Aerial Robot for Sewer Inspection

PDTI Urban Challenge

D2.1 ARSI operation requirements and system design

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Reference Documents

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29/12/2014	N/A	ECHORD++ PDTI Urban Robotics – Challenge Brief – “Utility Infrastructures and condition monitoring for sewer network. Robots for the inspection and the clearance of the sewer network in cities”.
14/03/2015	v1.0	Aerial Robots for Sewer Inspection (ARSI) Consortium Proposal Document
07/06/2016	N/A	ECHORD++ PDTI Urban Robotics – Evaluation Criteria Phase I
30/06/2016	v1.0	D2.2 Towards automatic sewer inspection. First results
07/2015	N/A	Market Study on Mobile Robots Market - Global Forecast to 2020 by marketsandmarkets.com. Report Code SE 3610.
03/12/2015	N/A	Robotics 2020 Multi-Annual Roadmap Release B published by SPARC – The partnership for Robotics

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Issue Date	Version	Title
30/06/2016	V1.0	Release of the document
30/06/2016	V1.1	Formatting of title fixed in pages 39-48

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Acronyms and definitions	
ARSI	Aerial Robot for Sewer Inspection
BCASA	Barcelona Cicle de l'Aigua
ESC	Electronic Speed Controllers
INS	Inertial Navigation System
LED	Light Emitting Diode
LIDAR	Light Detection And Ranging
MAV	Micro Aerial Vehicle
MEMS	Micro-Electro-Mechanical Systems
MTOW	Maximum Take-Off Weight
PDTI	Public end-user Driven Technological Innovation
ROS	Robotic Operating System
RPM	Revolutions Per Minute
UAV	Unmanned Aerial Vehicle

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1 Introduction and scope

1.1 Objective and scope

This document describes the concept of operation and system design of the Aerial Robot for Sewer Inspections (ARSI), our solution for sewer network inspection and monitoring. ARSI is a Micro Aerial Vehicle (MAV), multi-rotor type, endowed with sensors for its autonomous navigation along the sewer network, collecting data for its inspection.

The aim of this deliverable is to demonstrate the technical feasibility of the concept, the impact of this solution on the inspection procedures used nowadays and the appropriate use of resources in the remaining phases of the project.

This document corresponds to the deliverable D2.1 covering the activities of the ARSI consortium during the phase I System Design of the Urban Robotics Public end-user Driven Technological Innovation (PDTI) of ECHORD++ project. Therefore, acceptance of this deliverable serves as means of verification for the milestone 1 from ARSI work plan, as described in the proposal document. Further details on the preliminary tests results are provided in a separate document D2.2.

1.2 Structure of the document

The document has been organized as follows:

- Section 1: (current section) introduces the objectives and scope of this deliverable
- Section 2: describes the strategic principles of the use of an aerial system
- Section 3: provides a detailed design of the ARSI solution
- Section 4: covers the logistics and operational aspects of this solution from the perspective of a service solution company
- Section 5: introduces our business plan and demonstrates the economic feasibility of the solution
- Section 6: gives an updated overview of the work plan and project achievements
- Section 7: concludes the document with the key remarks and way forwards

1.3 Relation of the document with the phase I evaluation criteria

The document ECHORD++ PDTI Urban Robotics – Evaluation Criteria Phase I (Date 07.06.2016) establishes the main topics for the assessment of the phase I System Design. The following table relates them with the different content of ARSI deliverables:

Table 1. Relation of the document with the phase I evaluation criteria

<table>
<tr><th colspan="2">1.1 Positive evaluation of the tasks and documentation required during the period</th></tr>
<tr><td>Deliverables</td><td>Two deliverables are due at the end of phase I according to ARSI work plan: D2.1 (this document) and D2.2 submitted independently.</td></tr>
<tr><td>Milestones</td><td>Achievement of milestone 1 is justified in section 6.1 Review of Milestone I – Month 06</td></tr>
<tr><td>Technical KPI milestones</td><td>N/A according to ECHORD++ Urban PDTI representatives</td></tr>
<tr><td>Impact KPI milestones</td><td>N/A according to ECHORD++ Urban PDTI representatives</td></tr>
<tr><th colspan="2">1.2 Solution design</th></tr>
<tr><td>Detailed explanation of the solution design</td><td>See section 3 – Solution design</td></tr>
<tr><td>Logistics required and operational issues by using the solution</td><td>See section 4 – Logistics and Operations</td></tr>
<tr><th colspan="2">1.3 Test Series</th></tr>
<tr><td>Viability of the robotic solution mobility in the sewer network conditions</td><td rowspan="3">Initial results are detailed in the deliverable D2.2 Towards automatic sewer inspection. First results.

