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HYFLIERS

D4.1

Measurement data management service and path planning algorithm

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Abstract:

This document reports about the measurement data management service in pipe inspection operations. The service supports the communication among the hybrid robot (including its components comprising the measurement sensor, i.e. the arm or satellite), the mobile support platform and the remote data site. The hub of the communication is represented by the mobile support platform, which acts as a hotspot for inspection-related data streams and is also connected to the operator (inspection personnel) user interface terminal and the pilot controller. This document also presents the first developments concerning the path planning algorithms of the hybrid robots. These algorithms will allow autonomous operation since they bring motion plans that allow navigating both safely and efficiently through a sequence of inspection points. With this purpose, the planning algorithms will take advantage of the capabilities of hybrid motion offered by the system (rolling/flying). Furthermore, reactive behaviours will also be implemented in case the on-board sensors reveal the presence of obstacles not considered in the planning algorithms. This capacity of reaction reinforces the level of robustness and autonomy offered by the system. Because of its role in measurement data and in supporting hybrid robot navigation, this deliverable also reports about the design and development of the mobile support platform itself. The mobile support platform's functionality and a hardware overview is presented, as well as is the related testing equipment used in mobile support platform's development. In addition to the above roles, the platform is also exploited as a flexible power supply for the equipment used in inspection operations. Preliminary test results of the mobile support platform's hardware are briefly presented.

Keywords:

Battery charging. Battery management. Data management. Data visualization. Hybrid robot. Navigation support. Operations support. Path planning. Pipe inspection Remote control. Support platform. Unmanned aerial vehicle. Wireless networking.

Executive summary

This document describes the measurement data management service and path planning algorithm as well as the corresponding support platforms functions, based on initial system specifications and the considerations in the system architecture in earlier deliverables [D1.1] and [D1.2].

Firstly, this deliverable describes the measurement data management service and the corresponding environment. More in details, this document illustrates the following aspects.

- Measurement data service put into the context of oil and gas plants pipe inspection, with an emphasis on the measurement data from collection to delivery at end user. In particular, the data sources, the data types and their flow in the system up to the end user are described. The sequence of the messaging among the architectural elements is illustrated graphically.
- Architecture of the system, including the components of the related HYFLIERS subsystem, providing additional details on the data, the interfaces involved in data exchange, and the structure of the messages themselves.
- Data management environment, providing details on hardware and software components, including a detailed description of the communication among hybrid robot (HR), mobile support platform, pilot and support operator.

Secondly, the document covers the first developments concerning the planning algorithms of the movement of the HR and their associated navigation support (obstacle detection, reactive behaviours, etc.). These algorithms pave the way for autonomous operation of the HR in their inspection tasks. A general overview of the three work-lines under this topic is presented below. This document presents developments concerning mostly the first work-line. Additionally, some extensions related to the reactivity capabilities included in the third work-line have also been covered.

- Generation of motion plans that allow autonomous motion along complete sequences of inspection points.
  - Consideration of the obstacles included in the maps of the industrial environments to generate trajectories free of collisions.
  - Consideration of the hybrid motion capabilities (flying, rolling) offered by the HR to generate optimal trajectories accordingly to different indices (operation time, power consumption).
- Extensions of motion planner to guarantee safer trajectories for autonomous operation
  - Consideration of dynamic behavior of the system.
  - Consideration of aerodynamic effects produced by the proximity of the elements that require inspection (horizontal arrays of pipes, vertical pipes / deposits, etc.).
- Navigation support to enhance the level of autonomy offered by the system
  - Implementation of reactive behaviors in case the on-board sensors reveal the presence of obstacles not considered in the planning algorithms.
  - Implementation of re-planning strategies in case that modifications of the inspection tasks arise during the execution of the global mission.

Lastly, this document presents the hardware and software related to the MSP:

- The operations support utilized by the inspection personnel to link and operate with the hybrid robot.
- The software and hardware considerations for linking with the HR.

- Power distribution for the inspection and HR operation related hardware.
- Support functions related to HR battery charging.

The design and test results related to the mobile support platform are presented in this document, with the accompanying hardware that has been utilised during the testing process. This document describes the basic functionality of the mobile support platform for the HR, so that in later stages the support platform can be adjusted and fine-tuned according to the requirements of the project partners.

Abbreviations and symbols

3D	three-dimensional
3G	third generation mobile communication system
5G	fifth generation mobile communication system
AC	alternating current
API	application programming interface
AR	augmented reality
ATEX	explosive atmosphere (from French: atmosphères explosibles)
CAN	controller area network
CPU	central processing unit
DC	direct current
DMP	data management plan
EMI	electromagnetic interference
FCU	flight control unit
GCS	ground control station
GS	ground station
HDMI	high-definition multimedia interface
HMR	hybrid mobile robot
HR	hybrid robot (either HMR or HRA)
HRA	hybrid robot with arm
HYFLIERS	hybrid flying rolling with-snake-arm robot for contact inspection
ISO	International Organization for Standardization
JPEG	Joint Photographic Experts Group
Li	lithium
LiDAR	light detection and ranging
MCU	microcontroller unit
MSP	mobile support platform
NED	north, east, down
NFC	near field communication
PC	personal computer
PSU	power supply unit
UAV	unmanned aerial vehicle
UGV	unmanned ground vehicle
UI	user interface
USB	universal serial bus
Wi-Fi	Wireless Fidelity (synonym for WLAN, wireless local area network)

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Foreword

The following text reports the review comments (in italics and between quotation marks) followed by a summary of the changes implemented in this revised version:

"More elaboration on the measurement data management service is needed with respect to the project modules, the overall specifications and the needs of the use cases. The deliverable reports on the system architecture and hardware of the system, but it is lacking information about how data are handled, stored, processed and provided to the end user."

The section on measurement data management service part has been largely extended (from about 4 to about 14 pages), providing all the requested details. First, the measurement data service is put into the context of oil and gas plants pipe inspection, with an emphasis on the measurement data from collection to delivery at end user. Then, the data sources, the data types and their flow in the system up to the end user are described. The sequence of the messaging among the architectural elements is illustrated graphically. These two improvements are mainly responding to the review comments and recommendations. More, the architecture of the system, including the components of the related HYFLIERS subsystem, provides additional details on the data, the interfaces involved in data exchange, and the structure of the messages themselves. Finally, the data management environment provides details on hardware and software components, including a detailed description of the communication among hybrid robot (HR), mobile support platform, pilot and support operator. These two last points complement the first two above improvements.

In addition, with the revision of the report, also the path planning algorithm part has been extended (from about 4 to about 9 pages). The main improvement in this part concerns the description of the path planning algorithms features from the viewpoint of the autonomy levels. This aspect was not a remark for D4.1 and it is more thoroughly addressed in other deliverable revisions (namely, D1.1 and D1.2), but this issue is addressed also here for completeness.

Finally, some changes have improved the deliverable clarity throughout, in order to better present each part of the report, thus also addressing the review comments by better conveying the material included here. Mainly, the sections have been rearranged, to give a better progression along the topics (first the core topics, measurement data management service and path planning algorithm, and then mobile support platform, which has the role of actually supporting the two core topics).

As the last changes, this Foreword section has been added to document the revisions and the Executive summary has been extended to provide a more detailed view on the contents of the deliverable.

1. Introduction

This is the first deliverable of HYFLIERS workpackage WP4, dedicated to the Operation Support. The overall objective of WP4 is to study, specify and develop supporting functions for the operation of the hybrid robot and management of the measurement data.

This deliverable D4.1 reports about "Measurement data management service and path planning algorithm". Management of measurement data is covered by Task 4.2 "Measurement data management", whereas path planning and other navigation support functionalities to increase system autonomy are being addressed by Task 4.1 "3D navigation support" and Task 4.3 "Mobile ground support". The developments required for the mobile ground support platform are also provided by Task 4.3 "Mobile ground support". Results from all these three tasks are therefore included in this report, respectively in sections 2, 3 and 4.

The whole HYFLIERS system is depicted in Figure 1 [D8.1]. HYFLIERS project envisages two prototypes for the inspection robot: a hybrid mobile robot (HMR) and a hybrid robot with arm (HRA) [D8.1], either one denoted here as hybrid robot (HR). The HR is operated by an inspection operator through a portable control unit.

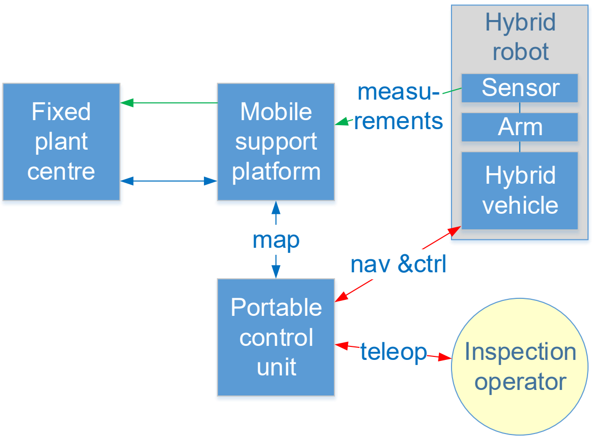

Figure 1. The role of the mobile support platform within the HYFLIERS system [D8.1].

2. Measurement data management (T4.2)

This section describes the measurement data management service and the corresponding environment. More in details, it will cover:

- The measurement data service put into the context of oil and gas plants pipe inspection, with an emphasis on the measurement data from collection to delivery at end user; the data sources, the data types and their flow in the system up to the end user; and the sequence of the messaging among the architectural elements graphically illustrated (section 2.1).
- The architecture of the system, providing additional details on the data, the interfaces involved in data exchange, and the structure of the messages themselves (sections 2.2 and 2.3).
- The data management environment, including its hardware and software components, and a detailed description of the communication among hybrid robot (HR), mobile support platform, pilot and support operator (section 2.4).
- The functional testing of the above features (section 2.5).

2.1. Measurement data from collection to delivery at end user

The scope of deliverable [D8.2] is the presentation of the data management plan (DMP) concerning data that can be made openly available. For the open data presented there, that deliverable must describe, in addition to this purpose, origin and utility of data collection, also source, type, format and size of the collected data themselves.

This section provides some details about the *measurement data* processed in the HYFLIERS system, thus also serving as a preparation for a possible contribution to the above DMP [D8.2], if applicable.

Figure 2 depicts the inspection use case diagram highlighting the main actors.

The measurement data of interest to the end user [D1.1, D1.2] are the thickness measurements performed by non-destructive ultrasonic sensors [D1.3] and the related supporting information, as explained below.

