a multi-robot traversability function spanning over a metric representation of space (ETHZ).

The functional architecture has been fully distributed over `nimbro_network`, an inherently fault-tolerant network transport solution for multi-master ROS systems (Fraunhofer). A hybrid communication model over this network leverages the inter-robot communication flow.

Concerning persistence, the architecture re-uses maps and robot trajectory histories retrieved from previous sorties for traversability analysis and topological mapping, respectively.

An implementation of the above architecture for `nimbro` has been released under two versions. The first version allows for the deployment of the TRADR system in virtual simulation. The second enables both multi-robot path planning and patrolling of a team of UGVs interconnected via the TRADR Core for real deployment.

Logs of the software development process as well as documentation and guidelines about the usage of the code are available on the channels used by the TRADR project (see Subsection 1.3.2, Section 1.3).

The research work on environment representation and storage has been done in collaboration with ETHZ. Fraunhofer supported us first in the deployment of the functional architecture over `nimbro` and then in the distribution over the TRADR Core. CTU together with Fraunhofer managed the upgrade of the robot network and of the new device that will provide on-demand restarting of the laser motor.

Role of Communication and knowledge flow gluing the multi-robot collaborative framework in TRADR

The work performed in Year 3 by WP4 contributes to the overall objective of TRADR project by providing a fully integrated *ready-to-use* framework for deploying a team of UGVs to patrol a set of interesting areas either given as input by end-users (via a suitable GUI) or built upon robot trajectories collected during previous sorties (see Subsection 1.3.1, Section 1.3).

WP4 also provided the consortium with a version of the above framework which allows any user to run the TRADR system, under `nimbro_network`, in virtual simulation, as benchmark (see Subsection 1.3.2, Section 1.3).

Persistence

WP4 addressed persistence in Year 3 by developing two communication protocols under the `nimbro` network infrastructure to save/load onto/from the TRADR Core (i) the maps of the environments explored by the UGVs during previous sorties and (ii) the trajectories followed by the robots during these exploration phases. This information is used to refine the estimation of the normals for both traversability assessment and path planning. It is also used to build an estimate of the topology of the areas to be patrolled. Patrol graphs are further stored onto the TRADR Core to be used in next sorties. Here, ETHZ managed the server side of the map saver. ROMA developed both the client side of the map service and the service for robot trajectory saving. Frauhnofer contributed to the integration of the above work with `nimbro` and the TRADR Core.

Contribution to the TRADR scenarios and prototypes

The research work of WP4 contributes to Year 3 Use-cases as documented on the related wiki page on Redmine (`https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Scenario_and_use_cases_Year_3`) and also described in Deliverable DR.7.3. Details are reported in Table 1

Use-cases in Table 1 have been accommodated on the basis of the document in Annex 2.2. Annex 2.2 collects useful information for the identification of interesting multi-robot tasks within the TRADR project. The objective of this document is two-fold: (1) to clearly define a set of doable tasks which will be actually implemented for the reviews and demos and (2) to foster collaboration and discussions within the TRADR team. An excerpt of the main content of Annex 2.2 in terms of multi-robot use-cases is given in Table 2. Additional details are also available at `https:`

N.	Description	Realization	Partners
7	The robot should be able to plan based on a map generated during a previous sortie (map should be obtained by merging two maps offline).	Robot collects map during 1st sortie and uses it in subsequent sortie Robots start at same location or use a tool to rigidly merge maps.	ETHZ, ROMA
8	Dynamic environment (among sorties) poses challenge for map creation.	During subsequent sortie something in the environment has changed.	CTU, ETHZ, ROMA
12	Mulit-robot Patrolling	Robots visit the nodes of a topological graph representation of the environment. These nodes can be also given as input by the user.	ROMA

Table 1: Contributions of WP4 to Year 3 Use-cases of TRADR.

ID.	Description
PCPSE1	The environment map is already available and given as input to the robots.
PCPSE2	The robots are able to continuously localize themselves w.r.t. the given map.
PCPSE4	Robots are able to continuously communicate and exchange their positions and relevant data.
PCPSE9	Dynamic mapping (at least considering robot occlusions)

Table 2: Table of requirements for multi-robot uses-cases.

`//redmine.ciirc.cvut.cz/projects/tradr/wiki/PCPSE`.

1 Tasks, objectives, results

1.1 Planned work

The planned work of WP4, in Year 3, concerning "Communication and knowledge flow gluing the multi-robot collaborative framework" is described in Task T4.3. Task T4.3 achieves the objectives described in Milestone MS4.3. An excerpt of the description of both Task T4.3 and Milestone MS4.3, from the DoW of the project, is given below

Task T4.3: The goal of Task 4.3 is to model the flows of information and knowledge to support robots collaboration and make it operative. Two different flows are devised by WP4.

The first flows connects terms for actions specifying motion and paths control to terms for actions specifying activities. It also connects terms for perceptual and sensory actions/tokens to terms specifying properties and relations over a common ontology.

The second flow connects means, modes and semantics of robots interaction, on the common ontology, allowing for a continuous exchange of information, wherever communication is feasible, while executing tasks and generating plans, via a model of robot communication.

The expected result of Task 4.3 is a framework connecting different knowledge spaces within robots cognitive structures and between robots, conveying knowledge exchange.

Milestone MS4.3: This milestone proves the role played by the two channels for communication and knowledge flow gluing the multi-robot collaborative framework.

1.2 Addressing reviewers' comments

This section reports how in Year3 WP4 addressed the comments of the reviews.

Overall comment 1: The work performed within WP4 should be refocused towards the needs of the TRADR system and reconnected with the rest of the project so that its contributions become integrated and relevant in the TRADR system.

Answer to overall comment 1: This issue has been widely discussed together with other project partners during last General Assembly meeting at ETH, Zurich, in early April 2016. During the discussion we mainly concentrated our attention to the needs of the TRADR system as suggested by reviewers as the basic step to reconnect the work of WP4. To this end, we discussed with end-users about what kind of capability a team of robots should have had in order to cope with the challenges of the use-case sce-

nario in Year 3. Among several feasible alternatives, the end-users came up with the need to have functionality to instruct a team of UGVs to regularly visit certain areas of interest, detected across previous sorties. After a preliminary study of the problem in the context of the Year 3 use-cases, we identified the main building blocks of the functional architecture needed to develop the above functionality as well as to make it operative in the TRADR project. In the next months, we arranged several meeting with individual partners, beside those already scheduled into the project roadmap, to integrate their research work. This effort involved ETHZ for mapping, ROMA for path-planning and traversability analysis, Fraunhofer for `nimbro` and the TRADR Core. We also improved the framework for virtual simulation, developed in Year 2, to test a prototype of the integrated functional architecture for multi-robot path planning and patrolling. We arranged during the TRADR evaluation meeting in Dortmund, Germany, last November 2016, several sessions in which the end-users have been trained to use in simulation the developed functionality. We improved the usability of the GUI according to the end-user insights gathered during this training session. We finally tested both the multi-robot path-planning and patrolling with two UGVs in real scenarios, resembling small-scale disaster situations, under `nimbro` and the TRADR Core (see Section 1.3).

Overall comment 2: In WP4, the work reported in the deliverable D4.2 and orally presented to the reviewers in the 1st day of the Y2 review meeting appeared quite disconnected with the standalone demonstration presented in the 2nd day of the review meeting.

Answer to overall comment 2: This is definitely true, although few references about the framework for virtual simulation as well as the content of the standalone demonstration have been given in Deliverable DR.4.2 and in the oral presentation, respectively. However, we recovered form such a discrepancy in Year 3.

Overall comment 3: Also, the contributions from other partners than ROME to this WP are not clearly visible.

Answer to overall comment 3: In Year 3 we have taken care of that and the contribution of the other project partners is clearly much more visible. In particular, ETHZ contributed to integrate mapping, Fraunhofer supported the integration with `nimbro` and with the TRADR Core. CTU provided support to upgrade the robot hardware (see Section 1.3).

Overall comment 4: Moreover, being persistent models for multi-robot acting a key scientific objective of the TRADR project, after two years of the project development, the theoretical multi-robot collaboration framework based on relational structures and tensor formulation presented in the 1st day has not been integrated in the TRADR system, nor demonstrated with data from either simulation or real robots yet. The consortium must address

this issue as soon as possible and put in practice a contingency plan during Y3, so that it does not become a serious threat to the projects success and the aforementioned projects scientific objective can be timely accomplished.

Answer to overall comment 4: After a discussion with other project partners we decided to activate a contingency plan. The main objective of this plan was to establish even more closer synergies with the others in favor of a framework which allows for real deployment of a team of UGVs for patrolling areas of interest (see Section 1.3).

Specific comment 1: In Y2, the research team demonstrated an overall acceptable progress in WP4 but the integration of the main parts in the TRADR system is unclear and not convincing yet.

Answer to specific comment 1: Considerable amount of work has been devoted by WP4 in Year 3 to integration in order to address this issue (see Subsection 1.3.2, Section 1.3).

Specific comment 2: Moreover, the contributions from other partners than ROME are not sufficiently visible.

Answer to specific comment 2: The work reported in this document as well as the content of the demonstration that we are going to present at the reviews very well describe the contributions of the other project partners in WP4 (see Section 1.3).

Specific comment 3: Despite being promising, the theoretical multi-robot collaboration framework was not visible in the integrated demonstration, even in the V-REP simulation environment presented in the standalone demonstration, and has not been published yet in a scientific venue.

Answer to specific comment 3: This research work has not been published yet. On the basis of the status of this research we have chosen to postpone the integration of this part of the work in TRADR.

Specific comment 4: Instead and surprisingly, the standalone demonstration showed in a simulation heterogeneous robots doing a coordinated multi-robot coverage task that adapts the heuristic of the real-time A* navigation algorithm to do a persistent search (the heuristic tends to direct robots to less visited nodes).

Answer to specific comment 4: This work has been the result of ROMA research efforts after the delivery of Deluverable DR.4.2 and before the Year 2 review meeting. That's why it has not been reported in DR.4.2 but has been shown at the review. We are sorry for such a discrepancy.

Specific comment 5: Also surprisingly, this coverage approach neither was reported in deliverable D4.2 nor presented orally to reviewers in the work-package presentations held during the first day of the review meeting. It is not clear whether it is meant to be a contribution or merely a demonstration

of collaborative path planning and plan execution.

Answer to specific comment 5: This comment is partially true. During the oral presentation few slides have been shown to the reviewers describing the demonstration in virtual simulation of a team of heterogeneous robots covering an environment. A video also accompanied this part of the presentation.

Specific comment 6: As only simulation experiments have been done in Y2, the chosen trade-off between simulation and experiments with real data, either from datasets of past exercises of the TRADR system or from integration and experiments with the TRADR system, was not appropriate to validate the theoretical framework also in real scenarios and make it a visible and relevant asset to the projects integrated demonstrator as it should be. Indeed, it did not seem that data at least from simulation was used to demonstrate the empirical usefulness of the collaboration framework.