Official tests will be carried out July 6th – 7th in front of independent evaluators. These tests do not require any further documentation from the ARSI consortium</td></tr>
<tr><td>Communications suitability in underground sewage system network</td></tr>
<tr><td>Autonomy versus mobility of the robotic solution</td></tr>
<tr><th colspan="2">1.4 Economic Viability of the proposal</th></tr>
<tr><td>Economic Viability of the proposal</td><td>See section 5 – Economic feasibility and business plan</td></tr>
</table>

2 Why an aerial solution?

ARSI consortium represents a strategic partnership among companies with demonstrated experience in sewer inspection and robotics research. On the one hand, FCC main business is in environmental services, water management and infrastructure maintenance and construction, with 40% of their activities in international markets. They provide ARSI with the industrial hands-on experience of daily sewer inspection in several large cities, including Barcelona, for over 100 years. On the other hand, IBAK, which is already a technology provider for FCC, is today the biggest manufacturer and supplier of pipes inspection systems worldwide. They provide ARSI with the required knowledge on specialized robots, cameras and software in use to support sewer inspections nowadays.

The industrial partners of ARSI consortium agreed that an aerial inspection platform will represent an ideal complement to the existing procedures and systems used in the inspections nowadays. However, the consortium is aware of the challenges of this choice, which are the key objectives for research and development of the ARSI partners.

The following subsections highlight the key advantages of using an aerial robot, namely: manoeuvrability, operational speed and low logistics needs.

2.1 Manoeuvrability

Sewer networks are extremely difficult environments for mobile robots to operate, due to the very narrow dimensions of most tunnels, the lack of illumination, and the lack of positional information such as GPS.

They are particularly difficult environments for ground robots, which must not only cope with the presence of water at ground level, but also with all the irregularities commonly found in large networks such as that of Barcelona. For example, steps can be found in 571 locations (1% of all sections), and 67 cases of siphons were reported in the Barcelona sewer network alone.

Bifurcations

Obstacles on the sewer banks

Galleries with strong inclines

Sections with steps or obstacles

Figure 1: Irregularities commonly found in the Barcelona sewer network

Moreover, sewer network infrastructure deteriorates rapidly due to the constant flow of water, which is precisely why frequent structural inspections are so critical. The figures**¡Error! o se encuentra el origen de la referencia.** below illustrate typical deteriorations at ground level.

While these would make operation extremely difficult for a ground robot, an aerial platform would still be able carry out inspections and provide valuable video data helping maintenance teams address the damage.

Damaged banks

Protruding metalic rails

Missing banks

Figure 2: Typical damages caused by the flow of water

2.2 Operational speed

One of the key advantages in using aerial robots for sewer inspection is their high operational speed, which can reach over 10m/s in outdoors environments. Such high speeds are not practical in sewers however, due to their very narrow dimensions and the lack of illumination which make piloting a very complex task. In any case, the requirements for high-quality and high-frequency video data collection require that the platform flies at lower speeds.

Based on our test flights and the video data collected, we anticipate an inspection speed of **0.5m/s**, which we expect will be higher than that of any ground robot operating in this type of environment. Details about the inspection speed can be found in section 4.3.2 – Coverage.

2.3 Simple logistics

Another advantage of aerial platforms is their small size and weight, which significantly eases the logistical effort compared to ground robots.

While ground robots can weigh over 100kg and require equipment such as cranes and special vans to be deployed, the ARSI platform weighs less than 3kg, making it easy to carry and transport. With a total width of 58cm, it fits through all standard manholes allowing it to be deployed on any inspection site.

Section 4 – “Logistics and Operations” details how our Concept of Operations was tailored to make the most of these advantages to develop an inspection system that is efficient yet easy to use.

2.4 A safer and more intuitive inspection profile

A flying inspection robot navigates at a certain altitude above the floor. Most of the assets in the sewer are located on the bottom half of the tunnel. Flying slightly above most of the drain inlets makes the system safer in terms of environmental hazards since it is less likely to suffer unexpected water dumps on the system.

Moreover, the view from this operational altitude, relative to the ground, will be similar to that of a human operator making data collected with the ARSI platform intuitive to use for human supervision and analysis.

2.5 Limitations

While aerial platforms have clear advantages over ground robots when inspecting sewer networks, they also have important limitations, most notably their relatively short battery life and reduced weight capacity due to the constraints in size.

2.5.1 Autonomy

While ground robots can carry large batteries and have an autonomy of several hours, aerial platforms typically have battery lives of 10 to 20 minutes. This is largely compensated by their larger operating speed, as it is the case with the ARSI platform. Our Concept of Operations, detailed in section 4, was designed to work around these limitations and allow inspection teams to carry out efficient inspection campaigns, exceeding the challenge brief minimum requirement of 1000m/day for robots, or even 1500m/day currently achieved by current inspection protocols.