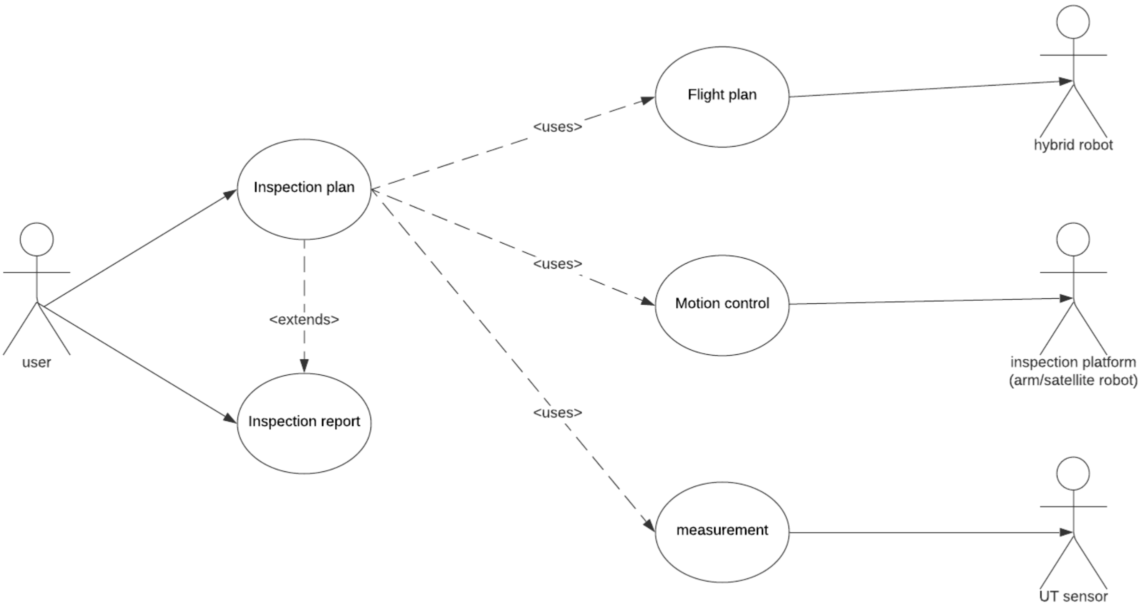

Figure 2. Use case diagram, considering the main actors in the system: user, aerial platform, inspection platform (robotics arm or satellite robot) and UT sensor.

Thickness measurements:

- for point measurements, the thickness reading assumes values in the range of 0,2 mm to 635 mm [D1.3];
- typically, the entire circumference is inspected and 4 to 16 points around the circumference are generated [D1.3];
- A-scan can be continuous, generating for example 50 to 100 measurements per second, but applying data reduction to reduce already at sensor side the sample size [D1.3], or punctual, generating for example 250 points; these measurements can be formatted as vectors of point measurements together with the adopted specified inspection location spacing, which is for example 150 to 300 mm [D1.3];
- B-, C- and D-scans are continuous measurements, see the subcase of A-scans above;

- grid measurements are point measurements performed on a grid with a side of for example 15 to 30 cm [D1.3]; these measurements can be formatted as matrices of point measurements together with the adopted specified inspection grid step.

Other measurement-related information:

- photograph(s) of the inspection point, could be none, one or more pictures per site, depending on the inspection plan and on the inspection result, see above;
- pipe location in the plant (local or geographic coordinates, or specific identification label); this may be a both ways parameter (i.e., from the back system to the HR, and vice versa; see inspection plan and report in Figure 3);
- position on pipe follows the reference system on the pipe given in section 1.1. of [D1.2], where a positive coordinate x is along the direction of the flux within the pipe; this also may be a both ways parameter (i.e., from the back system to the HR, and vice versa; see target in Figure 3);
- generic additional information such as timestamp of measurement (date and time, e.g. ISO 8601 format);
- optionally, additional information about measurement conditions such as meteorological (wind, temperature, rain, etc.).

Figure 3 depicts the inspection operations with a focus on the measurement data flow along the chain of the entire HYFLIERS system. For simplicity, the two prototypes are represented in the figure with the same element, the HR block including the HMR with its satellite or the HRA with its arm. Since the focus is on measurement data, the HR control/supervision happening through the pilot is not shown.

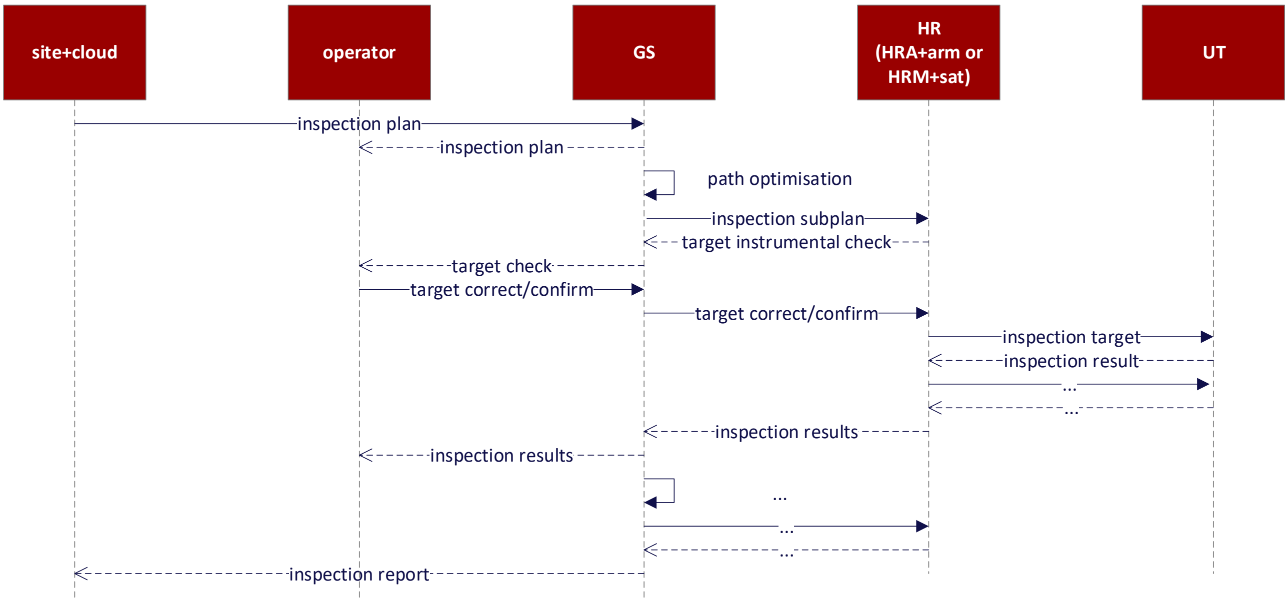

Figure 3. Sequence of inspection operations from the measurement data service perspective, along the HYFLIERS system: site/cloud – ground station GS with attached operator's device – hybrid robot HR (i.e. either hybrid mobile robot HRM with its satellite, or hybrid robot with arm) – ultrasonic sensor UT.

An inspection plan includes the coordinates of the inspection targets. The inspection plan is optimised regarding the path to follow, see section 3, and broken down into subplans. These include local inspection locations to which the inspection sensor is instructed to reach to perform the actual measurements. The sensing component returns the result of the inspection in the form of thickness readings and images of those locations, see text above. The results of the subplans are collated at the ground station to form the inspection report delivered to the plant site.

The end-user part of the system includes a site point at the plant and a cloud-based information management service. The inspection report generated at the GS is provided to the site/cloud through a dedicated application programming interface (API) designed to be compatible with interfacing the database management system at the back end. The interface is designed to properly manage the data and metadata outlined according to the databases structure. More details on this will be reported in the following WP4 deliverable D4.2.

The mobile support platform (MSP), see section 4, provides radio communication capabilities between the HR and the data sink (e.g. at or through the plant centre) by splitting the link into two hops, thus reducing requirements on transmit power, energy consumption and battery size and weight at the HR.

All the data are collected and processed in HYFLIERS according to the data management plan (DMP) [D8.2] and in accordance with ethical guidelines [D9.1]. The functionality has been planned and designed in accordance with [D1.2], system concept and architecture.

2.2. Architecture

The measurement data management service addresses how the measurement data collected by the HR are handled, stored, processed and provided to the users. Its definition should consider not only the system architecture but also the detailed specification about the measurement process and data formats. These are covered by this and the following sections.

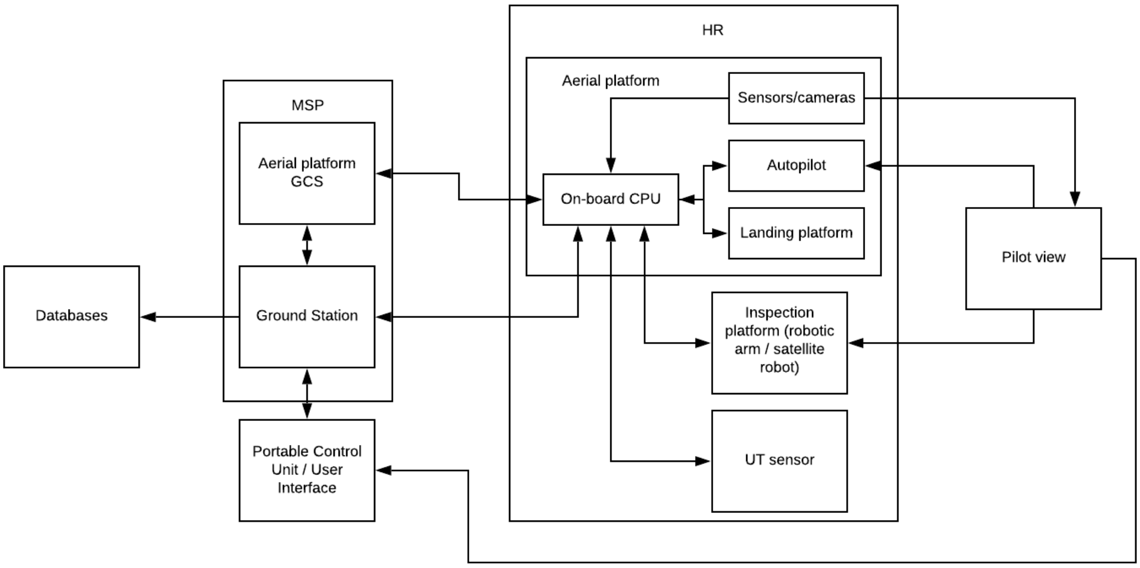

Figure 4. Data interchange diagram in HYFLYERS system.

The system is based on a ROS (robot operating system) Kinetic architecture, where the interfaces between the different modules are made through ROS topics and services. A mavros[1] node is in charge of connecting the ROS architecture within the autopilot through MAVLINK[2] messages. Figure 4 presents the overall system architecture based on the main modules and their interfaces. Regarding the considered reference system, four different frames are considered according to the deliverable [D1.2], see below.

2.3. Interfaces and data exchanged between modules

Table 2 summarises the interfaces and data-exchanged between the main modules in the system, with the coordinate conventions used therein illustrated by Table 1.

Table 1: Coordinate systems used in HYFLIERS [D1.2]

Name	**Purpose**	**Definition**
World (north, east, down, NED)	Fixed frame to describe positions in the plant to be inspected	Z = down (with gravity)
Pipe (P)	Fixed to the specific pipe to be inspected	X = pipe flow direction
Robot (B)	Local frame of the HR	Z = down X = forward
Ultrasonic transducer, UT (U)	Local frame at the inspection location, bound to the UT probe	Z = vertical to pipe surface, into the material X = flow direction

Table 2: List of messages used in HYFLIERS

	Data	**Source**	**Sink**	**Description**
1	Measurement points	User interface	MSP	List of points: (x, y, z, q)
2	Inspection plan	MSP	HR (on-board central processing unit, CPU)	List of ordered commands: (x, y, z, q, type {waypoint, landing, arm motion, measurement…})
3	UAV target position	HR (on-board CPU)	HR (autopilot)	Waypoint: (x, y, z, q)
4	Landing command	HR (on-board CPU)	HR (landing platform)	Command
5	Measurement target position	HR (on-board CPU)	HR (inspection platform)	Relative position in the tube: x, y, z, q
6	Measurement command	HR (on-board CPU)	HR (UT sensor)	Command
7	Telemetry data	HR (autopilot / on-board sensors)	MSP	Different messages with timestamp: uav position, uav attitude, uav flight mode, uav battery, imu data, gimbal attitude, inspection platform relative position

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[1] http://wiki.ros.org/mavros

[2] https://mavlink.io/en/messages/common.html

8	LiDAR (light detection and ranging) data	On-board sensors	MSP	Timestamp, points-cloud
9	UT measurement	HR (UT sensor)	MSP	Timestamp, measurement
10	Photograph	HR (cameras)	MSP	Photograph
11	Video	HR (high-definition HD camera)	Pilot view/ user interface	Video streaming
12	Inspection report	MSP	Databases / user interface	List of measurement reports: timestamp, id, measurement, photographs, telemetry
13	Map	MSP	Databases / user interface	id, Octo-map format
14	Camera remote control	User interface	Camera system	Commands to control gimbal and take photographs
15	Aerial platform remote control	Pilot view	Autopilot	Commands to control aerial vehicle (attitude control)
16	Inspection platform remote control	Pilot view	Inspection platform	Commands to control the inspection platform (robotics arm/ satellite robot)

2.3.1. Messages specification

Since the system is based on a ROS architecture, the messages have been defined considering the ROS messages packages: std_msgs[3], geometry_msgs[4], mavros_msgs[5], sensor_msgs[6]. Some of these messages, whose information is generated by on-board sensors, are defined by the onboard CPU through the proper drivers.