Answer to specific comment 6: We agree. Thanks for this note. We are dealing with this issue.

Specific comment 7: As the proposed framework requires considerable amounts of past data to become effective and requires eventually many sorties, the research team should also consider a technique that can tackle the mission with a shorter past history, i.e. during the first sorties of the mission. Using data from human- robot collaboration developed in WP5 can be an important source of test data to further develop and refine the framework.

Answer to specific comment 7: Many thanks for this suggestion. We are actually also considering this mode in our research.

Specific comment 8: The work progress in WP4 appears quite disconnected with the rest of the project and its contribution to the TRADR integrated system (i.e. simulator, scenarios, system integration) is unclear and not sufficiently visible. A contingency plan must be devised by all partners involved in WP4, in order to refocus the work that needs to be done throughout Y3, not only to compensate this divergence with respect the projects DoW, but also to make explicit and relevant the contribution of WP4 to the TRADR system used by the consortium in future joint exercises and evaluation exercises. The importance of this contribution on multi-robot collaboration will also be crucial in Y3 and in Y4 because missions will involve necessarily multiple and heterogeneous robots working in collaboration.

Answer to specific comment 8: We followed the suggestion of the reviewers. Indeed we actuated a contingency plan that, although it deviated for the work as planned in the DoW, bridged the gap between the contribution of WP4 to the TRADR system and the contribution of the other project partners to WP4 (see Subsection 1.3.2, Section 1.3).

Specific comment 9: Also the reported publication outcomes of WP 4 are below the average of other WPs.

Answer to specific comment 9: Many works are under submission. So we hope to bridge also this gap very soon.

1.3 Actual work performed

This section describes the research work of WP4 in Year 3 of TRADR project. It is organized as follows. Next subsection introduces the multi-robot path planning and patrolling. Subsection 1.3.2 refers to software documentation history, installation instructions and user manuals of the related code. Wiki pages for this have been set up and maintained. They are available to all the project partners. More details can be found in Annex 2.3 and in Annex 2.4.

1.3.1 Multi-robot path planning and patrolling

This subsection is organized as follows. Next paragraph introduces the functional architecture. Paragraph 1.3.1.3 describes the two-level coordination strategy. Paragraph 1.3.1.4 presents the two different procedures for patrolling graph building. Paragraph 1.3.1.5 briefly introduce the 3D GUI designed for end-user interaction purposes. Paragraph 1.3.1.6 describes the communication model. Finally experimental results in Paragraph 1.3.1.7. More details can be found in Annex 2.1.

1.3.1.1 The Functional Architecture

The functional architecture for the real deployment of a team of UGVs is depicted in Fig. 1. The main blocks are listed below.

- The robots (each one with its own ID $\in \{1, ..., N\}$): these host the onboard functionalities which concern decision and processing aspects both at topological level and at metric level (depicted in Fig. 1 as subblocks). Laser mapping, segmentation and traversability analysis are at the bottom of the metric level pipeline [25, 17, 18, 21, 20].
- The core services hosted in the TRADR core: these represent the multi-robot system persistence and provide crucial services which allow the various modules to load and save map, trajectories and patrolling graphs.
- The core modules hosted in the TRADR core: these include the patrolling graph builder and the patrolling monitor.
- The multi-robot 3D GUI.

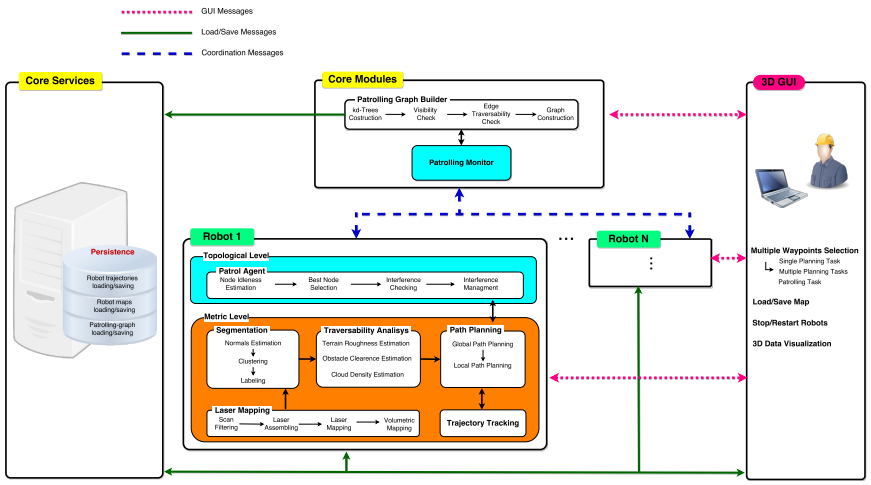


Figure 1: The functional architecture for multi-robot path planning and patrolling. Robots share the same architecture. Different kind of communication protocols based on different messages are established: a corresponding legend is depicted on the top left.

Each robot hosts its instance of the patrolling agent and of the path-planner. Hence, the implemented patrolling algorithm is fully distributed and inherently fault-tolerant.

1.3.1.2 Results

1.3.1.3 The Coordination Strategy

The architecture depicted in Fig. 1 implements a two-level coordination strategy in order to minimize the occurrence of robot interferences and spatial conflicts.

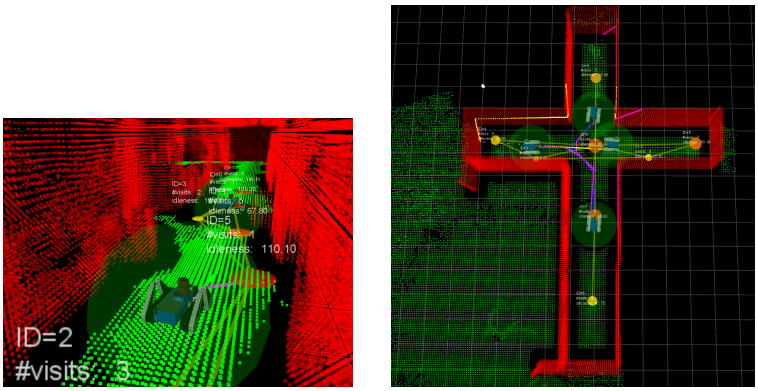
The two considered levels are the so called topological and metric levels.

On the *topological level*, each patrol agent uses a shared heuristic criterion and a coordination mechanism in order to select its target node and to prevent node topological conflicts (see Figure 2).

The *metric level* hosts strategies based on a metric representation of space, in which each robot path planner computes a traversable path towards the selected node position and minimizes the occurrences of spatial conflicts applying a multi-robot traversability function (see Task T2.3, Deliverable DR.2.3 for more details).

1.3.1.4 The Patrolling Graph

A *patrolling graph* is assigned to the robot team as input at the beginning of the task. This is a topological map representation of the environment region



(a) (b)

Figure 2: RVIZ Visualization (see Paragraph 1.3.1.5, Subsection 1.3.1) of a team of TRADR UGVs (2a) negotiating paths along a corridor and (2b) coordinating their planning strategy in a critical case. Point clouds are colored on the basis of the approach for traversability assessment described in [25, 17, 18]; yellow spots connected to straight lines of the same color denote nodes of the patrolling graph

the robots have to patrol. In this graph, a node represents an interesting 3D location to visit while an edge between two nodes represents the existence of a traversable path between the two corresponding locations.

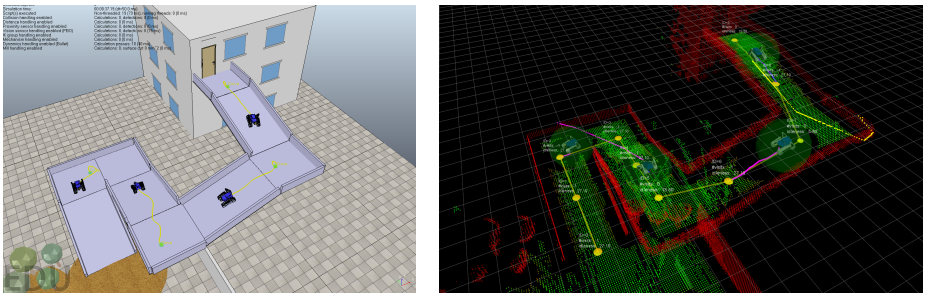
The patrolling graph can be defined by the user or from robot trajectories collected during past sorties.

In the first mode the user is provided with a 3D GUI. This GUI allows the user to load a saved map and to interactively build a patrolling graph on the corresponding traversable map (see Task T2.3, Deliverable DR.2.3 for more details).

In the second mode we resort to the approach similar to that described in [25] to estimate a potential patrolling graph in the form of an undirected graph from the trajectories followed by each robot during a past sortie,

1.3.1.5 3D Interface: RVIZ data visualization and commands

The 3D GUI allows to visualize the distinct robot maps and the distinct robot modules in the same main `/map` frame. This is possible since, in each robot, we added an intermediate `/robot_name/map` frame between the main `/map` frame and the `/odom` frame and we remapped each robot link frame by adding `/robot_name` prefix (more details can be found in Task T6.3, Deliverable DR.6.3).



(a) (b)

Figure 3: (3a) A team of TRADR UGVs deployed in virtual simulation (V-REP [14]) over `nimbro` and the TRADR Core; (3b) RVIZ Visualization (see Paragraph 1.3.1.5, Subsection 1.3.1) of scenario in Figure 3a.

1.3.1.6 Communication model

There are roughly three ways in which agents can communicate to each other: via flags, via blackboard, and via messages [24]. In this framework, we assume each robot directly communicates with the other robots of the team via broadcast messages. Message broadcasting is implemented on the top of a TCP layer[1] over a WIFI network. Each exchanged message includes the emitting robot ID in its header. Since TCP is a reliable connection-oriented protocol, messages are retransmitted in case of corruption or temporary connection loss[2].

1.3.1.7 Results

A preliminary test of the multi-robot path planning functionality has been carried out at T-Eval Meeting in Dortmund, last November 2016. In this meeting we collaborated with Fraunhofer (1) to set up `nimbro`, (2) to configure the TRADR Core to integrate (2a) traversability mapping; (2b) path planning; (2c) multi-waypoints planning; (2d) map saving and loading (in collaboration with ETHZ) and (2e) cycling patrolling ; (3) to deploy the 3D GUI, based on RVIZ, for both data visualization and end-user control interaction over the TDS workstations (more details can be found in Deliverable DR.7.3). In this meeting we also organized two training sessions in which we taught firefighters from FDDo how to use the 3D GUI to interact with the multi-robot path planning in virtual simulation (see Subsection 1.3.2, Section 1.3). See also Figure 3.

[1]This communication layer is actually implemented by using ROS as a middleware.

[2]The common known TCP model assumes that, in case of communication failures, TCP will be waiting again and repeating the retransmission process until a timeout happens that let it declares that the connection is over.