2.5.2 Sensor payload

The strict weight limitations of an aerial platform also impacts the type and number of sensors that can be included in the payload. Section 3.2 - Sensor equipment details the choices we made to meet the project requirements and ensure the quality of the inspection data collected with the ARSI platform.

3 Solution design

In this section we detail all aspects of the ARSI platform design.

3.1 Aerial platform

An aerial robot was designed by SimTech Design specifically for the ARSI project, taking into account the strict operational requirements inside the sewer network:

- It must be able to navigate in Navigable sewer galleries (>80 cm)
  (see section 4.1 Minimum criteria for drone-based inspection for definitions);
- It must fit through manholes (60cm in diameter) in order to be deployed and recovered easily during inspections;
- It must be able to accommodate and lift the ARSI sensor payload (see section 3.2);
- It must be resistant to humidity, dust, and occasional exposure to sewage water;
- It must be able to land on uneven ground, like the central basin in sewer tunnels;
- It must be reliable and safe to operate in sewer conditions.

3.1.1 Frame

The ARSI platform was designed as a quadrotor platform, meaning that it is propelled by 4 rotors positioned in a square shape. Quadrotors have many advantages over other types of configurations, in particular their stability, manoeuvrability and efficiency in terms of maximum flight time.

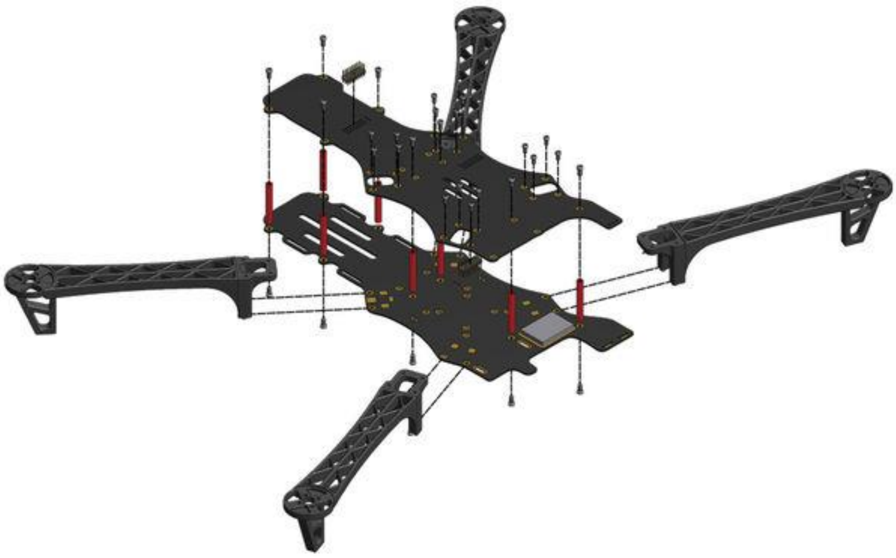


Figure 3: Original TBS Discovery quadrotor frame

In order to minimize the overall platform weight and dimensions while maximizing space for sensors and batteries, SimTech Design decided to use a custom-made carbon body with commercial components from the TBS Discovery platform (see Figure 3). The quadrotor arms were repositioned to reduce width of the platform down to 30.95 cm from motor to motor, or 57.2 cm in total when taking propellers and protections into account (see Figure 4 below). The platform is 71 cm long and 39 cm high including landing gear.