Measurement points

```
std_msgs/Header header
geometry_msgs/Pose[] poses
```

This message is generated by the user through the user interface (UI) and submitted to the MSP. It includes information about the location of the expected measurement points in the world frame (NED) in meters.

Inspection plan

```
std_msgs/Header header
geometry_msgs/Pose[] poses
std_msgs/UInt8[] types
```

This message is generated in the MSP by the GS and submitted to the aerial platform ground control station (GCS), which splits it into subplans (with the same format) and submit them orderly to the HR (on-board computer). It includes the waypoints and measurement points in the world frame (NED) in meters.

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[3] http://wiki.ros.org/std_msgs
[4] http://wiki.ros.org/geometry_msgs
[5] http://wiki.ros.org/mavros_msgs
[6] http://wiki.ros.org/sensor_msgs

UAV target position

The system publishes to the topic */mavros/setpoint_position/local (geometry_msgs/PoseStamped)*, at which is subscribed the autopilot through the mavros node. The waypoint is given in the world frame (NED) in meters.

Landing command

```
std_msgs/Header header
std_msgs/Bool land
```

This command is generated by the HR (on-board computer) and submitted to the landing platform when the aerial platform is in the landing operation.

Measurement target position

```
std_msgs/Header header
std_msgs/Pose relative_pose
```

This message is generated by HR (on-board computer) and submitted to the robotics arm. The relative position is given in the Robot frame in meters.

Measurement command

```
std_msgs/Header header
std_msgs/Bool measure
```

This command is generated by the HR (on-board computer) and submitted to the UT sensor.

Telemetry data

These data include the different topics published by the autopilot through the mavros node (more details about these messages may be found in the mavros package documentation[7]):

- */mavros/imu/data (sensor_msgs/Imu)*
- */mavros/imu/mag (sensor_msgs/MagneticField)*
- */mavros/local_position/pose (geometry_msgs/PoseStamped)*
- */mavros/local_position/velocity (geometry_msgs/TwistStamped)*
- */mavros/state (mavros_msgs/State)*
- */mavros/battery (mavros_msgs/BatteryState)*

Moreover, a new message relative to the gimbal pose has been defined:

```
std_msgs/Header header
geometry_msgs/Quaternion gimbal_quat
```

Finally, the relative position of the UT sensor, located in the inspection platform has been defined as follows:

```
std_msgs/Header header
std_msgs/Pose relative_pose
```

These messages are generated by the HR and submitted to the MSP.

Lidar data

```
sensor_msgs/PointCloud2 lidar_measures
```

This message includes information about distances to the sensors in the sensor frame in meters.

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[7] http://wiki.ros.org/mavros

UT measurement

```
std_msgs/Header header
std_msgs/Float64 measurement
```

This message includes information about the thickness reading, measured by the UT sensor in mm. More details about the measurement data can be found in section 2.1.

Photograph, Video

These messages are not ROS messages and they are not transferred through the Wi-Fi connection HR-MSP, but through a dedicated radio link between the camera system and the pilot view. Then, through a HDMI link they are transferred to the user interface and the MSP.

Remote control messages

Messages related to remote manual control (items 14,15, and 16 in Table 2) are not ROS messages and not transferred through the Wi-Fi connection HR-MSP, but through dedicated radio links between the HR and the pilot view (see Figure 7).

Map

Based on the previous data and the data collected from LiDAR sensors, the MSP generates an OctoMap based map[8], which is submitted to be viewed in the user interface and stored in the databases jointly with the inspection reports.

Inspection report

The inspection report is provided as a file including (see section 2.1) for each measurement point the identifier, the planned measurement point, UAV position, UAV attitude, inspection platform relative location, gimbal attitude and measurement.

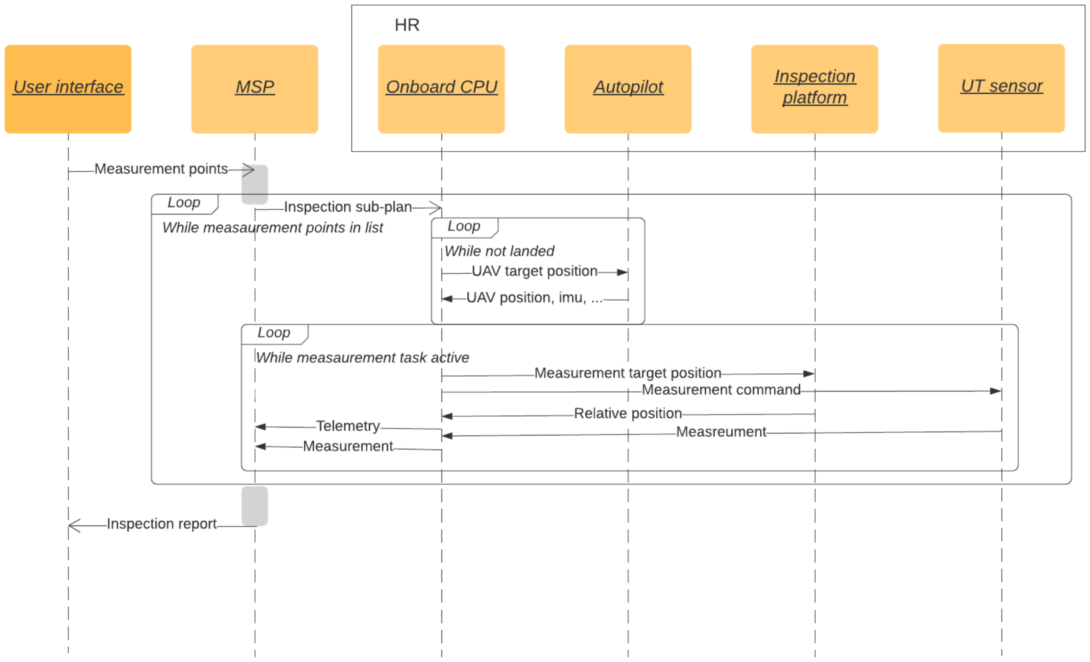

Figure 5. Sequence diagram of inspection operations from the measurement data service perspective, along the HYFLIERS system components.

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[8] https://octomap.github.io/

Additionally, if they are available, a set of photographs are associated with each measurement point through the metadata (including the identifier). More details about the measurement data may be found in section 2.1.

Figure 5 depicts the inspection operations with a focus on the measurement data flow along the chain of the entire HYFLIERS system, considering only the more relevant modules and messages. Again, the two prototypes are represented in the figure with the same element, the HR block including the HMR with its satellite or the HRA with its arm.

2.4. Data management environment

For providing local communication links between the HR and the GS residing on the MSP, all the communication and high power equipment are located on the MSP.

The MSP could also provide access to external networks, to the HR for example, via appropriate network routing, or it could be used as an Internet access point for other equipment used at the inspection site, if necessary.

Figure 6 illustrates the software components and the related hardware, all described in the following.

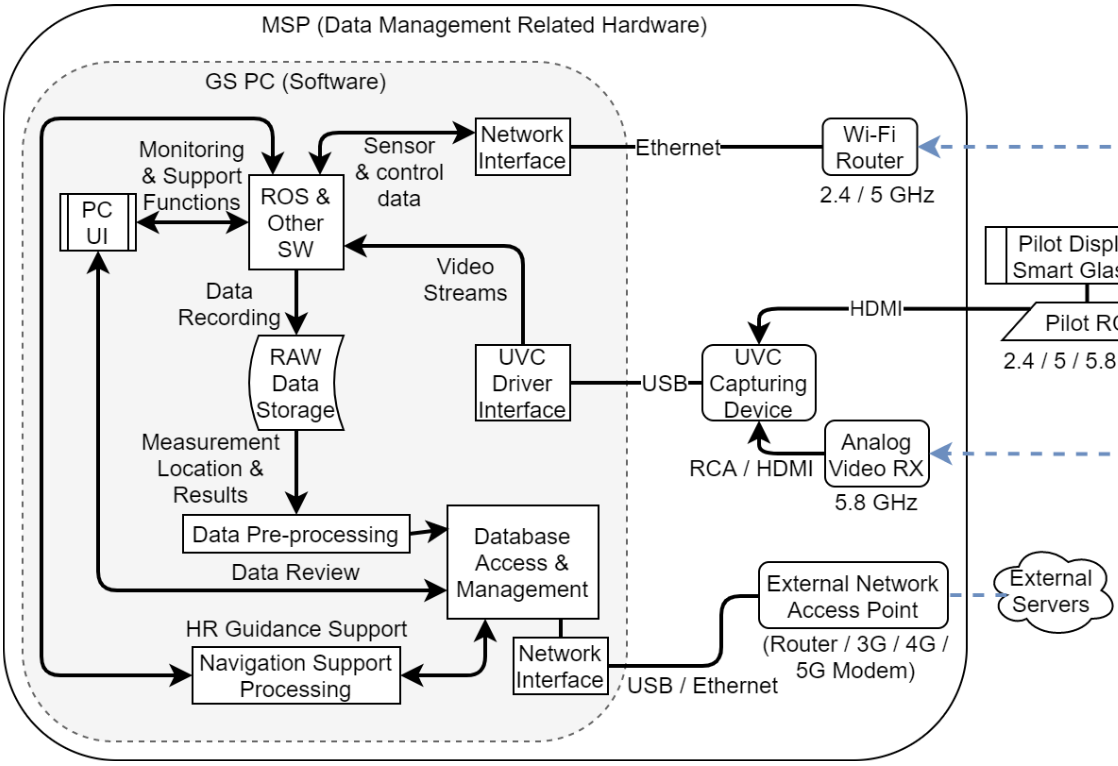

Figure 6. Overview of the data flow between hardware and software components of the MSP.

2.4.1. Onboard computer

Currently, the MSP's onboard computer is running Linux Ubuntu 16.04 and the Nvidia Jetson TX2 onboard the unmanned aerial vehicle (HR) is running L4T (Linux 4 Tegra) Ubuntu 16.04. Therefore, Ubuntu 16.04 is most likely going to be used to implement the preliminary UI for the MSP computer and the UI visible for the pilot. The MSP computer is equipped with enough storage capacity and processing power to support the functions required for operating with the HR.

The MSP computer currently uses an ASUS ROG Rapture GT-AC5300 [RaptAC5300] Wi-Fi router to provide high bandwidth link between the systems. In addition, an external modem is used (4G or 5G), to access external services on Internet and other services provided by the industrial plant centre via the MSP.