A further test for the multi-robot patrolling has been performed in collaboration with ETHZ during a meeting organized for this purpose, last December 2016. In this meeting we deployed the functional architecture described in Subsection 1.3.1, Section 1.3 on both ROMA and ETH UGVs - sent from Zurich for this work - at Alcor Laboratory in Rome, Italy. In this meeting we also tested `nimbro` over the TRADR Core (Fraunhofer). Apart from testing the integration, no additional performance measures have been taken in this meeting.

With the recent research advancements (see Annex 2.1), quantitative measures of the effectiveness of the multi-robot framework have been considered.

More results of multi-robot patrolling in virtual simulation can be found at `https://drive.google.com/drive/folders/0Bz1iamNH-s0kMEtpQ0NUeGduVGs`.

Due to the computational resources needed to deploy a team of TRADR UGVs in both virtual and real environments, the size of the team has been limited to four.

1.3.2 Software Development and Release

During Year 3 WP4 documented the process of software development. To this purpose two wiki pages on Redmine have been set up and regularly updated.

These pages mainly contain instructions about how to (i) get access to the software; (ii) build the code; (iii) make up and running the application and (iv) interact with the application.

The first page is reported under PDF format in Annex 2.3. It refers to how to build the TRADR System in virtual simulation via V-REP. It is also available at `https://redmine.ciirc.cvut.cz/projects/tradr/wiki/V-REP_Simulation`. Note that the above work builds upon the work presented in the oral presentation of Year 2 Review Meeting and partially reported Deliverable DR.4.2.

The second wiki page is attached in PDF format in Annex 2.4. It describe how to test the multi-robot path planning and patrolling framework. It is also available at `https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Launch_path_planning`.

These wiki pages are accessible to all the project partners to support them in the phase of running an application with the developed framework.

Finally, as reported in the last column of Table 1, the software interfaces with mapping have been done in collaboration with ETHZ. Fraunhofer supported us for the `nimbro` part, for the integration with the TRADR Core and for the upgrade of the network devices of the UGV. CTU together supported us for the update of the robot hardware related to the laser motor device.

1.4 Relation to the state-of-the-art

In this section we will describe how the results of WP4 in Year 3 are related to the state-of-the-art.

1.4.1 Multi-robot patrolling

Multi-robot patroling with advantages of spatial distribution and fault tolerance has found in recent years several applications in real domains where distributed surveillance, inspection or control are crucial (e.g., computer network administration [8, 13], security [3, 4, 22], search and rescue [1, 29, 7], persistent monitoring [38], hotspot policing [11], military [27]).

In this task, a team of robots is required to repeatedly visit a set of areas of interest, in order to monitor them [24, 12, 6, 15, 35, 32].

In the literature two main overlapping taxonomies can be identified for the existing approaches. They provide different classifications of them either on the basis of the kind of application [3, 4] or with respect to the applied theoretical principles [24, 12, 36, 15, 19, 22, 26, 34].

On the basis of the type of application, the existing approaches can be divided in adversarial patrol [40], perimeter patrol [5] and area patrol [32].

Regarding the theoretical baseline, they can be distinguished in pioneer methods [24], graph theory methods [12, 31] and alternative coordination methods [36].

The second taxonomy classifies the state-of-the-art approaches up to 2011 [32]. On the basis of recent research advancements in this field, an alternative subdivision might be devised. A proposal could be to further decompose alternative coordination methods in game theory methods [22], methods resorting to statistical approaches [36, 34], methods using principles from control theory [26] and also logic-based methods [7]. An alternative up-to-date review of some of the aforementioned works can also be found in [34] and in [39].

With respect to the aforementioned taxonomies, the approach that WP4 - in collaboration with other partners (e.g., with KIT, ETHZ, CTU and Fraunhofer) - developed in Year 3 of TRADR is at the intersection of the class of pioneer methods and the class of area patrol.

Scalability and computational complexity constraints and the end-user request of being provided with such a capability motivated the choice the pioneer architecture and the area patrol as type of application, respectively.

Pioneer methods are commonly based on simple architectures where heterogeneous robots with limited perception and communication capabilities are guided to locations that have not been visited for a while, aiming to maintain a high frequency of visits [32]. Under this setting, agents can behave either in a reactive (with local information) or in a cognitive (with access to global information) manner [24, 15]. Over the years, these methods

led to what is today better known as *frequency-based patrolling* [12, 16]. In this type of patrolling, the goal of the team of robots is to maximize a given frequency criterion, usually the *idleness* [31, 39], that is, the time between consecutive visits to a particular point within the patrol region [28, 33]. In [30], the authors state that in some cases, simple strategies, like the pioneer ones, with reactive agents, even without communication capabilities, can achieve equivalent or improved performance when compared to more complex ones. A study of the scalability and performance of some of the patrolling strategies mentioned above has been reported in [32].

Despite the focus that multi-robot patrolling has received recently, it can be noted that there is a manifest lack of practical real-world implementations of such systems [30]. Most of them do not account for 3D[10, 23, 28].

When dealing with real robots operating in harsh environments particular attention has to be payed on the communication, the coordination and the collaboration among the UGVs for safe joint navigation [2, 9, 37].

We improve the current state-of-the-art by proposing an approach, based on a two-level coordination strategy, to cope with the problems rising up in orchestrating a team of real robots deployed in a disaster environment. We migrated multi-robot patrolling on 3D worlds and, finally, we also provide a real deployment with a team of UGVs in an Urban Search & Rescue scenario, like that of Year 3 of TRADR project.

References

[1] J. J. Acevedo, B. C. Arrue, J. M. Daz-Bez, I. Ventura, I. Maza, and A. Ollero. Decentralized strategy to ensure information propagation in area monitoring missions with a team of uavs under limited communications. In *2013 International Conference on Unmanned Aircraft Systems (ICUAS)*, pages 565–574, 2013.

[2] José Joaquín Acevedo, Begoña C. Arrue, Ivan Maza, and Anibal Ollero. A distributed algorithm for area partitioning in grid-shape and vector-shape configurations with multiple aerial robots. *Journal of Intelligent & Robotic Systems*, 84(1):543–557, 2016.

[3] N. Agmon, S. Kraus, and G. A. Kaminka. Multi-robot perimeter patrol in adversarial settings. In *ICRA*, pages 2339–2345, 2008.

[4] Noa Agmon, Gal A. Kaminka, and Sarit Kraus. Multi-robot adversarial patrolling: Facing a full-knowledge opponent. *CoRR*, abs/1401.3903, 2014.

[5] Noa Agmon, Vladimir Sadov, Gal A. Kaminka, and Sarit Kraus. The impact of adversarial knowledge on adversarial planning in perimeter patrol. In *Proceedings of the 7th International Joint Conference*

on Autonomous Agents and Multiagent Systems - Volume 1, AAMAS '08, pages 55–62, Richland, SC, 2008. International Foundation for Autonomous Agents and Multiagent Systems.

[6] M. Ahmadi and P. Stone. A multi-robot system for continuous area sweeping tasks. In *ICRA*, pages 1724–1729, 2006.

[7] Derya Aksaray, Kevin Leahy, and Calin Belta. Distributed multi-agent persistent surveillance under temporal logic constraintsthis work was partially supported at boston university by the nsf under grants cmmi-1400167 and nri-1426907, and by the onr under grant muri n00014-09-1051. *IFAC-PapersOnLine*, 48(22):174–179, 2015.

[8] R de C Andrade, Hendrik T Macedo, Geber L Ramalho, and Carlos AG Ferraz. Distributed mobile autonomous agents in network management. In *Proceedings of International Conference on Parallel and Distributed Processing Techniques and Applications*, 2001.

[9] S. Bereg, L. E. Caraballo, J. M. Díaz-Báñez, and M. A. Lopez. Resilience of a synchronized multi-agent system. *ArXiv e-prints*, April 2016.

[10] Gonçalo Cabrita, Pedro Sousa, Lino Marques, and A De Almeida. Infrastructure monitoring with multi-robot teams. In *IROS*, pages 18–22, 2010.

[11] Huanfa Chen, Tao Cheng, and Sarah Wise. Developing an online cooperative police patrol routing strategy. *Computers, Environment and Urban Systems*, 62:19–29, 2017.

[12] Y. Chevaleyre. Theoretical analysis of the multi-agent patrolling problem. In *Proceedings of the IEEE/WIC/ACM International Conference on Intelligent Agent Technology*, pages 302–308, 2004.

[13] Timon C. Du, Eldon Y. Li, and An-Pin Chang. Mobile agents in distributed network management. *Commun. ACM*, 46(7):127–132, 2003.

[14] M. Freese E. Rohmer, S. P. N. Singh. V-rep: a versatile and scalable robot simulation framework. In *Proc. of The International Conference on Intelligent Robots and Systems (IROS)*, 2013.

[15] Y. Elmaliach, N. Agmon, and G. A. Kaminka. Multi-robot area patrol under frequency constraints. In *ICRA*, pages 385–390, 2007.

[16] Yehuda Elmaliach, Noa Agmon, and Gal A. Kaminka. Multi-robot area patrol under frequency constraints. *Annals of Mathematics and Artificial Intelligence*, 57(3):293–320, 2009.

[17] F. Ferri, M. Gianni, M. Menna, and F. Pirri. Point cloud segmentation and 3d path planning for tracked vehicles in cluttered and dynamic environments. In *In Proceedings of the 3rd IROS Workshop on Robots in Clutter: Perception and Interaction in Clutter*, 2014.

[18] F. Ferri, M. Gianni, M. Menna, and F. Pirri. Dynamic obstacles detection and 3d map updating. In *IROS*, pages 5694–5699, 2015.

[19] Antonio Franchi, Luigi Freda, Giuseppe Oriolo, and Marilena Vendittelli. The sensor-based random graph method for cooperative robot exploration. *IEEE/ASME Transaction on Mechatronics*, 14(2):163–175, 2009.

[20] M. Gianni, M. Garcia, F. Ferri, and F. Pirri. Terrain contact modeling and classification for atvs. In *ICRA*, pages 186–192, 2016.

[21] Mario Gianni, Federico Ferri, Matteo Menna, and Fiora Pirri. Adaptive robust three-dimensional trajectory tracking for actively articulated tracked vehicles. *Journal of Field Robotics*, pages n/a–n/a, 2015.

[22] Erik Hernández, Antonio Barrientos, and Jaime Del Cerro. Selective smooth fictitious play: An approach based on game theory for patrolling infrastructures with a multi-robot system. *Expert Syst. Appl.*, 41(6):2897–2913, 2014.

[23] L. Iocchi, L. Marchetti, and D. Nardi. Multi-robot patrolling with coordinated behaviours in realistic environments. In *IROS*, pages 2796–2801, 2011.

[24] Aydano Machado, Geber Ramalho, Jean-Daniel Zucker, and Alexis Drogoul. Multi-agent patrolling: An empirical analysis of alternative architectures. In *International Workshop on Multi-Agent Systems and Agent-Based Simulation*, pages 155–170. Springer, 2002.