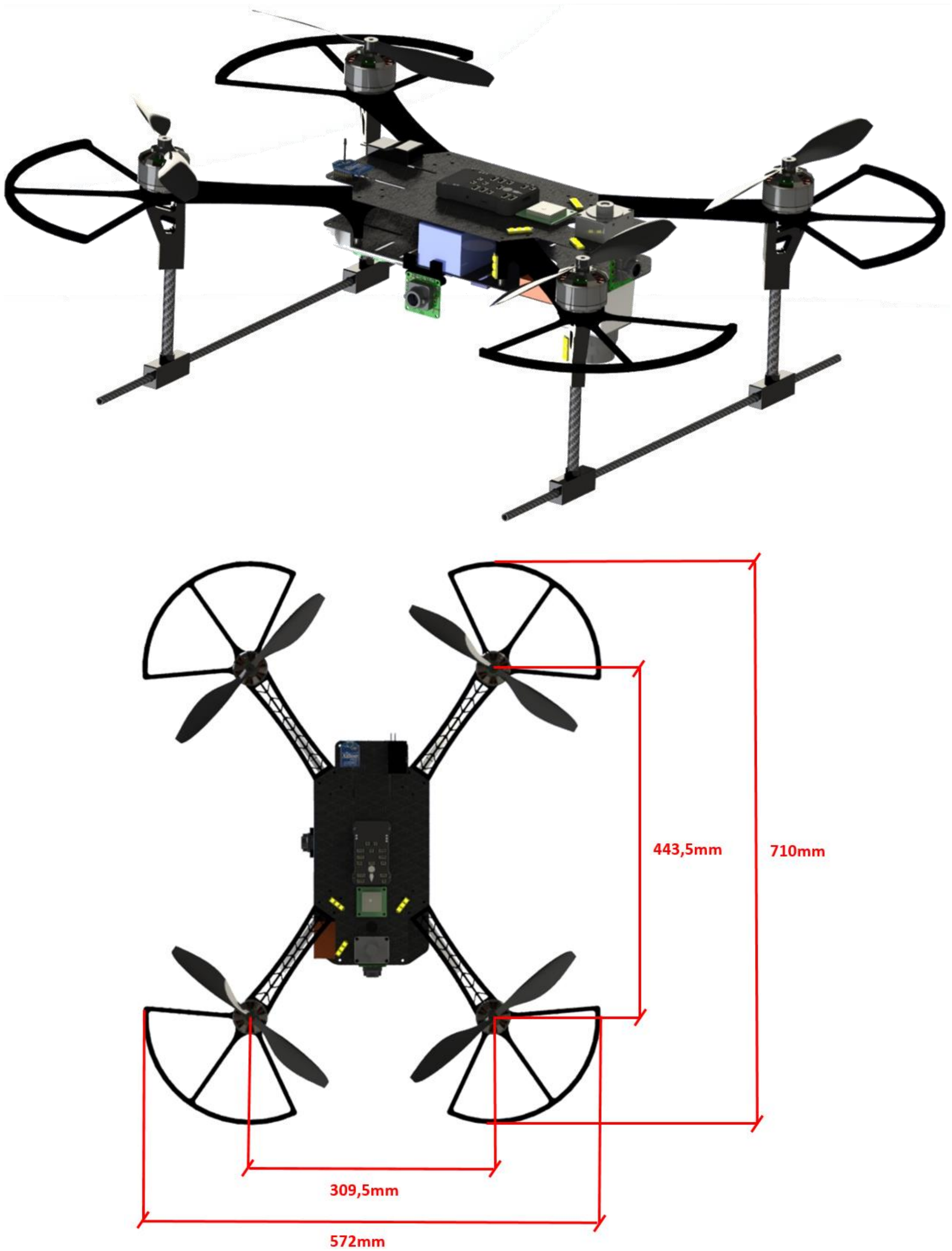


Figure 4: Custom-made frame of the ARSI platform

3.1.2 Robustness and safety

3.1.2.1 Resistance to humidity

Sewers are by nature very humid environments, due to the constant flow of sewer water on the ground or from pipes in the walls and ceilings. While the ARSI platform cannot be fully water-resistant yet, it is critical that it should be resistant to humidity and occasional contacts with sewage water.

Most critical components and sensors on the ARSI platform (onboard PC, cameras, laser, etc.) come in plastic cases which protect them from most of the debris and water. Some sensors, like the Hokuyo laser, are even rated IP65, meaning that they are resistant to dust and water ("water projected by a nozzle would have no harmful effect").

For more vulnerable electric components we used a hydrophobic and oleophobic coating which repels most water-based and some oil-based liquids. The coating was extensively tested and gave very good results in our tests.

Finally, the structure of the ARSI platform (see Figure 4) allows us to protect the most vulnerable or critical components by mounting them between the two metal plates forming the robot body.

3.1.2.2 Protections

Due to the very narrow dimensions of the sewers, even the smallest aerial robots have only 10cm or so of clearance from the tunnel walls. Additionally, flying a quadrotor in a confined environments creates turbulences, which in turn affect the stability of the flight. The consequence is that a drone operating under such constraints is likely to come in contact with the sewer walls. In order to protect the platform (in particular the propellers) in such events, we used 3D-printed plastic shields as shown in Figure 5.

Moreover, toxic gases are often present in the sewers, including potentially explosive gases such as methane. By using shields to prevent contact between the quadrotor propellers and the sewer walls, we also reduce the risk of sparks which could potentially trigger reactions with explosive or flammable gases.

Four propeller guards are mounted on the motor arms as shown in Figure 5.