2.4.2. Hardware interfaces

For transmitting data streams, the HR will have multiple data streams coming wirelessly to the pilot and the GS PC residing on the MSP. The Wi-Fi router will be used to mainly handle measurements related data from HR sensors, including those on the pipe measurement equipment that may reside on the satellite part of the HR. Additionally, Wi-Fi can be used to control some aspects of the HR when it is mounted on an inspection area where the operations do not require very low latency to perform, unlike during flight. These data streams will be interfaced to the GS PC via the router with an Ethernet interface.

During flight, the pilot's RC (remote controller) is used, with its low-latency video-link for the pilot, to have control over the HR in case it is required when the HR is not operating automatically or autonomously. If DJI control system is utilized, multiple bands are used simultaneously. The 2,4 GHz band is typically used for control signal while the higher 5 GHz and 5,8 GHz are used for video. The 5,8 GHz analogue video receiver (Analog Video RX) link provides the lowest latency video from the HR, in case it is needed during the operations of the HR, or its satellite. These video streams can be read by the GS PC using an UVC (USB Video Class) capturing device.

For any databases or support functions related servers located in external networks, off- or on-site the installation, an external network access point is required. Typically, this is either a Wi-Fi or Ethernet router, or if these are not used in the installation being inspected, a 3G – 5G mobile internet connection may be utilized.

2.4.3. GS PC Software components

The GS has to handle multiple functions simultaneously, where the main ones are the interfacing with the HR and the related support functions for its control. ROS is used to interface with ROS-related traffic corresponding network interface connected to the HR, via the Wi-Fi router. Other software can also be used to access, for example, the pipe wall thickness measurement sensor, or a ROS node could be implemented to import the measurement data to the ROS environment. The benefit of using ROS for data handling is to have one unified system for handling both the robot-related support functions and the data recording.

The raw data storage for all the recorded measurements is handled by storing them in the local hard drive of the GS PC. In the case of ROS, the raw data can be stored directly in ROS bag data containers, which will contain all the data processed within the system, time stamped according to the sequence has been recorded. This makes possible to view and replay the bag later, for further processing and analysis. The most important data to be recorded would be the measurement locations and results as accurately as possible. Other data that can be recorded include all the video and control streams.

The data pre-processing would be required for parsing the recorded data to the format the inspection client requires it. This would include extracting the significant inspection point measurement result, location, and images or video of the location. This pre-processed data can be then stored into databases of the installations or remote authorities by implementing a database access and management system on the GS PC. Other functions handled by the database access and management system include providing maps or other information for the navigation support system, which will be used by the HR algorithms in determining flight paths and routes to targets, with respect to available information of the installation being inspected, which could be, for example, up-to-date 3D maps of the plant. Additionally, newer maps may be generated from the HR data and stored to databases via data pre-processing, if the sensors are good enough.

As the database management system may need to access external network resources, they could be handled through an external network access point to other servers, which can be accessible through the plant network or other mobile internet connection. The PC UI will be used by the operators to monitor the HR operation, invoke required control actions and have access to the processed data of the measurements. Also, the operators should be able to easily review the measurements online and the validity of the stored measurement results.

2.4.4. Proposed approach for linking the HR real-time streams with the MSP

In order to have the operations split between the support operator and the pilot operating the HR, the UI-related communications should be designed in a way that the pilot only needs to be concerned of the video feeds and controls they need to operate the HR. In the system, the support operator handles informing the HR pilot during the approach to the measurement location and aiding in other actions that the HR needs to perform at the measurement location.

To minimize delays, the UI necessary for the pilot could be rendered on the HR's onboard computer. However, having a sophisticated UI for the pilot might not be possible if the autonomous operation of the HR would require a significant amount of onboard processing power, making rendering the UI on the HR unfeasible. Then, only the camera feeds from the HR would be transmitted for the pilot during flight.

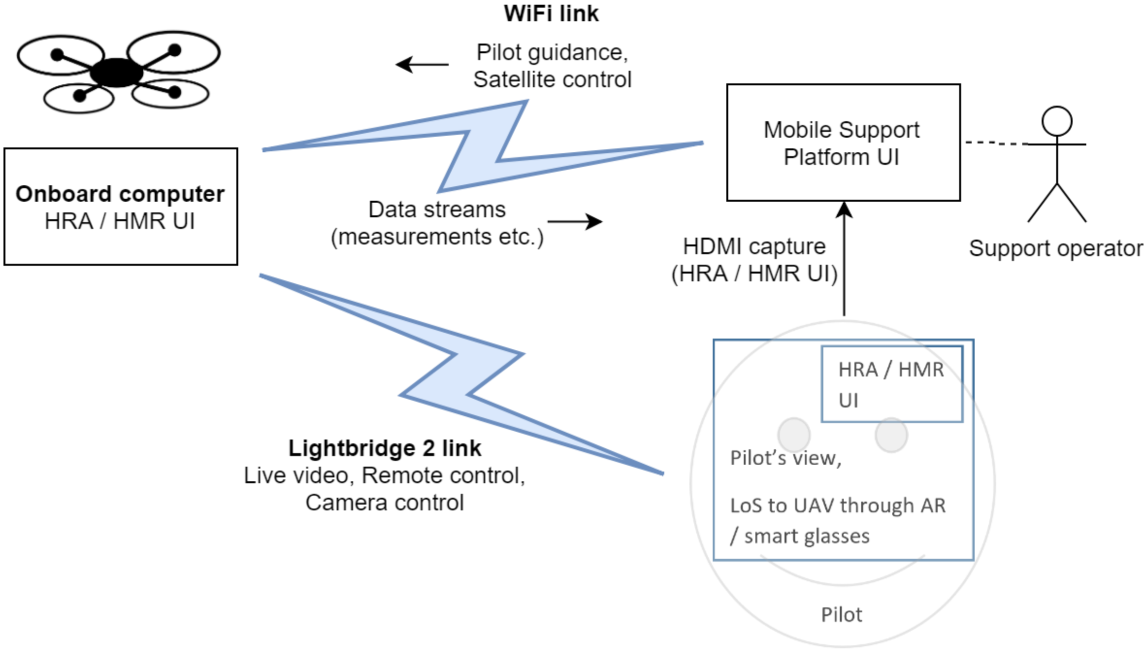

Figure 7. Suggestion for linking the HRA/HMR (HR) system between the pilot and the support operator.

During flight, the pilot's view is transmitted via the low latency link through HR's remote controller, which has minimum delay in the video feeds from the HR. From the pilot's controller, the pilot's view can be forwarded to the GS and the support operator, who has the access to control some parts of the HR’s systems via an UI and can convey guidance information to help the pilot, without affecting the pilot’s control over the HR. An overview of the linking structure is shown in Figure 7.

2.5. Functional testing

UOULU has done preliminary tests with the MSP related hardware using a custom-built UAV, see section 2.5.2. Among others, the communication and data streams related bandwidth sufficiency between the HR and the MSP has been tested. Initially, it has been used the ROS Kinetic distribution in ROS master-slave configuration, where the ROS master has been running in the HR side and the slave in the MSP. The ROS slave on the MSP is used to get the necessary streams from the HR and provides necessary support streams for the HR to navigate in the environment.

2.5.1. Real-time data streaming

The MSP computer as a ROS slave system can subscribe to the ROS data streams produced on the UAV/HR. Also, the ROS slave system can connect to the flight control unit (FCU), and other nodes, running on the HR for commanding and receiving real-time data. The data streaming has been tested over the Wi-Fi link on the GS computer, including point clouds produced by 3D sensors, shown in Figure 8.

Figure 8. The data streams visualized remotely on the GS PC over Wi-Fi. Test scenario.

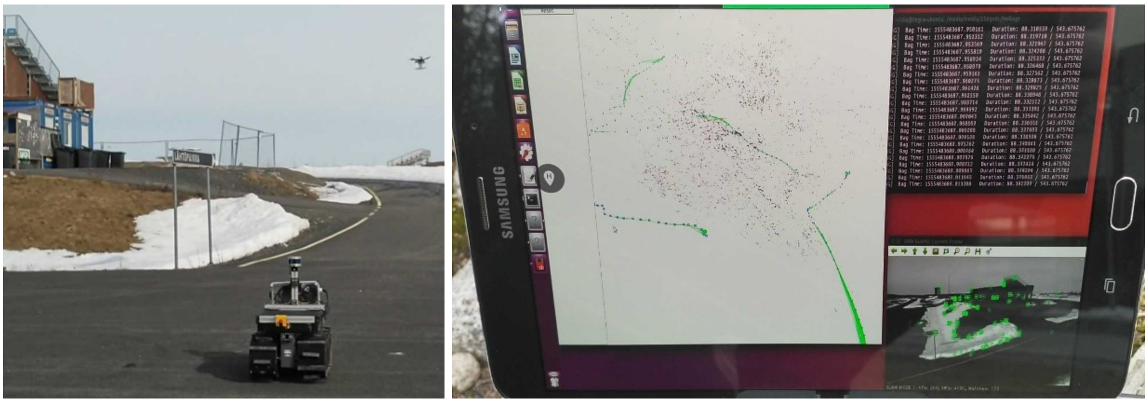

Figure 9. Tests of the MSP and other camera and SLAM visualizations at Ouluzone+ testing area. On the left, the testing MSP in the foreground and the testing UAV top right. On the right, the UAV’s UI over the DJI Lightbridge 2 video link, running on an Android tablet, visualizing ORB-SLAM2 being performed onboard the UAV in real-time.

For camera and other video feeds from the HR, the real-time view is primarily transmitted over the DJI Lightbridge 2 video link. For real-time video capturing, the HDMI (high-definition multimedia interface) video output from the Lightbridge 2 can be utilized from the remote controller of the HR that the pilot is using. For HDMI capturing, the Magewell HDMI to USB3 2nd generation UVC capturing device [MageUVC] is utilized.

In initial tests at UOULU, the video link has been used to visualize the onboard Nvidia Jetson TX2 computer's UI while performing tests with ORB-SLAM2 [MurEtal] used for real-time SLAM (simultaneous localization and mapping) on the test UAV. The DJI GL858A remote controller, which is used for the Lightbridge 2 video link, was also used for piloting during the tests. The platforms being tested at the Ouluzone+ [OzPlus] testing area are shown in Figure 9.

The low-latency onboard view, as shown in the example in Figure 9, could be supplied to the pilot by utilizing Android-based smart glasses or augmented reality (AR) glasses, so that the pilot can keep eye contact with the HR while seeing the real-time video output from the controller. The virtual screen could also include the inputs from the support platform operator, which the pilot could see on their virtual screen without having to turn to support operator for instructions, for example where to land on the seen inspection area. The use of bulky AR glasses, that would not work well outdoors, should be avoided. Hence, most likely something similar to the Epson Moverio BT-300FPV smart glasses [MovBT300], which are purpose-built for drone video viewing, will be utilized. However, as there are many new smart/AR glasses continuously coming to the market at a high rate, this might not be the final choice.

2.5.2. Other test platforms related to MSP functional testing

For testing the video streams and the remote systems, a portable case, shown in Figure 10, carries a computer system identical to the GS being used in the MSP, providing a clone of the MSP testing setup for remote visualization of the HR data streams

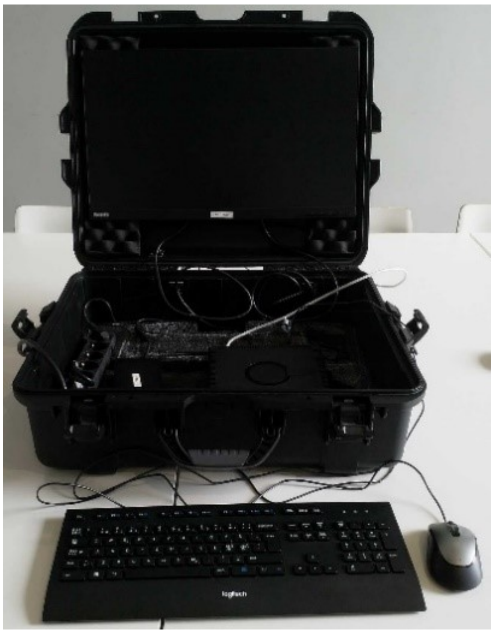

Figure 10. Testing setup for the MSP's GS PC.