[25] M. Menna, M. Gianni, F. Ferri, and F. Pirri. Real-time autonomous 3d navigation for tracked vehicles in rescue environments. In *IROS*, pages 696–702, 2014.

[26] D. Panagou, D. M. Stipanovi, and P. G. Voulgaris. Distributed coordination control for multi-robot networks using lyapunov-like barrier functions. *IEEE Transactions on Automatic Control*, 61(3):617–632, 2016.

[27] Chul-Hwan Park, Yeong-Dae Kim, and BongJoo Jeong. Heuristics for determining a patrol path of an unmanned combat vehicle. *Comput. Ind. Eng.*, 63(1):150–160, 2012.

[28] F. Pasqualetti, J. W. Durham, and F. Bullo. Cooperative patrolling via weighted tours: Performance analysis and distributed algorithms. *IEEE Transactions on Robotics*, 28(5):1181–1188, 2012.

[29] C. Pippin and H. Christensen. Trust modeling in multi-robot patrolling. In *ICRA*, pages 59–66, 2014.

[30] D. Portugal and R. P. Rocha. Scalable, fault-tolerant and distributed multi-robot patrol in real world environments. In *IROS*, pages 4759–4764, 2013.

[31] David Portugal and Rui Rocha. Msp algorithm: Multi-robot patrolling based on territory allocation using balanced graph partitioning. In *Proceedings of the 2010 ACM Symposium on Applied Computing*, pages 1271–1276, New York, NY, USA, 2010. ACM.

[32] David Portugal and Rui P. Rocha. Multi-robot patrolling algorithms: examining performance and scalability. *Advanced Robotics*, 27(5):325–336, 2013.

[33] David Portugal and Rui P. Rocha. *Retrieving Topological Information for Mobile Robots Provided with Grid Maps*, pages 204–217. Springer Berlin Heidelberg, Berlin, Heidelberg, 2013.

[34] David Portugal and Rui P. Rocha. Cooperative multi-robot patrol with bayesian learning. *Autonomous Robots*, 40(5):929–953, 2016.

[35] Tiago Sak, Jacques Wainer, and Siome Klein Goldenstein. *Probabilistic Multiagent Patrolling*, pages 124–133. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008.

[36] Hugo Santana, Geber Ramalho, Vincent Corruble, and Bohdana Ratitch. Multi-agent patrolling with reinforcement learning. In *Proceedings of the Third International Joint Conference on Autonomous Agents and Multiagent Systems - Volume 3*, AAMAS '04, pages 1122–1129, Washington, DC, USA, 2004. IEEE Computer Society.

[37] M. Shahriari and M. Biglarbegian. A new conflict resolution method for multiple mobile robots in cluttered environments with motion-liveness. *IEEE Transactions on Cybernetics*, PP(99):1–12, 2016.

[38] Cheng Song, Lu Liu, Gang Feng, and Shengyuan Xu. Optimal control for multi-agent persistent monitoring. *Automatica*, 50(6):1663–1668, 2014.

[39] Chuanbo Yan and Tao Zhang. Multi-robot patrol: A distributed algorithm based on expected idleness. *International Journal of Advanced Robotic Systems*, 13(6):1729881416663666, 2016.

[40] R. Yehoshua, N. Agmon, and G. A. Kaminka. Robotic adversarial coverage: Introduction and preliminary results. In *IROS*, pages 6000–6005, 2013.

2 Annexes

2.1 Freda (2017), "3D Multi-Robot Patrolling with a Two-Level Coordination Strategy: Simulations and Experiments"

2.1.0.1 Bibliography

Freda, L. Gianni, M. Pirri, F. Dubé ,R. Gawel, A. Cadena, C. and Siegwart, R. "3D Multi-Robot Patrolling with a Two-Level Coordination Strategy: Simulations and Experiments". Submitted to Autonomous Robots. Springer.

2.1.0.2 Abstract

Teams of robots patrolling harsh and complex environments can experience interference and spatial conflicts crucially affecting their activity. If neglected, these fundamental aspects can hinder patrolling methods to attain sound performances. In this work we present a distributed multi-robot patrolling technique in which a two-level coordination strategy is used in order to minimize and explicitly manage the occurrence of conflicts and interferences. On a first level, a topologically based strategy, under which each agent selects its target node on a topological map, relies on a shared heuristic criterion and a coordination mechanism so as to prevent topological conflicts, such as same target node selection. The second level hosts strategies based on a metric representation of space, using a laser-based SLAM system, in which each robot path planner manages and minimizes the occurrences of spatial conflicts applying a multi-robot traversability function. The approach is fully distributed and inherently fault-tolerant. Extensive simulations and experiments show how the proposed method can effectively and efficiently take care of conflicts and interferences amid robots in a patrolling team.

2.1.0.3 Relation to WP

This work presents the research advancements with respect to the coordination and collaboration at different architectural level of a team of UGVs patrolling a real disaster scenario, under the supervision of the end-users. Besides, this work wants to place emphasis on the close synergies with other project partners that actively contributed with ROMA to achieve the reported results.

2.1.0.4 Availablity

Restricted. Not included in the public version of this deliverable.

2.2 Wiki-MR-Use-Cases (2017), "Multi-Robot Use Cases Wiki page on Redmine"

2.2.0.5 Bibliography

Freda, L. Gianni, M. "Multi-Robot Use Cases Wiki page on Redmine.". 2016-2017.

2.2.0.6 Abstract

Wiki page on Redmine collecting useful information for the identification of interesting multi-robot tasks within the TRADR project. The objective of this page is two-fold: (1) to clearly define a set of doable tasks which will be actually implemented for the reviews and demos and (2) to foster collaboration and discussions within the TRADR team.

2.2.0.7 Relation to WP

It is related to the contribution of WP4 to use-cases of Year 3 of TRADR project (see Section).

2.2.0.8 Availablity

Unrestricted. Included in the public version of this deliverable. Also available at `https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Multi-Robot_Use_Cases_Definition`.

2.3 Wiki-VREP (2017), "V-REP Simulation Wiki page on Redmine"

2.3.0.9 Bibliography

Freda, L. Gianni, M. "V-REP Simulation Wiki page on Redmine.". 2016-2017.

2.3.0.10 Abstract

Wiki page on Redmine describing how to make up and running in V-REP the TRADR system.

2.3.0.11 Relation to WP

It is related to the implementation of the research work presented in Subsection 1.3.2, Section 1.3.

2.3.0.12 Availablity

Unrestricted. Included in the public version of this deliverable. Also available at `https://redmine.ciirc.cvut.cz/projects/tradr/wiki/V-REP_Simulation`.

2.4 Wiki-MR (2017), "Multi-Robot Path Planning and Patrolling Wiki page on Redmine"

2.4.0.13 Bibliography

Freda, L. Gianni, M. "Multi-Robot Path Planning and Patrolling Wiki page on Redmine.". 2016-2017.

2.4.0.14 Abstract

Wiki page on Redmine describing how to get access to the code related to the implementation of the multi-robot path planning and patrolling. It contains a detailed set of guidelines describing how to set up the application in a virtual simulated environment as well as how to use it.

2.4.0.15 Relation to WP

It is related to the implementation of the research work presented in Subsection 1.3.2, Section 1.3.

2.4.0.16 Availablity

Unrestricted. Included in the public version of this deliverable. Also available at `https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Launch_path_planning`.

Multi-Robot Use Cases

The **goals** of this page are:

1. to collect useful information for the identification of interesting multi-robot tasks within the TRADR project
2. to clearly define a set of **doable tasks** which will be actually **implemented** for the reviews and demos
3. to collect all the related implementation details and issues that will arise along the way
4. foster collaboration and discussions within the TRADR team on multi-robot collaboration topics

End-users are kindly invited to add relevant information and define the desired tasks.

N.B.: Some of the target implementations have **dedicated wikis**:

- Pseudo-Collaborative Patrolling in a Static Environment: Pcpse

Assumptions

Robots deployment
- *Ground layer*: two UGVs collaborate on the ground level in order to perform the assigned cooperative tasks (exploration, patrolling, etc..)
- *Air layer*: one UAV independently flies over the facility in order to continuously monitor it and provide a strategic overview

End-users Requirements

End-users are kindly invited to add relevant requirements for the identification/selectection of the multi-robot tasks which will be actually implemented.

FDDO (Norbert)
- common monitoring
- common search in a building keeping connection between each other and to the command car or an other human -> relay function, swarm behaviour
- common exploration of a special dangerous area as fast as possible, UGVs alone and/or in collaboration with the UAVs
- common exploration by UAVs

Questions
Luigi: what do you mean by *monitoring*? Does it match with the patrolling task defined below?

> *Vlada: I guess those are just synonyms; my impression is that Norbert would like to see robots moving around and monitoring things like fire, gas, or major changes in the mission area (blocked corridor for example)*
> *Norbert: patrolling means you look around for changes, dangers ... but more or less without concrete objectives. Monitoring means the other way around you have fixed places where you take measurements, ...*
> *Luigi: in my view, Norbert's patrolling definition can be implemented as an exploration or coverage task as defined below (see sect. Low-Level Mission/Task Definition), depending on the availability of a previously built map, and should be combined with a parallel detection module (which is responsible for instance of detecting victims or other specific objects of interest). Norbert's monitoring definition can be implemented as a patrolling as defined below (see sect. Low-Level Mission/Task Definition). We took the definitions below from robotics literature.*

High-Level Mission/Task Definition

Here some **conceptual** definitions of the multi-robot collaboration tasks.

- **Use case specifications**:
  - a fire/accident causes the discharge of dangerous substances into the air -> UGVs get the order for monitoring, persistant data of environment + data about weather = autonomous plannig and measuring -> value driven measurement concerning path planing
  - a building of "second priority" could be explored by UGVs which relieves the In-field rescuer/Attack Teams (after reorganisation)
  - the exploration of an unknown, may be damaged area, should be done quick. UAVs deliver Lidar data for a predictive UGV path planning -> Lidar mapping (discussed in Zurich) -> systematologies of area exploration
  - time critical beginnig of a mission: UAVs split the job into parallel executable tasks 1) overview, 2) victim search, 3) 3D model and further images, 4) other risks (fire, substances, ...), 5) monitoring -> UGVs for details
- **Human interface definition**:
  - end-user selects interesting areas for patrolling in RVIZ (is that possible?)
  - message passing through memory (StarDog)

Low-Level Mission/Task Definition

Here we define a small collection of low-level multi-robot tasks which can be relevant within the TRADR project:

- **Offline coverage**: *cover* (with sensory perceptions) an environment which is a priori known in the most "efficient" way.
- **Patrolling**: an environment must be continually surveyed by a group of robots such that each point is visited/covered with equal frequency - given a *graph-representation* of the environment (*nodes* represent reachable and safe regions, *edges* represent traversable paths joining them), patrolling requires continuously visiting all the graph nodes so as to minimize the time lag between two visits. In an automated surveillance system, at each goal station, the robot stops and analyses the scene searching for victims, scene variations or abandoned/removed objects. *NOTE*: patrolling is a persistent task, it never ends, no notion of completeness.
- **Online coverage** (aka **exploration**): cover (with sensory perceptions) an unknown environment in the most "efficient" way. See below *Exploration Requirements*.