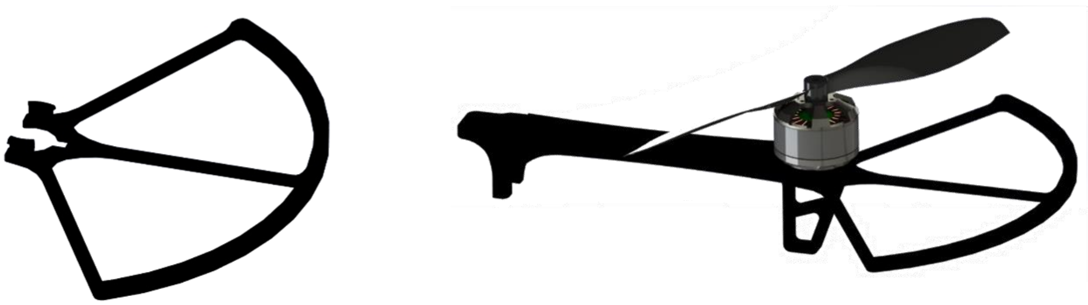


Figure 5: 3D-printed protection for quadrotor propeller

3.1.3 Landing gear

Figure 6: Sewer galleries in Carrer de Valencia, Barcelona

While some large sewer galleries (like Passeig Sant Joan) have bridges and islands allowing us to land the aerial platform, smaller tunnels don't exhibit such features (see Figure 6). In order to handle possible faults or emergency situations such as unexpected obstacles, it is critical that the ARSI platform should be able to land in most locations in the sewer network.

The original TBS landing gear was customized with custom-made attachments to include transversal carbon fibre bars in order to provide a larger ground surface (see Figure 7), wide enough to allow safe landing over the central basin in the sewer galleries, even if the vehicle lands with incline or in the complete absence of a flat floor.

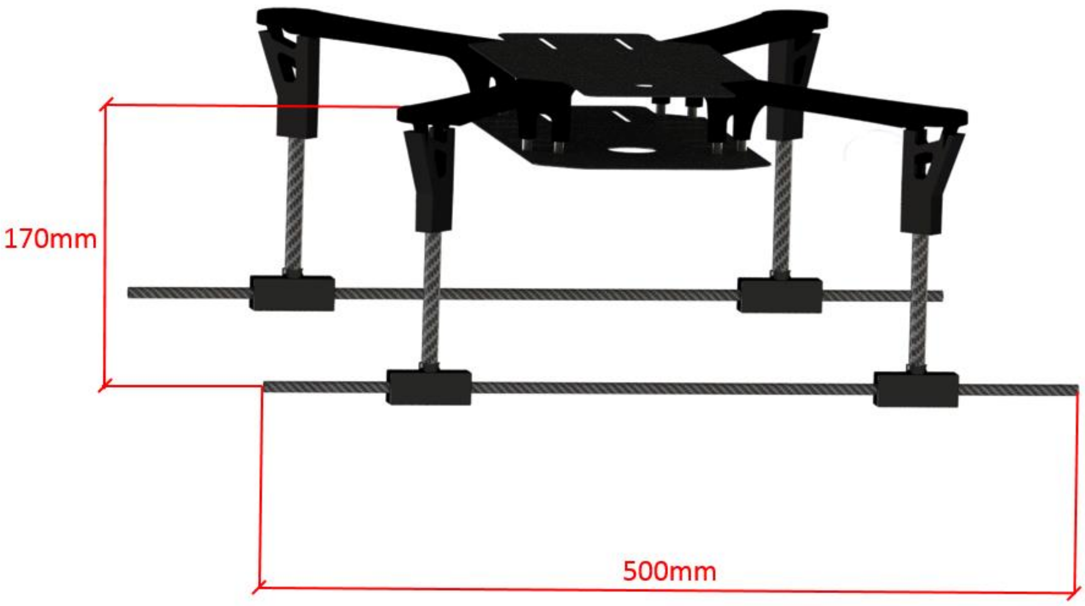


Figure 7 TBS frame with custom-made landing gear

Our landing gear will be designed to allow landing in water up to 10cm as long as current remains moderate. Its height ensures that all sensors are kept at safe distance from the water flow, and its thin carbon fibre structure minimizes the resistance against the water flow, avoiding the platform being dragged away by the flow.

3.1.4 Payload configuration

The ARSI aerial platform must be able to carry heavy batteries, electric components, as well as all navigation and inspection sensors described in section 3.2 — Sensor equipment.

The diagram below depicts all components of the payload on the platform.