In addition, UOULU currently has two UAVs for testing the navigation and other UAV-related operations (e.g. battery charging). The UAVs have Nvidia Jetson TX2 onboard computers and DJI

Lightbridge 2 for long-distance remote control communications and video link. UOULU has currently tested the basic functionality and hardware for the UAVs so that they can be used for algorithm development related to MSP and HR functions.

The primary test UAV, the hexacopter shown in Figure 11, is made to be relatively cheap with minimum hardware required for onboard navigation support and algorithm testing. The hexacopter frame is highly customizable, so it can be easily fitted with different kinds of sensors and tools to manipulate the environment. Also, because the hexacopter has been kept as cheap and modular as possible, crashing the UAV during testing would have a smaller economic impact than crashing a more expensive and difficult to fix commercial drone.

Figure 11. Hexacopter for testing support platform related operations.

Currently, the copter is fitted with a PX4 compatible PixFalcon FCU, Nvidia Jetson TX2, DJI Lightbridge 2, ZED Mini stereo camera, 1D and 2D LiDARs and a PX4Flow optical flow sensor. The copter cameras and onboard computer UI can be visualised over the DJI Lightbridge 2 video link, which should work up to 5 km range in direct line-of-sight operation without occlusions. The Lightbridge 2 is also used for remote controlling the UAV. Later, the optical flow and stereo cameras will be replaced with Intel’s RealSense T265 [T265] tracking and D435i [D435i] depth cameras for improved tracking performance and collision avoidance. Optionally, an Ouster OS1-16 360 degree 3D LiDAR could be mounted on the UAV as well.

Figure 12. DJI Matrice 210 RTK used in navigation related development.

The secondary test UAV is a commercial DJI Matrice M210 RTK, shown in Figure 12, with centimetre-level accurate positioning available in open areas, where good quality and unobstructed GPS (global positioning system) signal is available. This copter is used in navigation and vision-based algorithm development, and to implement compatibility with DJI autopilots the other project partners are using. The copter has exceptional flight stability and unparalleled imaging quality. Using both of these drones, the compatibility with the most commonly used UAV platforms, that are based on Pixhawk and DJI systems, can be developed.

3. Path planning and navigation support for autonomous operation (T4.1)

This section presents the path planning algorithms and the navigation support functionalities to increase system autonomy that have been developed in “Task 4.1 3D navigation support” and “Task 4.3 Mobile ground support”. These developments mainly correspond to the first implementation of the planning algorithm that allows autonomous hybrid navigation along the inspection points, as well as to some basic reactivity capabilities to reinforce system autonomy.

The final objective is the generation of motion plans that allow the hybrid robot to inspect a set of measurement points on a pipeline in a safe and efficient manner. For that purpose, the robot can navigate through the environment either flying or crawling on the pipes. Figure 13 represents a possible application scenario that illustrates the problem to be solved.

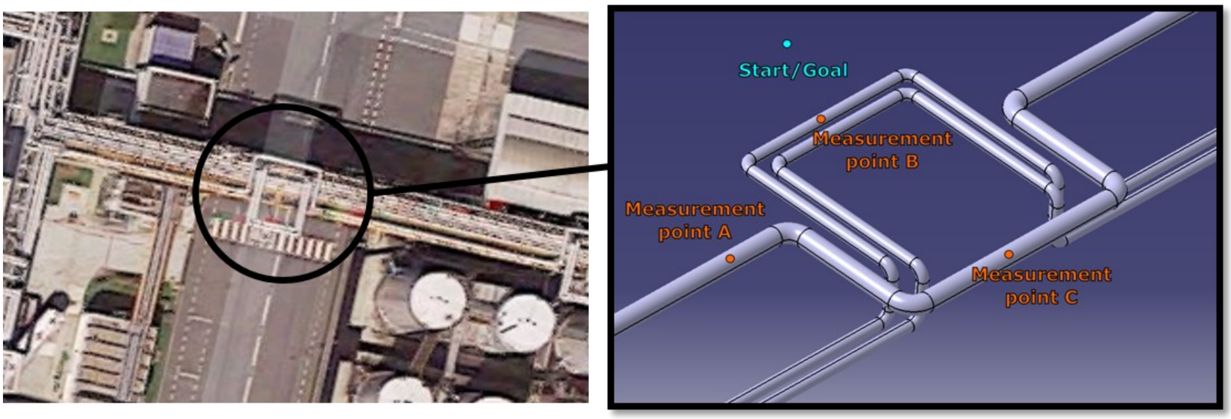

Figure 13. Example of application scenario in the Chevron Oronite chemical plant located at Gonfreville-l'Orcher in France (coordinates 49°29'35.8"N 0°12'48.9"E). Real image from Google Maps (left) and extracted CAD model (right).

3.1. Introduction

This introductory subsection provides a general overview of the main research areas under planning topic that will be addressed along the project in the aforementioned tasks T4.1 and T4.3. Furthermore, the navigation architecture that is proposed as reference framework to incorporate the latter will also be presented. This complete description will bring a better assessment of the autonomy level that can be achieved in the final stage of the project. Once this overall frame has been clarified, subsequent subsections will present the particular developments covered by this deliverable.

As anticipated in the executive summary of this document, the three main research areas under planning topic as well as their associated work-lines are enumerated below:

- Generation of motion plans that allow autonomous motion along complete sequences of inspection points.
    - Consideration of the hybrid motion capabilities (flying, rolling) offered by the HR to generate optimal trajectories accordingly to different indices (operation time, power consumption).
    - Consideration of the obstacles included in the maps of the industrial environments to generate trajectories free of collisions.
- Extensions of motion planner to guarantee safer trajectories for autonomous operation
    - Consideration of dynamic behaviour of the system.
    - Consideration of aerodynamic effects produced by the proximity of the elements that require inspection (horizontal arrays of pipes, vertical pipes, deposits, etc.).
- Navigation support to enhance the level of autonomy offered by the system
    - Implementation of reactive behaviors in case the on-board sensors reveal the presence of obstacles not considered in the planning algorithms.
    - Implementation of re-planning strategies in case that modifications of the inspection tasks arise during the execution of the global mission.

The navigation architecture proposed in Figure 14 to meet these requirements is composed of two main subsystems, the *Motion planner subsystem* and the *Reactive behaviour subsystem*.

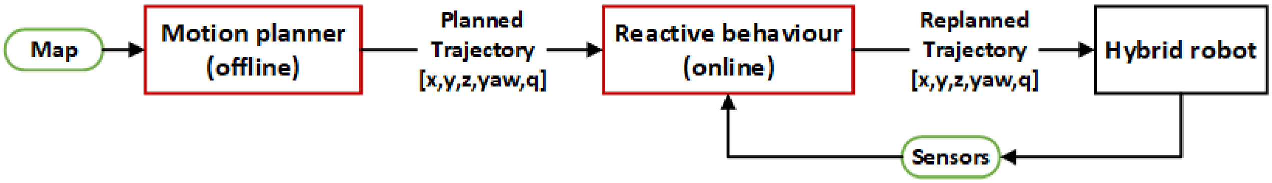

Figure 14. Overall navigation architecture.

A basic description of the main blocks included in the previous scheme is provided below:

- *Motion planner subsystem*

  Given a map of the environment, a description of its navigation constraints, and a set of inspection points, this block will be in charge of a generating a global trajectory that allows autonomous hybrid navigation through the inspection targets. At this level, the configuration variables of both the aerial platform (x, y, z, yaw) and the robotic arm (q) - if manipulation is required for the inspection task - will be considered within the planning space. The resultant trajectory will be given to the hybrid robot as control reference.

  This subsystem will also include any extension of the motion planner that could bring more safety and robustness to the system operation. The consideration of the dynamics and aerodynamics of the hybrid robot during the expansion of the planning tree would therefore be framed within this subsystem.

- *Reactive behaviour subsystem*

During the execution of the planned trajectory, the *Reactive behaviour subsystem* will be continuously monitoring the information delivered by onboard sensors. If any obstacle not considered in the motion plan appeared, this subsystem would check if the latter could provoke a collision. In that case, the *Reactive behaviour subsystem* will locally modify the global trajectory for collision avoidance, minimising as much as possible the deviations with respect to the global plan.

On the other hand, it may occur that the global trajectory generated by the *Motion planner subsystem* becomes outdated during the execution of the global mission. This could be motivated by changes in the inspection tasks that may arise during the mission (e.g. re-inspection of certain areas could be necessary after online post-processing of data gathered in previous phases of the mission). In this case, the *Reactive behaviour subsystem* will use re-planning strategies that adapt the global trajectory to the new requirements.

3.2. Planning algorithm for autonomous hybrid motion

Once a sequence of inspection points has been defined, the *Motion planner subsystem* will generate the trajectory between consecutive points following a hybrid approach (see Figure 15 for illustrative purposes). On the one hand, a RRT*-based algorithm will be implemented for the exploration of the planning space associated to fly zones. This algorithm has demonstrated high potential in finding optimal and fast solutions for high-dimensional robots, as is the case with the hybrid robot. The exploration of the planning space associated to the crawling movement on the pipes could be addressed with the same algorithmic approach mentioned before for the flying mode. However, another alternatives with a lower computational load could also be explored. The consideration of algorithms that address the shortest path problem could be one of these alternatives, where the pipes would be treated as graphs. This family of algorithms offers optimal and fast solutions for environments allowing a graph-based description. Finally, both explorations will be connected in order to plan the optimal global trajectory.

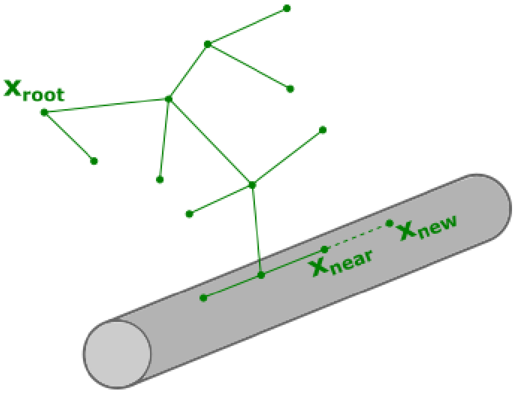

Figure 15. Hybrid planning strategy. Both aerial and pipe branches are considered within the planner operation.

One of the main advantages of the previous approach for hybrid planning is the possibility of optimizing metrics like power consumption or operation time (see Figure 16 for illustrative purposes). With this purpose, the algorithm will integrate the cost functions shown below. They allow characterizing the cost increment between two nodes with respect to such indices and for both operation modes (flying or crawling).

$$\text{Operation Time} \quad \rightarrow \quad \Delta\, CF_{ot} = \|\boldsymbol{p_i} - \boldsymbol{p_j}\| \cdot \left[\frac{\alpha}{u_{roll}} + \frac{1-\alpha}{u_{fly}}\right] \quad \alpha = \begin{cases} 0 & (flying) \\ 1 & (rolling) \end{cases}$$

$$\text{Power Consumption} \rightarrow \Delta CF_{pc} = \|\boldsymbol{p_i} - \boldsymbol{p_j}\| \cdot [\alpha \cdot w_{roll} + (1-\alpha) \cdot w_{fly}] \quad \alpha = \begin{cases} 0 & (flying) \\ 1 & (rolling) \end{cases}$$

where $\|\boldsymbol{p_i} - \boldsymbol{p_j}\|$ is the distance between nodes, α a parameter describing the transition nature between the nodes (flying or rolling), and finally, $u_{roll/fly}$ and $w_{roll/fly}$ denote, respectively, the velocity and power consumption associated to roll/fly.