> *Vlada: Not feasible during Y3, let's focus on Patrolling*
> *Luigi: PSE and PLDE had the priority*

- **Sensor network deployment**: deploy robot sensors in order to completely cover a given region and guarantee uniform spatial density. This requires the deployment of a significant number of robots.

> *Vlada: Nice to have, but again, patrolling makes more sense with our resorces*
> *Luigi: here the list just aims at identifying interesting tasks (at least in principle)*

In this context, **efficiency** can be evaluated by defining suitable metrics which take into account task completion time, traveled path, used communication bandwidth, etc.

A multi-robot task can be defined within one or multiple sorties.

Single-sortie Missions

In a single-sortie mission the two UGVs can be required to perform one of the following tasks:

- **Y3: Autonomous patrolling**: a map of the environment is already available and provided to the robots; robot autonomously plan their paths in order to visit/cover all the regions of the environment with equal frequency.
- **Y3: Assigned waypoints patrolling**: a map of the environment is already available and provided to the robots; users assign a set of waypoints to the robot team by using a suitable GUI; the robots negotiate the waypoints and then autonomously plan their paths in oder to cyclically visit all the waypoints without interfering with each other.

> *Vlada: From the implementation point of view, isn't this actually an implementation of the previous point?*
> *At least the "cover" requirement? I would suggest to stop here and postpone the following point to Y4*
> *Luigi: the path-planning (input: start,goal,pcl -> output: safe trajectory) and trajectory-control modules*
> *can be arranged to be the same. The **cooperative** and **autonomous** planning algorithms which determine*
> *where to go (which waypoints) and when, are an important/required add-on.*

- **Y4: Exploration**: the UGVs autonomously explore and map the facility.
- **Y4: Coverage**: a map of the environment is already available and provided to the robots; the UGVs autonomously plan their paths in oder to cover the environment with sensory perceptions.
- **Y5: Lost robot**: a UGV is missed and no connection to the base station. But the taken path is available from waypoint navigation. The second UGV and/or UAV are looking for it.

Multi-sortie Missions

In a multi-sortie mission the two UGVs can be required to perform one of the following tasks:

- **Parallel patrolling w/o collaboration**: Map is given, user defines areas by polygons or whatever to patrol, each robots patrols a single area.
- **Exploration + Patrolling**: in a first sortie, the robots explore the environment and build a map; in a second sortie the robots execute a patrolling task (autonomous or through assigned waypoints) by exploiting the previously built map
- **Exploration + Coverage**: in a first sortie, the robots explore the environment and build a map; in a second sortie the robots execute a coverage task by exploiting the previously built map

Target Implementations

Here we specify the multi-robot tasks that will be actually implemented for reviews and demos.

1. Pseudo-Collaborative Patrolling in a Static Environment (PCPSE)

This is a Vlada's proposal for TJEX/TEVAL 2016, Luigi is editing/commenting as well.
Since Abel and Renaud expect to have multi-robot-mapping/cooperation not sooner than end of Y3, let's define lighter version of patrolling. We can still claim that it is multi-robot, but these robots will perform patrolling of distinct areas in parallel. Let's assume a patrolling mission in a static environment. A map of the environment is already available and was built in a previous dedicated sortie. If we get this running during summer, we can build and test based on it until review, where additional inter-robot communication and planning could be added and tested.

See the dedicated page: PCPSE

2. Patrolling in a Static Environment (PSE)

We can start experimenting with the simplest multi-robot task: a patrolling mission in a static environment (see *Issues->Dynamic Environments* below). A map of the environment is already available and was built in a previous dedicated sortie. In order to implement a PSE algorithm the following requirements are fundamental.

PCPSE - Table of Requirements

ID	Description	Status	Estimated Delivery Date	Key Partners	Notes	Issues/Questions
PSE1	Environment is static	-	-	-	-	-
PSE2	The environment map is already available and given as input to the robots	OK	Now available	ETH	-	-
PSE3	The robots are able to continuously **localize** themselves w.r.t. the given map	?	?	ETH	This means the robotS share a single "map" reference frame	-
PSE4	Robots are able to continuously **communicate and exchange** their positions and relevant data	?	?	FRA, ROMA, ...	In principle, if a map is available and the environment is static, all the robot trajectories can be planned and shared beforehand (when mission starts) without requiring further data communications. Nevertheless, exact temporal execution of the planned trajectories cannot be guaranteed in a USAR environment and each robot can be seen as an high-dynamic obstacle by the other robots. Therefore, for robustness reasons, it is desirable that robots keep on continuously exchange information (at least their estimated positions) and possible plan updates.	See below *General Issues->Multi-robot communication*
PSE5	GUI definition/implementation for waypoints assignment	?	?	FRA, ROMA, CTU, ...	Patrolling can be completely autonomous (if the waypoints are autonomously planned by the algorithm) or end-users can explicitly assign a set of interesting goal stations. See more details in *Low-Level Mission/Task Definition* above.	-
PSE6	TRADR DB management for persistency	?	?	FRA, ROMA, ETH, CTU, ...	We need to define and store relevant data structures in MongoD (e.g. maps, traversability, related infos). We need to implement the interface towards MongoDB.	-
PSE7	PSE algorithm implementation	WIP	T-Eval	ROMA	Currently testing/developing under simulation	...
						Consider a starting narrow

PSE8	Dynamic mapping (at least considering robot occlusions)	TODO	T-Eval	ETH, CTU, ROMA	Mapping has to be able to clean robot ghost/trails from the built map.	corridor, robot A starts behind robot B. Robot A will perceive robot B as an obstacle. Robot A mapper module must be able to clean the ghost/trail of robot B from the map, otherwise the path planner of robot A won't be able to compute a plan and move from its starting position. So we have to avoid robot A from being trapped by ghosts :-) . In order to cope with that, **without a decent dynamic mapping**, we have to (1) select a sufficiently large region where to the start (2) suitably arrange the initial robot positions (3) suitably procrastinate the start of robot A (4) guide the robots to patrol two distinct and well-separated regions in order to avoid further problematic meetings (5) do some tests...
PSE+	...	...	...	...	...	...

To be defined:

- Do robots start from the same point or from distinct points?

3. Patrolling in a Low-Dynamic Environment (PLDE)

As a second step we can consider an environment with low-dynamic objects (see *Issues->Dynamic Environments* below). Also in this case, a map of the environment is already available and was built in a previous dedicated sortie. In order to implement a PLDE algorithm the following requirements are fundamental.

PLDE - Table of Requirements

ID	Description	Status	Estimated Delivery Date	Key Partners	Notes	Issues/Questions
PLDE1	Environment has some low-dynamic features (e.g. some obstacles were moved w.r.t. previous mapping sortie)	-	-	-	-	See below *General Issues->Dynamic Environment*
PLDE2	The environment map is already available and given as input to the robots	OK	Now available	ETH	-	-
PLDE3	The robots are able to continuously **localize** themselves w.r.t. the given map	?	?	ETH	This means the robotS share a single "map" reference frame	-
PLDE4	Robots are able to continuously **communicate and exchange** their positions and relevant data	?	?	FRA, ROMA, ...	-	See below *General Issues->Multi-robot communication*
PLDE5	GUI definition/implementation for waypoints assignment	?	?	FRA, ROMA, CTU, ...	Patrolling can be completely autonomous (if the waypoints are autonomously planned by the algorithm) or end-users can explicitly assign a set of interesting goal stations. See more details in *Low-Level Mission/Task Definition* above.	-
PLDE6	Mapping module communicates the necessary map updates to the planner module (as early as possible) taking into account moved/changed obstacles	?	?	ETH	For efficiency reasons, it is desirable the mapping module also communicates a geometrical description of the changed regions to the planner module (so as to allow efficient local updates of traversability/segmentation data)	

PLDE7	TRADR DB management for persistency	?	?	FRA, ROMA, ETH, CTU, ...	We need to define and store relevant data structures in MongoD (e.g. maps, traversability, related infos). We need to implement the interface towards MongoDB.	-
PLDE8	PLDE algorithm implementation	WIP	T-Eval	ROMA	Currently testing/developing under simulation	...
PLDE+	...	...	...	...	...	...

To be defined:

- Do robots start from the same point or from distinct points?

Other Tasks

...

Multi-Robot Communication

Here we specify the communication interfaces and the data which need to be exchanged by the robots for the tasks of interest.

Required data

- Pseudo-collaborative Patrolling Static Environment (PCPSE): each robot must broadcast
  1. its position w.r.t. the shared map
  2. required sensory data, at the moment available ones are: flammable gasses, smoke, victims. Planned: fire and hot-spot detection in thermo
  3. its ability to proceed with the assigned plan - if not able, broadcast an alarm informing about major change in the assigned area
- Patrolling Static Environment (PSE): each robot must multicast/broadcast
  1. its position w.r.t. the shared map
  2. its planned path to the next target position
  3. required sensory data, at the moment available ones are: flammable gasses, smoke, victims. Planned: fire and hot-spot detection in thermo (usually only one robot bears thermocam).
- Patrolling Low-Dynamic Environment (PLDE): each robot must multicast/broadcast
  1. its position w.r.t. the shared map
  2. its planned path to the next target position
  3. local map updates
  4. required sensory data
- Exploration: each robot must multicast/broadcast
  1. its map (global or local map updates)
  2. its position w.r.t. the shared map (assuming individual maps overlap and map merging/registration can be successfully applied)
  3. its planned path to the next target position
  4. required sensory data

Multi-Robot Database Management

Robot1 and Robot2 cooperatively explore the environment and need to store their data in the DB.
The two following approaches can be envisioned.

Centralized multi-robot localization and map fusion

Each robot writes its individual map into the DB. During the mission a map-fusion-global-optimizer receives/reads the individual maps from the DB, globally register (additional loop closure detections?) and fuse them in a *new multi-robot map*. This new multi-robot map is then sent back to each robot. Each robot re-localizes in it, replaces its individual map with the new received/queried multi-robot map and starts extending it and sharing its position w.r.t. It. In this approach, the DB stores an individual map for each robot + a new resulting multi-robot map. A mechanism should be decided to manage further individual map updates (which should trigger somehow the map-fusion-global-optimizer to start a new job).
PROS: kind of "simpler" centralized approach.
CONS: robustness issues w.r.t. network disruption.