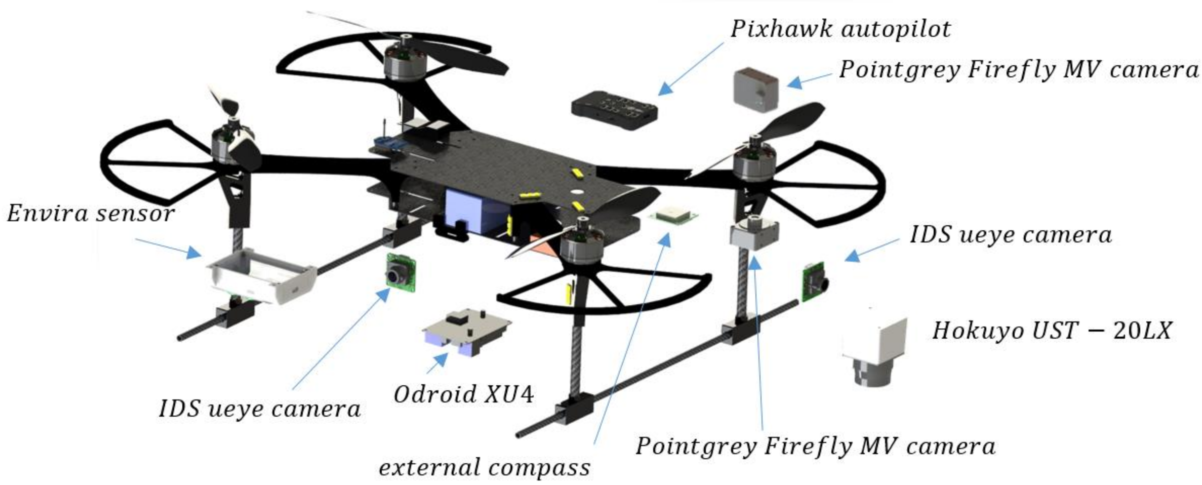


Figure 8 ARSI platform payload configuration

As shown in Figure 8, the ARSI payload configuration was carefully designed to make the platform as stable and easy to use as possible, in particular for common operations such as replacing batteries or accessing on the onboard PC. Components were positioned to make the most of the space available on the frame, minimize the amount of cabling, and ensure that relevant USB or Ethernet connectors are easy to access.

At the same time, the weight of the system was equally distributed among all the axes and, when possible, below the location of the motors. An equal distribution ensures the system is mechanically stable and therefore improves manoeuvrability and reduces energy consumption. Likewise, lowering the components below the plane formed by the four propellers makes the system more stable, and therefore, less energy is required to stabilize it; however, the response time is typically reduced.

Cameras and laser sensors are mounted to provide the best possible field of view given their characteristics:

- HD cameras with fisheye lenses are mounted on the platform front and rear, to provide wide-angle views of the ground and ceiling as well as a first-person view (FPV) for the pilot and obstacle detection.
- 2 lateral VGA cameras for close-range inspection of the walls. These will be used mainly for defect detection algorithms.

- The 2D LIDAR is mounted at the front of the platform, in order to provide an unobstructed view for obstacle detection algorithms, and in post-processing to produce geometry models of the sewer galleries (see section 3.3 — Localization and motion planning).

3.1.5 Payload weight

Weight is a critical aspect in the design of an aerial robot, because it affects autonomy as well as controllability. Heavier platforms need to push more air to sustain their weight, and in narrow confined spaces like sewer tunnels, this increased air flow results in turbulences due to ground and wall effects. Turbulences create instability in the vehicle control and must be minimized. Table 2 below provides a weight breakdown of the ARSI platform.

Table 2: Weight breakdown for ARSI platform

Item	*Model*	*Number*	*Weight (g)*	*Total (g)*
Frame	Custom model adapted from TBS/DJI F450	1	1200	1200
Motors	Tiger MN3110 780Kv	4	80	320
Batteries	GensAce 6000mah	1	593	593
Autopilot	3DR Pixhawk	1	38	38
External compass	3DR GPS/Compass (only Honeywell compass is used)	1	17	17
Embedded PC	Odroid XU4	1	90	90
Wi-Fi antenna	Alfa AWUS036AC	1	60	60
USB 3.0 hub	Generic model	1	20	20
2D Laser	Hokuyo UST-20LX	1	130	130
HD camera	IDS UI-3251LE	2	12	24
VGA camera	PointGrey Firefly MV	2	37	74
LED lights	VOLO Ultra compact	6	5	30
Air sensor	Custom made for ARSI project by Envira SL	1	60	60
Cables	Generic wiring of components	8	5	40
12V adapter	Power regulators for the required voltages	2	10	20
			Payload total	**600g**
			ARSI platform total	**2.7kg**

3.1.6 Propulsion chain

Unlike other types of mobile robots, aerial platforms are characterized by a tight coupling between their weight, dimensions, and autonomy. Their general performance is typically defined by:

- Maximum Take-Off Weight (MTOW),
- Maximum flying time in nominal conditions and worst case.