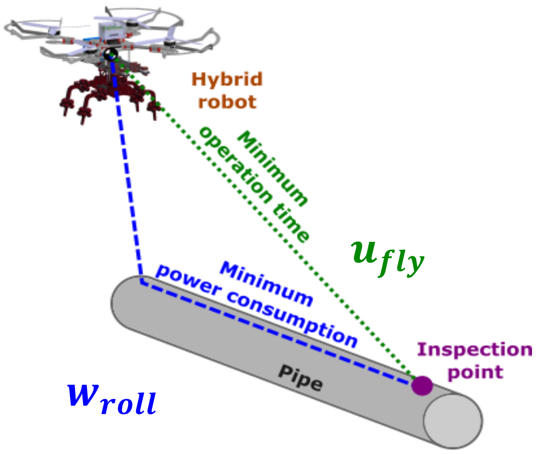

Figure 16. Hybrid planning strategy. Behaviours corresponding to the optimization metrics. Flying is prioritised over rolling when minimising operation time $u_{fly} > u_{roll}$ whilst rolling is prioritised over flying when minimising power consumption and $w_{roll} < w_{fly}$.

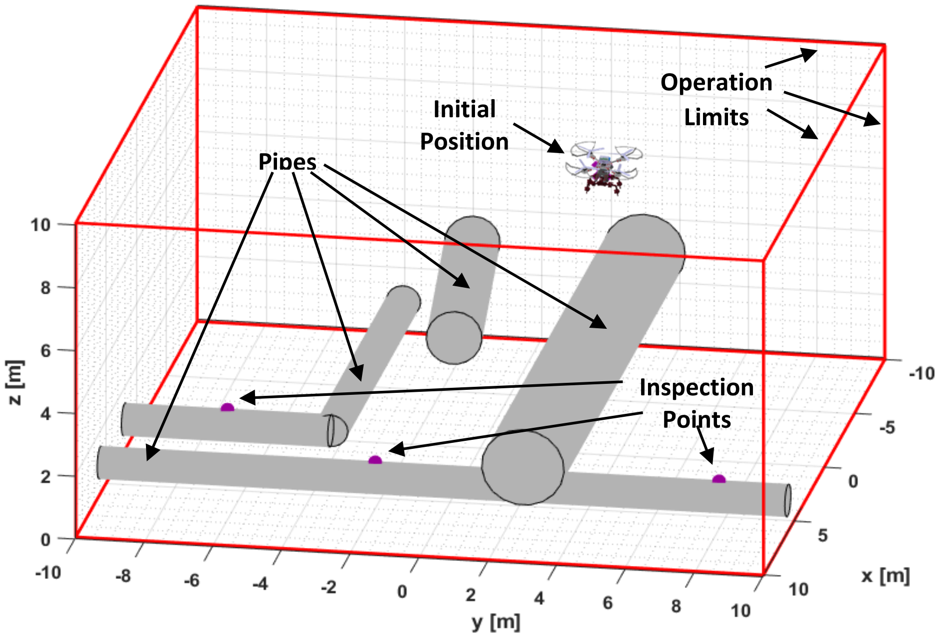

Figure 17. Motion planning for pipe inspection. Application scenario.

In addition to the specific features of the hybrid approach, the algorithm will also incorporate other valuable functionalities such as the smart discretisation of the planning space to guarantee bounded computation times or the optimized functions for collision avoidance that allow a trade-off between safety and computational load. All these features will lead to safe and efficient trajectories with reduced planning times.

The aforementioned discretization satisfies actually a two-fold purpose, since it also allows to establish the ratio between flying and crawling states, an important parameter to determine the behavior of the algorithm.

In this first stage of the work, a basic version of the *Motion planner subsystem* has been derived. This implementation makes use of a RRT*-based algorithm for the exploration of the complete planning space since individual pipes - instead of pipe arrays - will be assumed as inspection targets. The latter will ease the analysis of the hybrid operation of the planning algorithm in these first implementations.

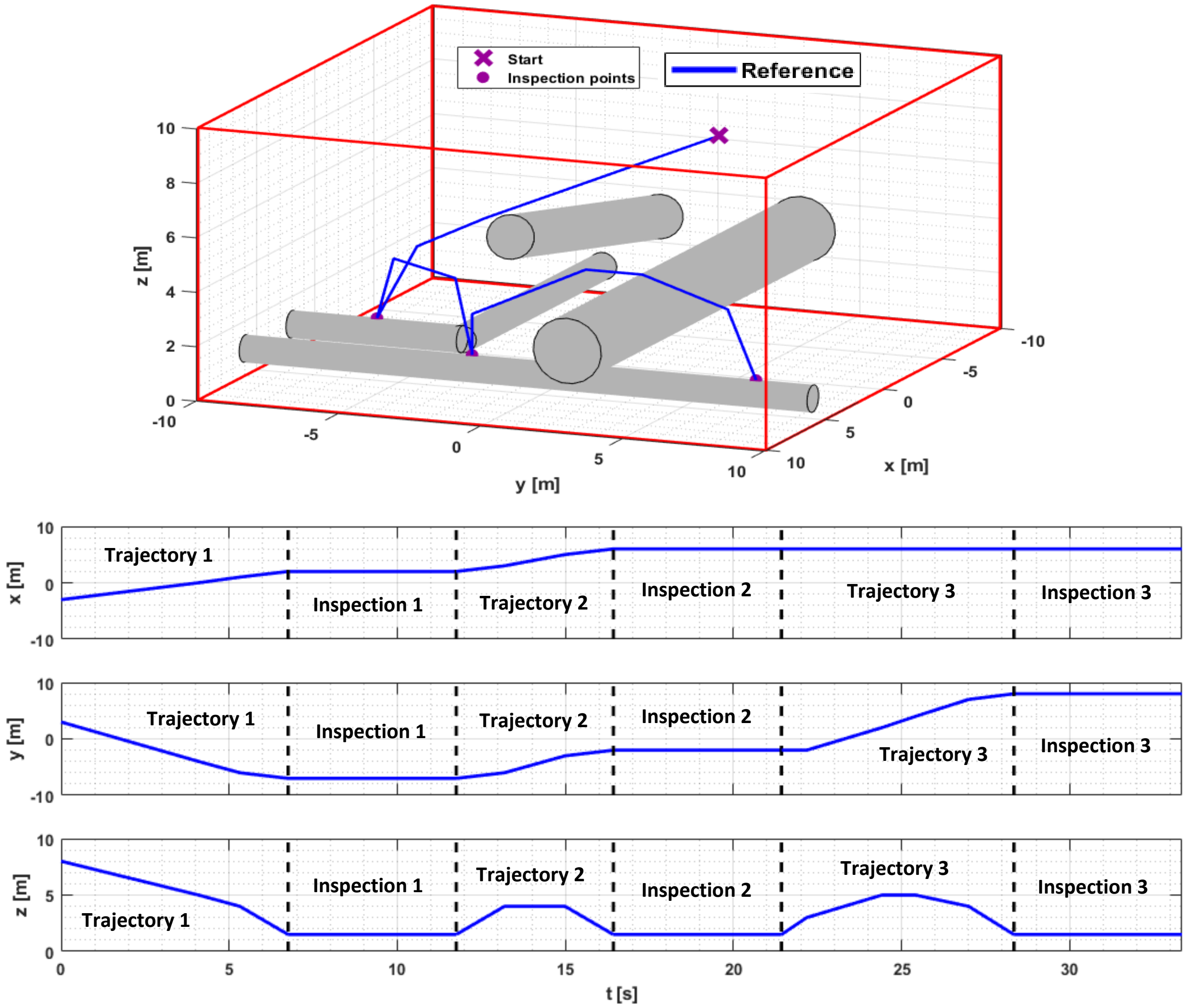

Figure 18. Motion planning for pipe inspection when minimising the operation time.

The application scenario that has been considered is depicted in Figure 17. As it can be seen, several pipes with different diameters, inclinations, and connections amongst them, have been included. The hybrid robot will initially be flying in the start point and its objective will be the inspection of the different target points without overreaching the operation limits denoted by red lines. For that purpose, the robot can navigate through the environment either flying or crawling on the presented pipes.

The validation simulations of the planning algorithm have been included in Figure 18 and Figure 19. These graphs show the computed motion plans for the hybrid robot when minimising the operation time (Figure 18) and the power consumption (Figure 19). In view of the results, it can be concluded that this first implementation of the *Motion planner subsystem* is capable of generating both safe and efficient trajectories for the HR.

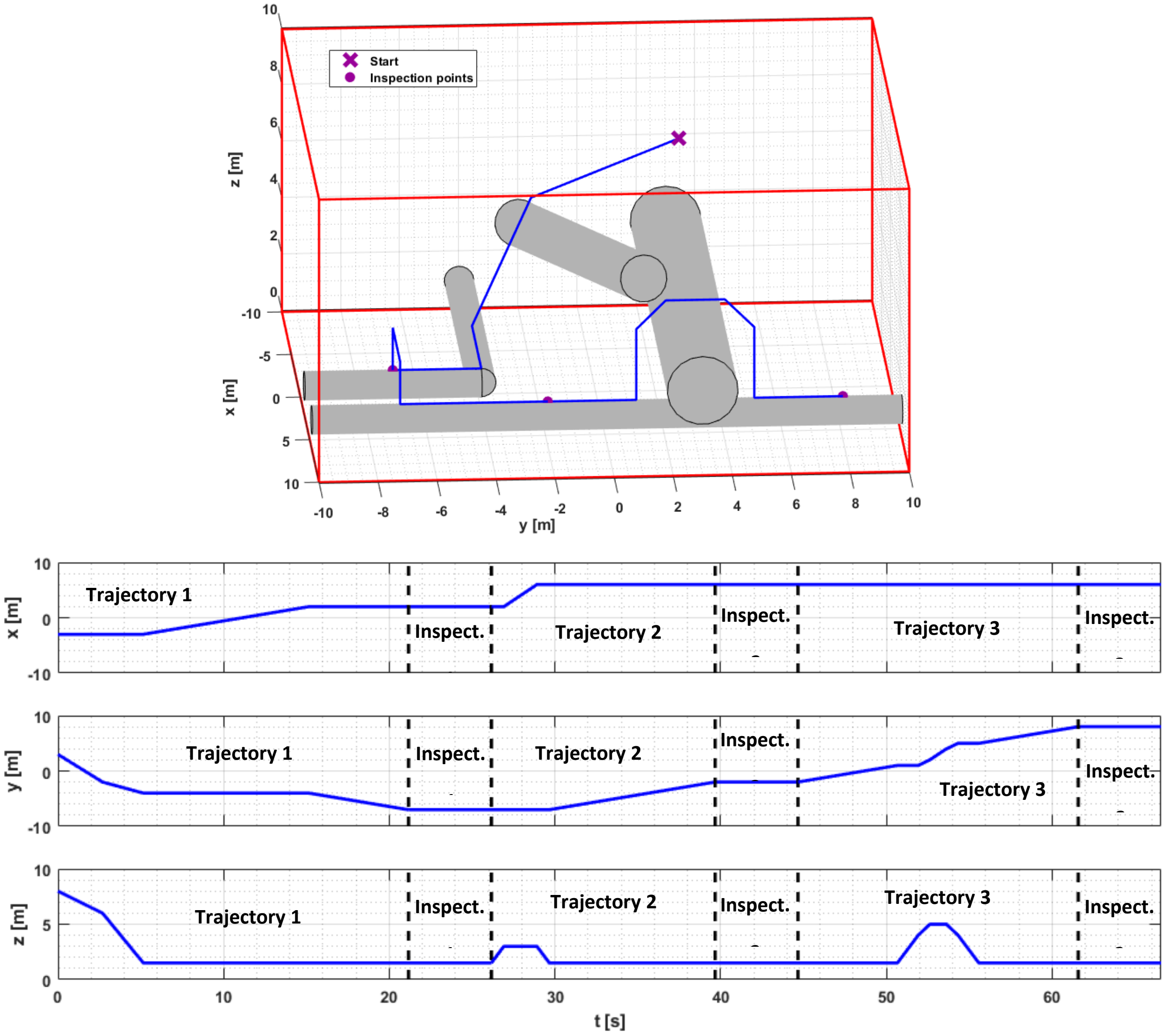

Figure 19. Motion planning for pipe inspection when minimising power consumption.