Decentralized multi-robot localization and map fusion

Each robot receives/queries the individual maps coming from the other robots and is responsible of independently fusing them with its own map. Each robot writes its map updates to the DB and share them with the other robots by using network communication (or DB?). In this approach, the DB stores a map for each robot. In principle, if robots forms disconnected

subnetworks each individual map can be different from the others; on the other hand, if robot network graph is complete (each pair of robots can communicate) the individual maps should coincide up to measurement noise and assuming perfect global optimization (and no critical loop closure errors). Here, the DB could also be used just to store the "best" individual map that is built by the robots. But how?
PROS: robust w.r.t. network failures
CONS: more complex (obviously)

Questions

- In a multi-robot context, do we need to use the DB (as a common blackboard) for sharing intermediate results? See for instance the decentralized multi-robot DB management above: in principle, we could use the DB just for storing a final acquired world representation (e.g. select the best map and just store this).

See also the discussion here
https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Database_Management_for_Mapping_and_Planning_20160609

General Issues

- **Dynamic Environment**: the environment can change substantially over time. This has to be explicitly managed by both the mapping and planning modules. Environment can have low-dynamic or high-dynamic features depending of the considered time-scale and actual rapidity of the changes. **Low dynamic** environments are in general composed of static and low-dynamic entities that can be moved or changed at any time, such as small obstacles, barriers and walls. In this case, a simple and widespread approach is to detect and treat them as outliers and locally update the map. On the other hand, **high-dynamic** objects continuously change the environment and must be represented and tracked explicitly with suitable techniques such as multi-target tracking. In this latter case, obstacle avoidance techniques (relying on fast data acquisitions) are also in order after global path planning guarantees the existence of a path toward a designated goal on the basis of the available built map. In principle, each robot can be also seen as a moving obstacle by the other robots: in this case data sharing and distributed/coordinated motion planning can efficiently manage inter-robot collision avoidance.

> *Vlada: Y3: Lets deal with dynamic environment by halting execution and informing end-user that something major has changed - goes well with patrolling task*

- **Y4: Mutual localization**: in order to collaborate the robots must know their mutual positions in their individual maps. This can be achieved by using suitable techniques such as *map registration*, *map merging*, *place recognition* (appearance-based localization), etc. Map registration is obviously possible when a *minimal overlap* among individual maps occur so as to allow a consistent map merging. In order to ease this process we can make the robots start from the same point in order to guarantee an initial minimal overlap.

> *Vlada: Let's concentrate on this feature in Y4*

- **Multi-robot communication**: a multi-robot task can be actually performed as long as **inter-robot communication** is working and information are shared.
  - *Ensuring communication constraints*: in order to communicate, robots may be required to jointly satisfy some geometrical constraints at all times (e.g. maintain mutual line-of-sight visibility and maintain their mutual distance below a certain maximum threshold) or may be called for a rendezvous after communication loss lasts more than a certain time interval. This is required to guarantee better cooperation/coordination: map/information integration should be done as early as possible, since the availability of a shared map/information greatly facilitates the coordination between robots.
  - *Robustness*: even if one robot fails catastrophically, others should take over its subtask. Fault-tolerant methods should be deviced. What actually happens when the robot communication completely falls down?
  - Careful *network analysis and profiling* must be performed in order to ensure that the actual network bandwidth is sufficient to allow all the required data to be exchanged among robots.

> *Vlada: For Y3, I propose to check mutual distance only to avoid collisions.*
> *Vlada: I think the following points might by addressed for Y4 if we manage to get the inter-robot communication and robot-database running during Y3*

- **Multi-robot heterogeneous collaboration**: w.r.t. the tasks defined above, define how to efficiently/properly consider each robot specific characteristics in the role assignment and team deployment. Can we/end-users assign different labels to each environment region beforehand in order to suggest preferred task assignments or team deployments? (e.g. label regions where samples have to be analysed in order to prefer their assignment to UGVs equipped with robotic arm).

- **Interface definition**:
  - How a single operator can efficiently guide the two UGVs and assign them a cooperative task? An efficient and (hopefully) simple interface should be defined to this aim.
  - Is the operator allowed to interrupt a robot for assigning it a different task?
  - Which are the allowed control modes of the single robots during a multi-robot task execution? (e.g. Am I allowed to move the camera during a patrolling?)

- Clarify the **control modes** as well as the technologies to develop the interaction, the communication and the collaboration between robots and humans.

- Discuss problems related to the integration with the TRADR ontology, the low-level database (MongoDB) and the high-level database (Stardog)

V-REP Simulation

Installing V-REP

1. Download version 3.2.2 (tested) from here
   http://coppeliarobotics.com/files/V-REP_PRO_V3_2_2_64_Linux.tar.gz
   You don't need to compile anything. Just extract the files in your V-REP installation folder and you are ready to execute the main launcher (vrep.sh) from there.
   Note: V-REP 3.3 does not work. You'll have to use 3.2.2 or fix the UGV script for 3.3

1. Set the environment variable *VREP_ROOT_DIR*: add in your .bashrc the following line
   export VREP_ROOT_DIR=<here you put the absolute path of your V-REP installation folder (which contains the launcher vrep.sh)>

Updating and Compiling the *tradr-simulation* Stack

1. Open a shell, get into your tradr workspace and update your working copy of the repo git@gitlab.ciirc.cvut.cz:tradr/tradr-simulation

   ```
   $ cd tradr_ws/src/tradr-simulation/
   $ git pull
   ```

2. Then compile the workspace with your favorite catkin tool

Installing the *vrep_ugv_plugin* Package

Once you have updated and compiled the tradr-simulation stack, you have to copy the lib *tradr_ws/devel/lib/libv_repExtRos.so* in the installation folder *VREP_ROOT_DIR* (NOTE: this lib enables V-REP to get and parse track velocity command messages)

Testing the *vrep_ugv_simulation* Package

In order to test the package, two procedures are possible

1. **Lauch script**
   - open a terminal, source the tradr workspaces and execute

     ```
     $ roslaunch vrep_ugv_simulation vrep_ugv_simulation.launch
     ```

   - **press the play button on V-REP**
2. **Manual**
   - open a terminal and run roscore
   - open another terminal and execute

     ```
     $ cd $VREP_ROOT_DIR
     $ ./vrep.sh
     ```

     V-REP will be launched: from its *File* menu open an environment file.ttt in the package folder *vrep_ugv_simulation/data*. Use one of the following files: *ugv1_rescue_grousers.ttt* or *ugv1_rescue_stairs_grousers.ttt*
   - open another terminal and execute

     ```
     $ roslaunch vrep_ugv_simulation vrep_ugv_teleop_keyboard.launch
     ```

   - **press the play button on V-REP**
   - **N.B.**: if you kill the roscore you need to restart V-REP again.

Once you completed one of the above procedures, you should have your simulator running and a small window with title *"UGV TeleOp"* should appear. Keep the focus on that window (click on it) and you will be able to move the UGV with the arrow keys. By using the keys 'A','S','D','W' you are also able to change the configuration of its flippers in order to climb stairs.

The keyboard settings can be modified by editing the python script *vrep_ugv_simulation/script/vrep_ugv_teleop_key*.

V-REP with the Path Planner

1. Update and compile the path planning stack as described on this page
   https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Launch_path_planning
2. Lauch the UGV simulation on V-REP: open a new terminal, source the tradr workspaces and run

   ```
   $ roslaunch vrep_ugv_simulation vrep_ugv_simulation.launch
   ```

3. **press the play button on V-REP**
4. Run the path planner with its RVIZ interface:
   - If you want to run the **single-waypoint** path planner, open a new terminal and run

     ```
     $ roslaunch path_planner sim_main_path_planner_ugv1.launch
     ```

   - Otherwise, if you want to run the **multi-waypoint** path planner, open a new terminal and run

     ```
     $ roslaunch path_planner sim_main_queue_path_planner_ugv1.launch
     ```

On the following page you can find a concise description of how to use the RVIZ interface in order to feed new goals to the path planner
https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Launch_path_planning

V-REP with the Multi-Robot Mapping and Path Planning

1. As above, update and compile the path planning stack as described on this page
   https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Launch_path_planning
2. Compile the laser_slam workspace as described here
   https://github.com/ethz-asl/laser_slam/wiki/How-to-build-laser_slam-packages (official installation guide)
   https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Laser_SLAM_Workspace_Installation (you need to use a separate installation of PCL 1.8, this is short guide on how to solve compilation and RVIZ issues)
3. Lauch the multi-UGV simulation on V-REP: open a new terminal, source the tradr and laser_slam workspaces and run

```
$ roslaunch vrep_ugv_simulation vrep_ugv_simulation_mapping.launch
```

4. Run the multi-robot mapping nodes:

```
$ roscd path_planner/scripts
$ ./sim_launcher_mapping_ugv1n2
```

5. **press the play button on V-REP**
6. On RVIZ: the path planning is enabled for both robots. In order to select the WPs for **ugv1** press **"m"** and then stick the WPs on ugv1-traversability cloud and start (as explained in https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Launch_path_planning).
   In order to select the WPs for **ugv2** press **"l"** and then stick the WPs on ugv2-traversability cloud and start.

You will see different xterms opening (one for each main group of nodes) and reporting you the messages of the distinct nodes.
Attached to this page, you can find the diagrams of the frames and of the nodes.

Brief description of the architecture:
- robot i has its own laser_mapper, which is responsible for the localization of the robot i with respect to its own map_i and odom_i frames
- from V-REP we provide the tf server with the transformations from /map_i to /map (as agreed during the last meetings this is a an important input we must provide to the real system at the beginnig of the mission)
- one octomap manager integrates/merges the two maps coming from the single robots in single global map: the result is a single volumetric map which is available w.r.t. /map frame
Hence, at present time, we still have a /map frame :-)

V-REP with Multi-Robot Patrolling

1. Update and compile the path planning stack as described on this page
   https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Launch_path_planning
2. Compile the laser_slam workspace as described here
   https://github.com/ethz-asl/laser_slam/wiki/How-to-build-laser_slam-packages (official installation guide)
   https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Laser_SLAM_Workspace_Installation (you need to use a separate installation of PCL 1.8, this is short guide on how to solve compilation and RVIZ issues)
3. Download and compile in your TRADR workspace the **repo**: tradr-multirobot **@branch**: patrolling_sim_devel (see the README of the repo for detailed instructions)
4. Open a new terminal and source the TRADR workspace along with the new tradr-multirobot workspace, then execute

```
roscd patrolling_sim/scripts
./sim_launcher_ugv1n2_light
```

5. **press the play button on V-REP**

What is going to happen?

- a proper V-REP world will be automatically launched
- a pre-built volumetric map will be loaded in the robot map managers (for convenience, this map has been already built and pushed in the repo; you can built it by yourself and use it)
- a pre-built graph (which nodes to visit) will be loaded and used by the patrolling agents (for convenience, this graph has been already built and pushed in the repo)
- the robots will start patrolling the environment: given a graph-representation of the environment (nodes represent reachable and safe regions, edges represent traversable paths joining them), patrolling requires continuously visiting all the graph nodes so as to minimize the time lag between two visits (node idleness)
- see the README file of the repo tradr-multirobot for advanced instructions

Videos: see in this shared folder https://drive.google.com/drive/folders/0B1oevBvCpw_vTGtIOUcxMl9Banc

V-REP and the Path Planner with Multimaster_fkie

The following instructions explain how to work with a multi-master V-REP simulation:

- V-REP runs on one host along with its ROS master
- your nodes run on a second host along with a second ROS master
- the two masters discover each other and sync their info by using multimaster_fkie (http://wiki.ros.org/multimaster_fkie?distro=kinetic): the distributed nodes will behave like they were under a single ROS master.