This performance depends on the ARSI platform total weight (see previous section) and the combined performance of several elements that form the propulsion chain:

- Power of motors defined by the motor size $\mathbf{K_M}$ and velocity constant $\mathbf{K_v}$,
- Electronic Speed Controllers (ESC) characterized by the maximum current,
- Dimension and shape of the propellers,
- Battery voltage and capacity.

In general terms, given a set of requirements like weight and desired flight time, there is an optimal configuration of motors, propellers, battery voltage and capacities. Any changes may bring your platform outside the limits. For instance, an increase in weight leads to higher power consumption which requires the use of either more powerful or multiple batteries, either of which results in an increased overall platform weight, etc.

Recent trends in multicopter design have shown that the most efficient approach in open spaces is to use larger blades turning at lower RPM, therefore using motors with lower K_v. However, in our case, we have already highlighted the constraints in terms of size, which limits the possible dimension of propellers (to a maximum of 10”), thus limits the lift power, and therefore the size of batteries.

The analysis and design of the propulsion chain is for us a constrained multivariable optimization problem. In order to find the best compromise between these different elements and the inspection requirements, an analysis was carried out using specialized modelling software.

Once the total weight of the system was fixed, several configurations with increasing complexity:

- capacity of the batteries: 5000 or 6000 mAh batteries,
- single or dual battery configuration,
- various models of motors,
- various models of propellers, dimensions, pitches and materials

Table 3 below summarizes the outcomes of our analysis for the five most representatives configurations. For each proposed configuration, three parameters are defined:

- Flight time [min]: refers to the estimated flight time in realistic environments (mixed time). This is smaller than the maximum hover time estimated for open spaces without turbulences.
- Additional payload [g]: refers to the extra weight that the platform can lift, excluding the ARSI setup. This is a contingency capacity in case we need to fit new equipment, but will impact on the expected flight time.
- Nominal Throttle [%]: percentage of total throttle for hover. This is the force needed to compensate for gravity given the current configuration of the platform. It is an indication of platform capacity and optimality.

We concluded that the best configuration is the fourth one (marked in green), with 780KV motors, 1x 6000 mAh battery and 10x3.3” carbon fibre propellers. Using this configuration and a nominal payload weight of 600g, the expected flight time in realistic environments is around 10 min, nominal throttle of 72%, and gives us spare payload capacity of over 400g for contingency. We consider this configuration optimal and appropriate for the ARSI system. We consider this configuration optimal and appropriate for the ARSI system.

Table 3 Propulsion chain analysis

Configurations					
Motor model	T-Motor MT2216 KV900	T-Motor MT2216 KV900	T-Motor MT3110 KV780	T-Motor MT3110 KV780	T-Motor MT3110 KV780
Battery type	Zippy 5000mAh 4s 30C	Zippy 5000mAh 4s 30C	GensAce 5000mAh 4s 45C	GensAce 6000mAh 4s 35C	GensAce 6000mAh 4s 35C
Number of batteries	1	2	2	1	2
Propeller type	APC SF 10x4.5”	APC SF 10x4.5”	APC SF 10x4.5”	Carbon Fiber 10x3.3”	Carbon Fiber 10x5”
Platform weight [g] (including frame, drive components and ARSI payload)	2550	3076	3144	2637	3231
Analysis					
Flight time [min]	6,3	-	11	10.1	13,3
Additional payload [g] (excluding ARSI payload)	733	-	374	427	485
Throttle [%]	69	-	79	72	73

The first configurations was discarded due to very low flight time. The second solution shows how adding a second battery increased weight and brings the motors beyond their limits. This is giving as an example of a physically non-feasible configuration.

The third one was discarded for two reasons: i) the nominal throttle is close to 80% which pushes the motors to their limits, reducing lifetime and robustness; and ii) the estimated RPM for hover are higher than the limits of the propeller grade. The maximum RPM is a relation of a constant describing the properties of the material and the shape:

$$Max\ RPM = K/prop\ \ diameter\ (inches)$$

For the APC Slow Flight (SF) propellers this limit is 6500rpm. According to the analysis, the expected nominal RPM during flight are 7728 rpm which may lead to propeller failure.

Therefore, we have converged to the selection of the fourth configuration for the ARSI solution. According to the analysis, this setup leads to an optimal and balanced performance in the three observed parameters. However, the setup does not bring the system beyond any limit. Ensuring a conservative margin on the system limits seems reasonable and appropriate for this stage of the project.