When comparing in Figure 18 and Figure 19 the behaviours associated with the different indices employed for trajectory optimization, it is quite straightforward to conclude that the HR flies directly between inspection points for missions with minimum operation time, while it tries to maximise the crawling movement on pipes for missions with minimum power consumption. These observed behaviours are consistent with the higher velocity and power consumption associated to the flying mode (in comparison with crawling mode).

3.3. Navigation support to reinforce system autonomy

In case that the *Reactive behaviour subsystem* has to locally modify the global trajectory for collision avoidance, the same algorithmic basis of the *Motion planner subsystem* will be used. However, this new scenario requires a lower computation time for assuring real-time reactions in the presence of unexpected obstacles. In this respect, the reduction of the planning space associated with the local nature of the reactive behaviour may help to satisfy this requirement.

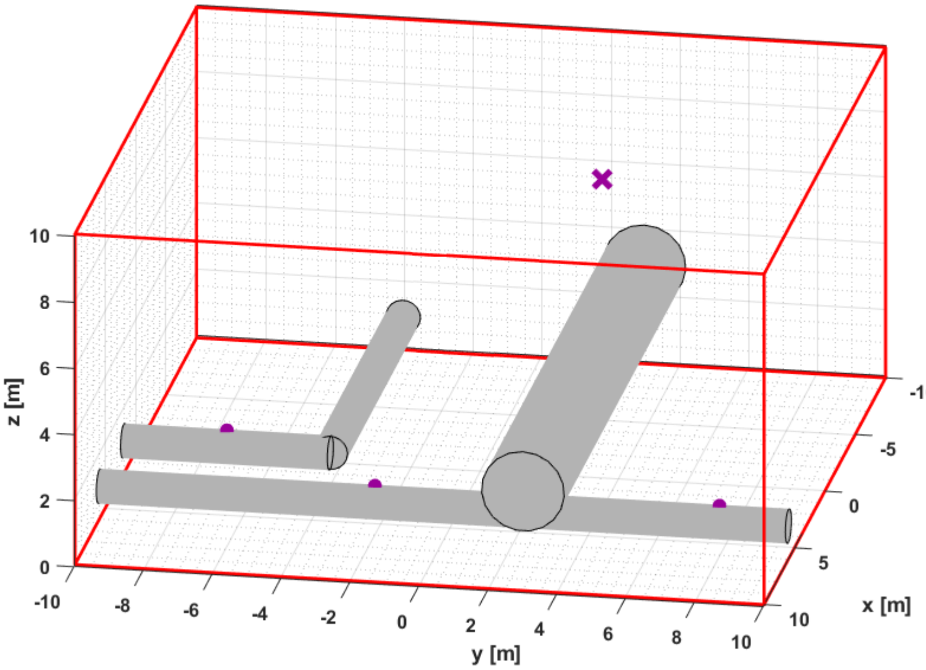

Figure 20. Reactive capabilities for pipe inspection. Modified map without central pipe that will be used for global planning

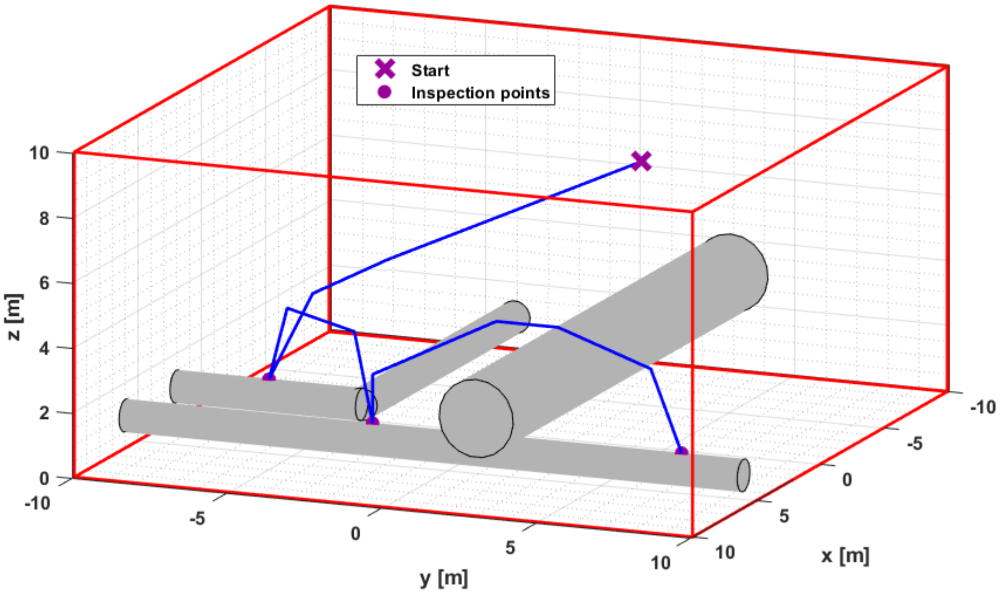

Figure 21. Reactive capabilities for pipe inspection. Global trajectory generated by the *Motion planner subsystem* when the central pipe is not taken into account within the planning algorithm.

The scenario for illustrating the reactive capabilities that have been implemented during this first phase of the work will be given again by Figure 17. However, in this case the planning algorithm will receive a map that does not include the inclined pipe located in the central area (see Figure 20).

The execution of the *Motion planner subsystem* with this modified map will lead consequently to a different global trajectory that does not avoid the central pipe, as can be seen in Figure 21

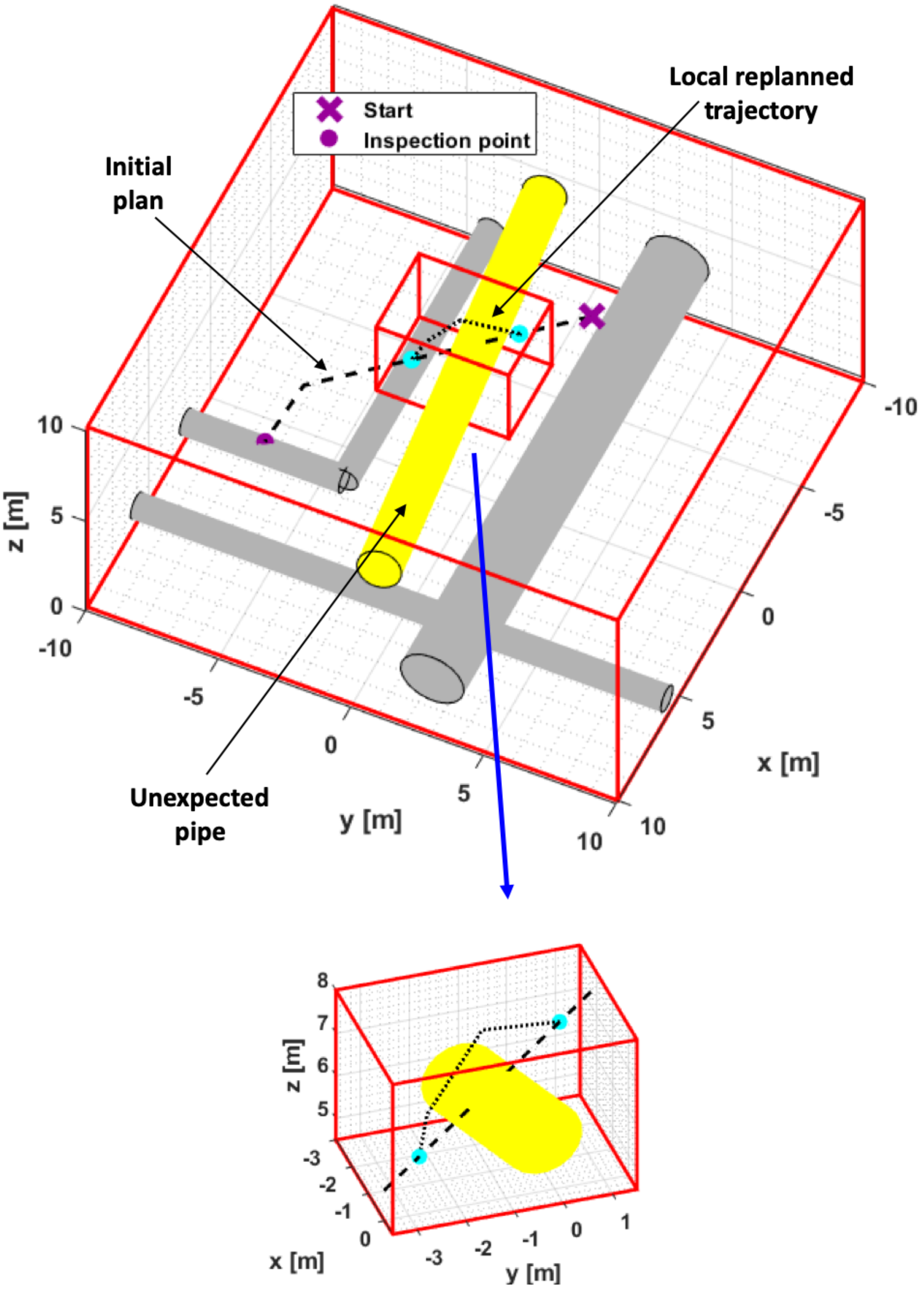

Figure 22. Reactive capabilities for pipe inspection. Local trajectory re-planned by the *Reactive behaviour subsystem* when the central pipe is detected by onboard sensors.

During the execution of the global planned trajectory, the central pipe - highlighted in yellow in Figure 22 - will be detected by onboard sensors. Since this pipe was not in the initial map of the environment, the trajectory is locally re-planned using the same algorithmic basis as in the *Motion planner subsystem*, but in a reduced planning region (red region inside the bigger one that is augmented in the figure). The validation of this reactive capability reinforces the autonomy of the system since these algorithms allow safe operation even in the presence of obstacles not originally considered in the motion plan.

4. Mobile ground support platform (T4.3)

This section reports about the the design and development of the mobile support platform, which has a role in supporting measurement data and HR navigation. Here are presented the MSP functionalities with a hardware overview and the testing equipment used.

4.1. Introduction

The support platform is mobile and follows roughly the location of the HR. The role of the mobile support platform is (see Figure 1):

- to aid the flying and inspection operations of the HR (navigation support for example in obstacle avoidance to enhance safety, mission planning);
- to act as a hub for inspection data management (both ways between the inspection plant centre and the hybrid inspection robot); and
- to aid in couplant refill and in battery energy management, compatibly with ATEX (explosive atmospheres) zone operation.