Steps:
1. install the package multimaster_fkie on both hosts
2. be sure that the ROS_IP is set on both hosts; this can be done by adding to the .bashrc files the following lines

```
# ROS: set automatically ROS_IP
export ROS_IP_=`hostname -I | head -n1 | awk '{print $1}'`
if [ "$ROS_IP_" != "" ]; then
    export ROS_IP="$ROS_IP_"
fi
```

3. on the first host:
   - open a new terminal and run: $ roscore
   - open a new terminal and run: $ roslaunch tf_remapper multimaster_discovery_and_synch.launch

1. on the second host:
    - open a new terminal and run: $ roscore
    - open a new terminal and run: $ roslaunch tf_remapper multimaster_discovery_and_synch.launch
    - open a new terminal and run: $ roslaunch vrep_ugv_simulation vrep_ugv_simulation.launch

1. on the first host:
    - open a new terminal and run: $ roscd path_planner/scripts; ./sim_launcher_ugv1n2

V-REP Patrolling, Path Planning and Mapping over NIMBRO Network

Introduction: in order to develop and easily test the multi-robot network framework, we have prepared a VREP robot simulator which emits the same topics of an actual robot. Two instances of this simulator are launched, each one running on a distinct computer (as if they were two distinct actual robots). Laser mapper, traversability and path planner are normally launched (as on the actual robots). One of this computer is also used as a "tradr core" (by using a distinct roscore; clearly this is not a limitation since an additional computer can be also used without problem). Nimbro relays are activated and fully work.

In this simulation framework, you need two computers (PC). Two instances of V-REP will be launched.
Each instance of V-REP acts as an actual robot and will emit the same topics of an actual robot (the main ones).
The simulated robot 'sim1-robot' and a minimal tradr-core interface will run on the first computer.
The second robot 'sim2-robot' will run on the second computer.

1. Update and compile the path planning stack as described on this page
   https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Launch_path_planning
2. Update, compile and install the vrep_ugv_plugin package as explained above.
3. Compile the laser_slam workspace as described here
   https://github.com/ethz-asl/laser_slam/wiki/How-to-build-laser_slam-packages (official installation guide)
   https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Laser_SLAM_Workspace_Installation (you need to use a separate installation of PCL 1.8, this is short guide on how to solve compilation and RVIZ issues)
4. Now go through the following steps

- setup the hostname in the configuration file of the robots 'sim1-robot' and 'sim2-robot' in the dir tradr-network/tradr_relay_conf/; open a new terminal
  `$ roscd tradr_relay_conf/conf`
  `$ gedit sim1-robot.xml &` <-- set the prefix=ugv1 and hostname=localhost
  `$ gedit sim2-robot.xml &` <-- set the prefix=ugv2 and set the hostname of your second PC
- remove the labels `ugv1` and `ugv2` from any other actual robot configuration file <name>-robot.xml
- then run the following command
  `$ rosrun tradr_relay_conf generate_launchfiles.py`
- you can accomplish the above first steps on your PC/laptop and then synch the files between your PC/latop and the second PC (you can use rsynch for instance)

- in a first PC, launch the first robot 'ugv1'
  1) launch VREP
  `$ roslaunch vrep_ugv_simulation vrep_ugv_simulation_robot_ugv1.launch`
  press the play button
  2) launch the robot nodes and the nimbro robot relay
  `$ roscd path_planner/scripts`
  `$ ./sim_launcher_nimbro_robot 1` <-- set the CORE_HOSTNAME and the first arguments in the script
  here the usage is: ./sim_launcher_nimbro_robot <robot-id> <core-hostname>

- in a second PC, launch the second robot 'ugv2'
  1) launch VREP
  `$ roslaunch vrep_ugv_simulation vrep_ugv_simulation_robot_ugv2.launch` <-- NB use the file with suffix ugv2!
  press the play button
  2) launch the robot nodes and the nimbro robot relay
  `$ roscd path_planner/scripts`
  `$ ./sim_launcher_nimbro_robot 2` <-- set the CORE_HOSTNAME and the first arguments in the script
  here the usage is: ./sim_launcher_nimbro_robot <robot-id> <core-hostname>

- in the first PC, launch the minimal tradr core relay
  `$ roscd path_planner/scripts`
  `$ ./sim_launcher_nimbro_core true` <-- set the first arguments therein ->
  here the usage is: ./sim_launcher_nimbro_core <RUN_SIM> where RUN_SIM=true/false specifies if we are running a simulation or not. With REAL robots you can simply launch
  `$ ./sim_launcher_nimbro_core` on SIMULATION you instead have to run `$ ./sim_launcher_nimbro_core true`

- now you will see a global RVIZ and the patrolling starting

- in order to let the robots plan a path on the patrolling graph you have to command each robot to load the map; for each robot
  1) enable on RVIZ the /ugvi/slam_marker (Interactive marker)
  2) right-click over it and select the action "Reset octomap and load previous map"

- building a patrolling graph: in order to have this feature enabled you have to set BUILD_PATROLLING_GRAPH_ON_START="true" on both the scripts "path_planner/scriptsscreen_launcher_ugvmulti_lasermapper_pathplanner" and "path_planner/scripts/sim_launcher_nimbro_core";
  on RVIZ, load the map on ugv1 (this procedure won't work on ugv2);
  press 'm' on the keyboard and stick a set of waypoint on the traversability carpet then right-click on one of the waypoint marker and select the action "Patrolling - send task";
  the patrolling graph will be saved and can be used on further patrolling missions by setting BUILD_PATROLLING_GRAPH_ON_START="false" on both the scripts;
  now the patrolling will automatically start

- using a saved patrolling graph: in order to have this feature enabled you have to set BUILD_PATROLLING_GRAPH_ON_START="false" on both the scripts "path_planner/scripts/sim_launcher_nimbro_robot" and "path_planner/scripts/sim_launcher_nimbro_core"

- pause/restart patrolling: on RVIZ press 'm' and then 'q' for pausing or 'w' for restarting

- if you want just to test the multi-robot path planning, you can set the variable ENABLE_PATROLLING=0 in both the scripts sim_launcher_nimbro_robot and sim_launcher_nimbro_core.
  In this case, you can set the waypoints for the two robots by using the keys "m" and "l".
  In order to select the WPs for the robot sim1 press "m" and then stick the WPs on ugv1-traversability cloud and start (as explained in

Multi-Robot Path Planning and Patrolling

Required Git repos and their branches

- **repo**: tradr-loc-map-nav @(master) **package**: path_planner
  https://gitlab.ciirc.cvut.cz/tradr/tradr-loc-map-nav/tree/master/path_planner
- **repo**: tradr-loc-map-nav @(master) **package**: trajectory_control
  https://gitlab.ciirc.cvut.cz/tradr/tradr-loc-map-nav/tree/master/trajectory_control
- **repo**: tradr-msgs @(master) **package**: trajectory_control_msgs
  https://gitlab.ciirc.cvut.cz/tradr/tradr-msgs

Please, install Octomap packages in oder to compile the path_planner package.
You can find a concise documentation at https://gitlab.ciirc.cvut.cz/tradr/tradr-loc-map-nav/blob/master/path_planner/README.md.

Launch the Basic Modules Needed by the Path Planner

Launch the ugv_multi drivers and the new ETHZ laser mapper

- on robot:

```
roslaunch nifti_drivers_launchers ugv_multi.launch
```

- on robot, start the new ETH mapping:
  ~~roslaunch nifti_mapping_launchers mapAndNav.launch~~

```
roslaunch laser_mapper main_laser_mapper_tf_remapped.launch
```

Launching the Single-Waypoint Path Planner

First launch the basic drivers and laser mappers as described above.
Then, to run the path planner and connect it to the output of the ETHZ laser mapper

- on robot, start the planner:

```
roslaunch path_planner main_path_planner.launch
```

- on your laptop, start our rviz interface:

```
roslaunch path_planner rviz_path_planning.launch
```

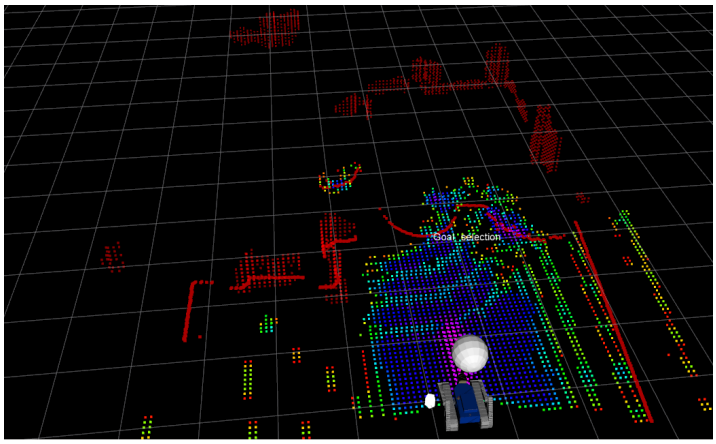
On RVIZ, you can set a goal for the planner by using the dedicated **interactive marker**. The interactive marker (a sphere) will appear over the robot when you launch the path_planner node.

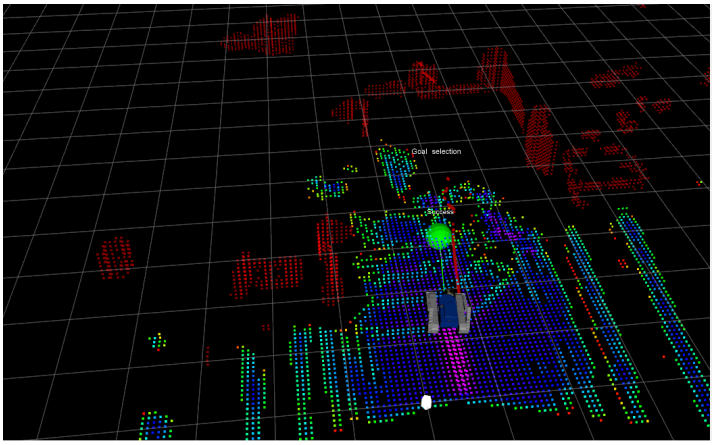
1. Move the marker at your desired position (hold left click on it and move it w.r.t. image plane; if you also hold SHIFT button you will change the depth of the marker)
2. Then right-click on it and select from the menu the action *"Select Goal"*. If you want to abort the goal once is selected, select the action *"Abort Goal"* from the same menu.
3. Text messages will appear over the marker explaining you what is happening. The **marker color** will change accordingly:
   - *Grey*, path planner is waiting for a goal selection
   - *Yellow*, the path planner is planning
   - *Green*, a path has been found
   - *Red*, the path planner could not find a path

N.B.: a path to the designated goal can be actually computed if the shown traversability map actually "connect" the goal and the robot positions. You may be required to wait few seconds till the traversability node actually complete the traversability map construction from the ICP mapper inputs.