Initial system specifications, including end user requirements, have been identified in [D1.1], whereas the system concept and architecture is described in [D1.2].

4.2. Mobile support platform hardware

Currently, all the computer and other necessary hardware are mounted on an experimental unmanned ground vehicle (UGV) platform at the UOULU. This platform currently simulates the MSP for testing the support platform hardware, but the implementation should be directly transferrable to the MSP that will be utilized in this project.

The correct functioning of the computer with the necessary network switch, router and regulators has been tested in varying outdoor conditions and no significant problems were experienced with the system. Figure 23 shows the prototype enclosure for the GS computer, mounted temporarily on the UGV for testing purposes. With this setup, the ground platform computer has been tested for several months.

The box dimensions are 38 cm × 28 cm ×13 cm. The whole system has been initially fitted in an industrial beam-mountable composite plastic casing, which includes most of the system hardware, and is easily transferable between platforms. The 24 V, 19 V, 12 V and 5 V regulators are temporarily in a separate box, shown on the right side of Figure 23, but they will be mounted in the same casing with the computer so that there will be only one transferable unit that needs to be mounted on the mobile support platform. The 12 – 24 V regulators are each rated for 320 W power, and the 5 V regulators are 20 W each. The 320 W power supplies are chassis mountable Vicor VIA DCM [VicoPow] series regulators. The 5 V regulators are used with smaller power equipment, such as network switches, USB hubs, and other adapters.

Figure 23. Enclosure for the ground platform computer.

The power switches are weatherproof, but in the final system they could be also changed to air tight switches, and utilize solid state relays, to avoid any sparks being generated if needed to be operated in hazardous environments. The main power bus will consist of multiple parallel batteries, constructed of intelligent battery modules containing all the necessary hardware for battery system management. The intelligent battery modules will be in a separate storage compartment, where they can be added and even hot-swapped, if required.

The running time for the MSP computer (mounted onboard with its sensors simulating the power system load on the MSP) under heavy use is around two hours with a 488 Wh Li-polymer battery. Therefore, the platform needs at least four such battery modules for eight hours of operation. However, bigger batteries could also be fitted to each intelligent module to reduce the amount of required modules. For reserving capacity to charge the HR, the platform would need additional modules, depending on how much power is used by the HR.

4.2.1. MSP Battery Management

The MSP has a parallel battery bus consisting of multiple parallel intelligent battery modules. The battery modules utilized here have been partially developed previously in collaboration between the University of Oulu and Probot Ltd [ProBot], a UOULU spin-off, and therefore they are not considered a result of the HYFLIERS project. Nevertheless, customized versions of the modules could be used in this project.

The bus control features of the intelligent battery modules allow several to be used in parallel in a shared common power bus, allowing flexibility in the battery system construction of the MSP. Each module supports up to two parallel batteries with two to twelve cells. Supported battery types include all Li-polymer and Li-ion battery types.

The modules can be interfaced to the GS PC via a controller area network (CAN) bus and an appropriate USB converter. The battery modules may also be interfaced with a small screen to monitor the battery status independently of the GS computer. The parallel bus structure is shown on the left side of Figure 24. The Power Path controller together with Battery Management module determines whether the onboard systems are being powered from the external AC supply or from internal batteries. When AC is present, the system is primarily powered from AC and batteries will be charged. When AC is not present, intelligent batteries will be used to drive the onboard power sources.

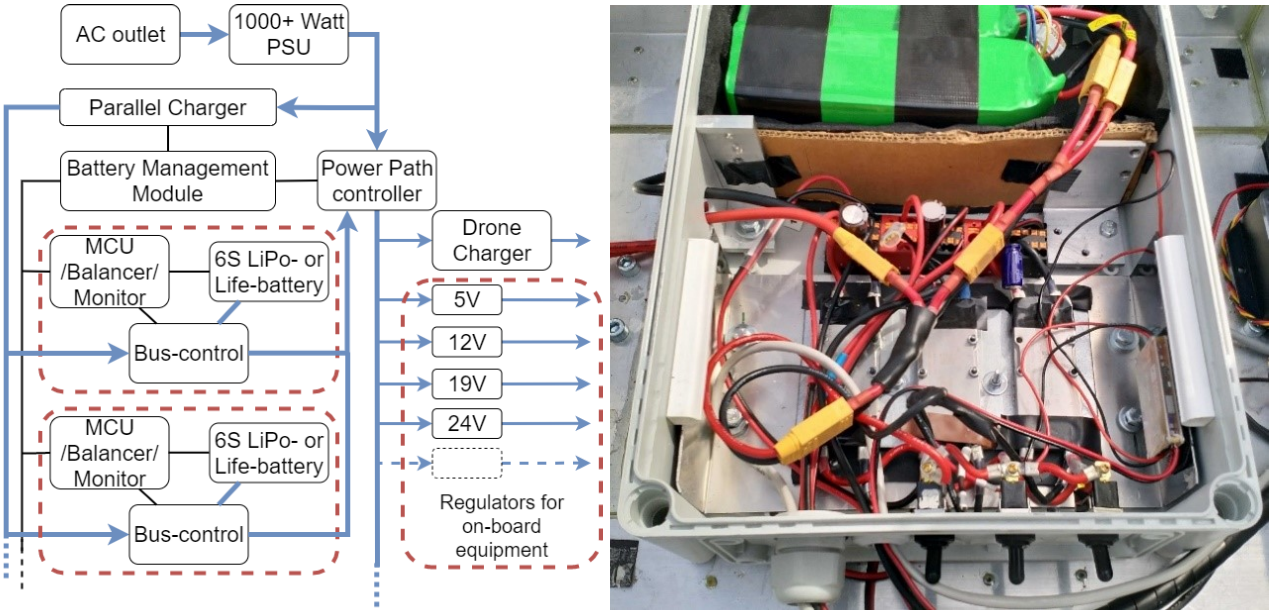

Figure 24. On the left; the power bus structure to be utilized in the MSP. On the right; the temporary testing setup of the power bus with its regulators.

4.3. Optional charging support for the HR on the MSP

It is possible to utilise the batteries onboard the MSP to power a battery charger for the HR. It is also possible that spare batteries could be carried with the MSP, which would require switching batteries from the HR. However, in both cases, plugging and unplugging high power connectors can present issues in some operating environments due to electrical arcing.

Because of potentially operating in hazardous environments with the possibility of ignitable fumes and gases, the HR charging should be handled in a suitable manner; either the batteries are switched in a safe location or the HR can be charged in a safe manner by the MSP. In the case of charging the HR via the MSP in a potentially dangerous area, a contactless charging approach would be the safest option to avoid any electrical arcing or sparking. In this way, the round trips to a safe charging location could be avoided, especially in a case where there are multiple HRs available to be used at the inspection site. The contactless charging system is described in more detail in the following section.

It needs to be stressed that contactless charging has been considered as an optional feature for the system. The implementation of the proposed charger is not guaranteed to work to a high enough degree to be implemented in the final structure of the HR, due to electromagnetic interference (EMI), in addition to other mechanical and electrical design challenges.

4.3.1. Contactless battery recharging system for the HR

From the mechanical standpoint, the contactless charging system would consist of two helical coils in a coaxial configuration, having their casing to ensure mating the secondary side coil with the primary. The primary side coil would be fixed on the ground charging platform, and the secondary on the drone. The coils can be cased to form a sort of a (mechanical) plug to ensure mating, where there is no electrical contact between the coils and therefore no chance of sparks.

From the electrical standpoint, the primary side coil would be modulated by a driving circuit that will generate an alternate current (AC) into the coil. After coupling with the secondary coil, this will induce an AC voltage and current at the HR side, which would need to be rectified and regulated to the DC voltage of the battery with a low-loss rectifier circuit. The biggest problem is that the frequency used may have to be quite high to have enough power transfer capacity without having coils that are too big and heavy, which makes the electrical requirements for controlling the system quite complicated. Also, the high-power transfer requirement may force to use a ferrite core on the primary side of the charging circuit, residing on the MSP, to keep the HR side connector as small as possible.

For controlling the charging system, the secondary side would utilize a the battery monitoring circuit and a microcontroller unit (MCU) to monitor the cell voltages and amount of power going in to the battery. The cell voltages need to be balanced as well. For precisely regulating the current flow and the charging process, a wireless communication link needs to be established between the primary and secondary sides. For communications, near field communication (NFC) could be utilized to transmit data between the HR and MSP sides of the charger.

In 2018, Wurth Elektronik designed a wireless high-power transfer circuit. Their development kit 760308EMP [WeOnl] could be used as a starting point for testing the implementation of the wireless charging system, with the coils being customized to our needs. The development kit comes configured for 200 W power transfer. The main components that would be utilized in our own design later, would be the Infineon IR1161L synchronous rectification controller, which can handle high frequency rectification (up to 500 kHz) on the secondary side of the charging system. With this controller, the power transfer capacity should be possible to be scaled up to above 1 kW range. The primary side coil modulation is performed by an MCU controlling the current flow direction in the coil using four high speed MOSFETs in a H-bridge configuration. The communication between the primary and secondary side MCUs could be handled by an appropriate small NFC link.

A comparable power transfer system has been studied by Ojika et al. [OjMiIs], where they established that a roughly four-by-four cm helical coil could be used to implement power transfer of up to 1 kW with over 90% efficiency. They did not use a ferrite core in their system so relaxing the maximum power output, for example, to around 300 W – 500 W and utilizing a ferrite core, it should be possible to significantly reduce the size of the secondary side connector that would be on the HR. However, using a ferrite core might not be feasible for very high frequency applications due to energy losses inherent to changing the magnetic polarization of the core material.

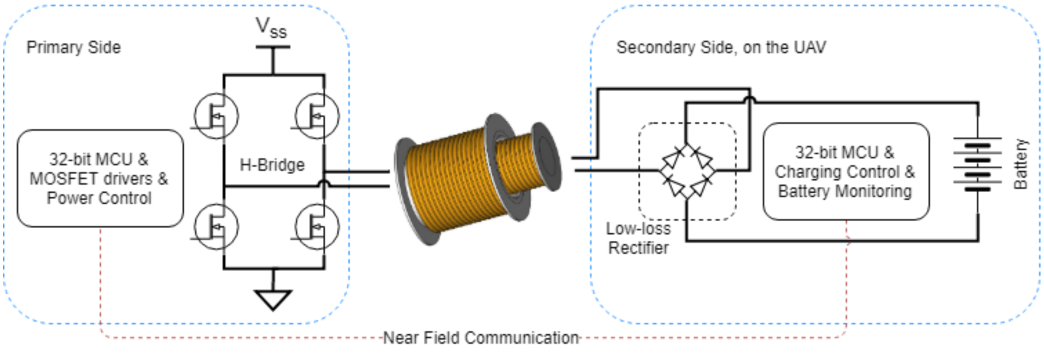

Figure 25. Operating principle of the contactless charging system.

If applied to contactless charging of the HR batteries, the fast-charge time would be the HR battery capacity, in Wh, divided by the maximum power output of the charging circuit. For example, if the HR battery capacity was 150 Wh, the charging would take roughly 30 to 45 minutes with a 300 W version of the charger. In practice, the HR battery capacity may be 400 Wh or more. The weight for the HR side circuit is difficult to be estimated at this early stage of development, but attempts will be made to keep it well under 100 grams. An overview of the contactless charger structure utilizing two coaxial helical coils to implement the coupling between the primary and secondary sides of the charging circuit is presented in Figure 25.

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