Once a path has been found, the path planner will publish it towards the trajectory controller which will make the robot automatically follow the path.

There are **visualization topics** for the planned path, the normals of the point cloud and the merged point clouds. If you launch our script **rviz_path_planning.launch**, you will find everything already set up.





Launching the Multi-Waypoint Path Planner

First launch the basic drivers and laser mappers as described above.
Then, to run the multi-waypoint path planner and connect it to the output of the ETHZ mapper

- on robot, start the planner:

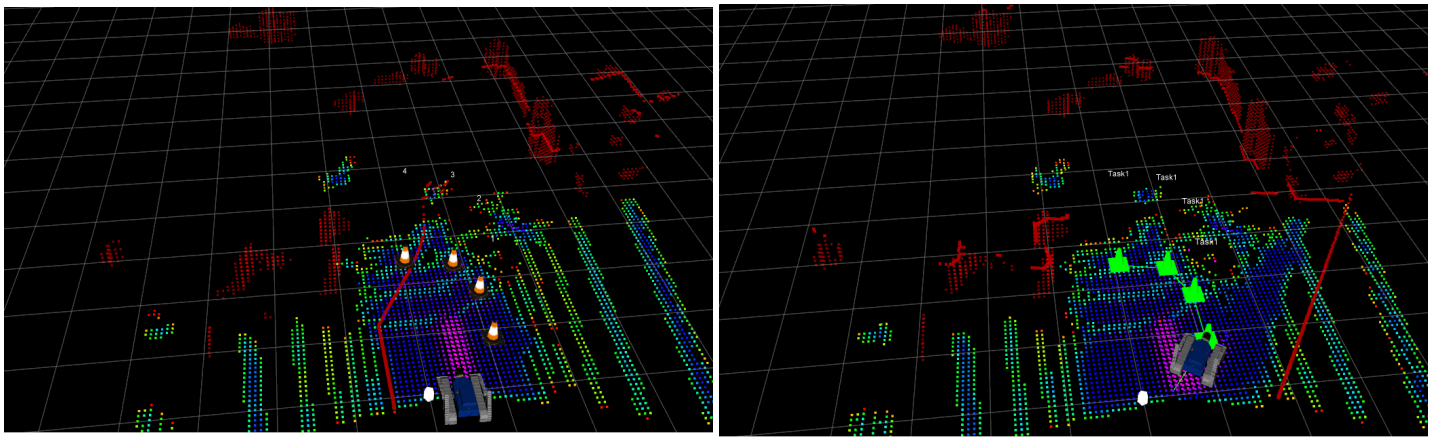
```
roslaunch path_planner main_queue_path_planner.launch
```

- on your laptop, start our rviz interface:

```
roslaunch path_planner rviz_path_planning.launch
```

On RVIZ:

1. Press the key 'M' in order to add a new waypoint directly on the traversability cloud. You can move each created waypoint by holding right click on it and moving. The waypoints should automatically stick to the traversability cloud.
2. Once you have selected your desired number of waypoints you can right click on one of them and select from the menu the action *"Append Task"*. If you want the robot to continuously revisit the waypoints you set (**cyclic path**), then select the action *"Append Cyclic Task"*.
3. The **marker colors** will change accordingly:
   - *Orange*, the marker has not been added
   - *Yellow*, the path planner is planning
   - *Green*, a path has been found
   - *Red*, the path planner could not find a path
4. Once the waypoints get green, you can right click on one of them and select from the menu the action *"Stop the controller"* in order to stop the trajectory control and the robot.



Multi-robot Patrolling, Path Planning and Mapping over Nimbro Network

Before starting this procedure, you have to build a map of the environment and save it.
In order to achieve that you can execute just the following step 1 and step 2 on one selected robot.
Once the selected robot is active and you get the global RVIZ interface running, move the robot around and build your map.
Once you are satisfied with the map, you can save it by enabling and using the /ugvi/slam_marker (Interactive marker): right-click on it and select the action "Save current map and trajectory".

(1) on your laptop (used as core) and on the two selected robots (for instance, you can use roma and eth robot):
setup the nimbro configuration file of each robot in the dir tradr-network/tradr_relay_conf/

- you can accomplish this first step on your laptop and then synch the files between your laptop and both the selected robots (you can use rsynch for instance)
- open a new terminal
  `$ roscd tradr_relay_conf/conf`
  `$ gedit <your robot-name>-robot.xml &`
  see the README.md of the package tradr_relay_conf which explains how to setup the nimbro configuration file.
  The labeling in roma-robot.xml and eth-robot.xml files should be the following
  `roma-robot->prefix: ugv1` this corresponds to a multi-robot robot_id = 1
  `eth-robot->prefix: ugv2` this corresponds to a multi-robot robot_id = 2
  N.B. the label `ugv1` and `ugv2` are used to label the robots which will be actually used in the nimbro network for patrolling and path-planning.
  These labels can be used for activating a pair of simulated robots OR a pair of actual robots, but only a pair of robots at once!
  This means that when you use `ugv1` and `ugv2` for roma-robot::prefix and eth-robot::prefix, you should remove these labels from sim1-robot::prefix and sim2-robot::prefix,
  otherwise nimbro won't work.
- set and check the configuration variables in the two scripts "path_planner/scripts/screen_launcher_ugvmulti_lasermapper_pathplanner" and "path_planner/scripts/sim_launcher_nimbro_core",
  in particular set the same PATROLLING_MAP_NAME=DIAG3D (this corresponds to a folder patrolling_sim/maps/DIAG3D which must exist)
- then run the following command
  `$ rosrun tradr_relay_conf generate_launchfiles.py`
- if you want you can now synch the files with rsynch between your laptop and both robots

(2) copy your map and graph files on each robot and on your laptop

- copy the saved map files ('map.bt map.ply trajectory.csv') on each robot and on your main laptop in the ".ros" folder
- to this aim, you can use for instance the script path_planning/scripts/copy_maps_to_robots

(3) on the first robot ugv1

- start the robot in the same position where you started the robot which built the saved map (reference starting position)
- kill all the nodes which are running on the robot: you can do that by executing the following command on the robot
  `$killall -9 screen; screen -wipe`
- open a new terminal
  `$ rosrun tradr_relay_conf generate_launchfiles.py`
  `$ roscd path_planner/scripts`
- then launch the main script
  `$ ./screen_launcher_ugvmulti_lasermapper_pathplanner <robot-prefix> <robot-id> <core-hostname>`
  for instance on roma robot (tagged `ugv1`)
  `$ ./screen_launcher_ugvmulti_lasermapper_pathplanner 1 192.168.2.54`
  and on eth robot (tagged `ugv2`)
  `$ ./screen_launcher_ugvmulti_lasermapper_pathplanner 2 192.168.2.54`
  in order to kill everything you can use
  `$ killall -9 screen; screen -wipe`

(4) on the laptop

- check the file /etc/hosts and if needed add your robot hostname-IPs
- open a new terminal and run
  `$ rosrun tradr_relay_conf generate_launchfiles.py`
  `$ roscd path_planner/scripts`
  `$ ./sim_launcher_nimbro_core <RUN_SIM>`
  where RUN_SIM=true/false specifies if we are running a simulation or not.
  With REAL robots you can simply launch
  `$ ./sim_launcher_nimbro_core`
  on SIMULATION you instead have to run
  `$ ./sim_launcher_nimbro_core true`
- now you will see a global RVIZ
- load the map on the first robot: enable on RVIZ the /ugv1/slam_marker (Interactive marker), right-click over it and select the action "Reset octomap and load previous map"

(5) on the second robot ugv2

- start the robot in the same position where you started the robot which built the saved map (reference starting position)
- repeat the actions described on the step 3 above for the first robot
- load the map: enable on RVIZ the /ugv2/slam_marker (Interactive marker), right-click over it and select the action "Reset octomap and load previous map"

(6) on the laptop: building a patrolling graph

- in order to have this feature enabled you have to set BUILD_PATROLLING_GRAPH_ON_START="true" on both the scripts "path_planner/scriptsscreen_launcher_ugvmulti_lasermapper_pathplanner" and "path_planner/scripts/sim_launcher_nimbro_core"
- on RVIZ, load the map on ugv1 (this procedure won't work on ugv2)
- press 'm' on the keyboard and stick a set of waypoint on the traversability carpet
- then right-click on one of the waypoint marker and select the action "Patrolling - send task"
- the patrolling graph will be saved and can be then used on further patrolling missions by setting BUILD_PATROLLING_GRAPH_ON_START="false" on both the scripts
- now the patrolling will automatically start

(7) on the laptop: using a saved patrolling graph

- in order to have this feature enabled you have to set BUILD_PATROLLING_GRAPH_ON_START="false" on both the scripts "path_planner/scriptsscreen_launcher_ugvmulti_lasermapper_pathplanner" and "path_planner/scripts/sim_launcher_nimbro_core"
- copy the saved file patrolling_sim/maps/DIAG3D/DIAG3D.graph (which is on your laptop in the map folder specified by the var PATROLLING_MAP_NAME=DIAG3D, which corresponds to the folder patrolling_sim/maps/DIAG3D) in the same folder patrolling_sim/maps/DIAG3D/ on both robots

(optional) on the laptop: pause/restart patrolling

- on RVIZ press 'm' and then 'q' for pausing or 'w' for restarting the patrolling

(optional) on the laptop: aligning a robot current map with a saved map

- copy the saved map (map.bt, map.ply and trajectory.cvs) on both robots and on the laptop
- on RVIZ enable the interactive marker and select "Reset octomap and load previous" in order to load the saved map (which should be copied on the selected robot)
- then if you want to align by using the interactive marker
  `$ roscd path_planner/scripts`
  `$ ./sim_launcher_core_interactive_point_cloud_publishers`

If you want just to test the multi-robot path planning, you can set the variable ENABLE_PATROLLING=0 in both the scripts sim_launcher_nimbro_robot and sim_launcher_nimbro_core.
In this case, you can set the waypoints for the two robots by using the keys "m" and "l".
In order to select the WPs for the robot sim1 press "m" and then stick the WPs on ugv1-traversability cloud and start (as explained in https://redmine.ciirc.cvut.cz/projects/tradr/wiki/Launch_path_planning).
In order to select the WPs for the robot sim2 press "l" and then stick the WPs on ugv2-traversability cloud and start.

Playing with the Path Planner on V-REP

You can find the details on this page
https://redmine.ciirc.cvut.cz/projects/tradr/wiki/V-REP_Simulation

Videos

- TJex 2016 Mapping and Point Cloud Segmentation
  https://www.youtube.com/watch?v=74yp_fHpDpY&feature=youtu.be