However, the ARSI consortium holds the required knowledge to optimize any of the performance parameters and push the current limits if required. An obvious direct improvement would be to reduce weight optimizing the current design. In terms of flight time, the best option is to use a dual-battery setup. However, given the current limits on the propeller dimension, the increase of weight requires also to change the propeller pitch (10x5”). This configuration is shown in the fifth column. It has been initially discarded since the increase of platform weight and propeller pitch induces and increase of air flow in hovering. During our preliminary tests in the sewer, we have observed that this increase of air, and therefore, turbulences, in such a confined area impacts the platform nominal stability and goes beyond the expected skills of a tele-operator. For the purpose of first phase, this configuration is discarded. However, it remains as a candidate for future optimization to increase flight time once that the motion control algorithms are in place, and the operator can benefit from the enhancements of the flight modes proposed in this project (see section 3.3.2).

3.1.7 Electrical design

The electrical design of the ARSI platform is given in the Figure 9 below. The ARSI consortium carefully selected low-consumption components and performed a power consumption analysis to ensure appropriate dimensioning for all electronic components in terms of maximum current and other characteristics. This study pursued the following objectives:

- to ensure platform reliability and safety,
- to meet all power and electrical requirements for each sensors,
- to provide connectivity between all sensors and the onboard PC and autopilot,
- to provide efficient illumination for the inspection of the sewer.

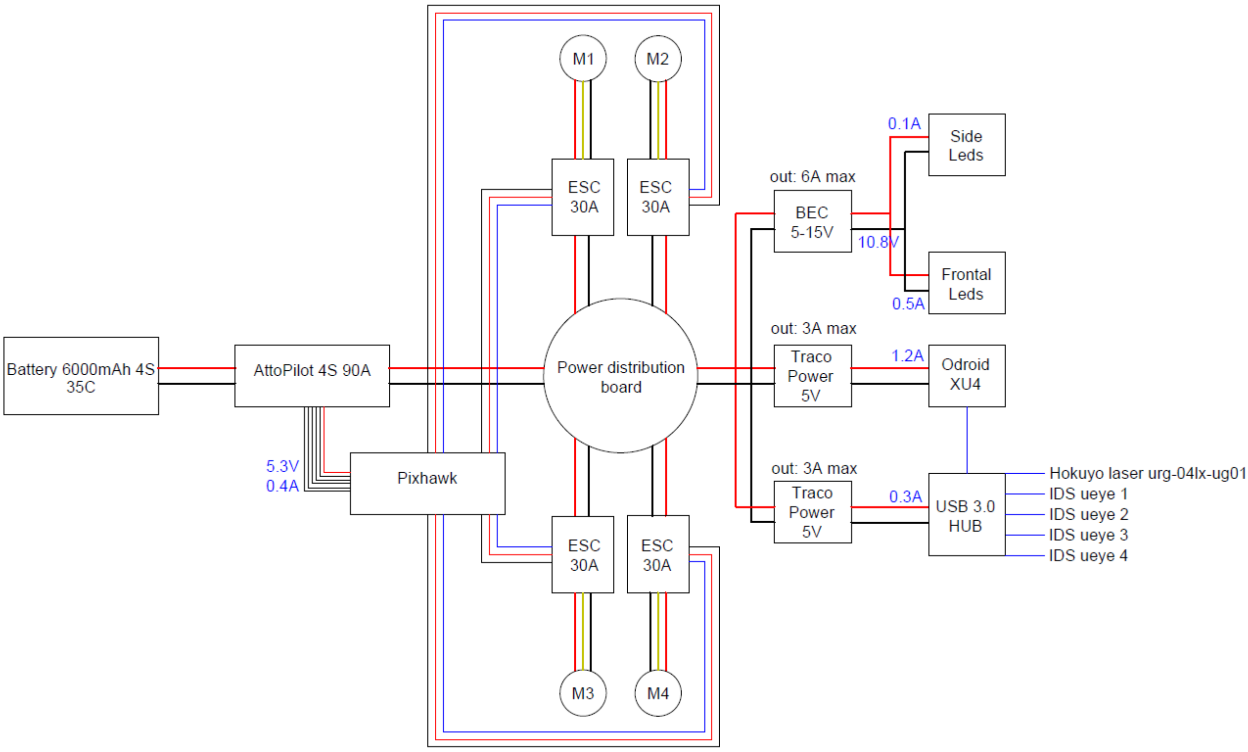


Figure 9: Electrical design of the ARSI aerial platform

A key principle in our design was to share the main batteries as power source both for the motors and the payload. Some other designs install a dedicated battery for the sensors but, according to our analysis, this would have required an extra load of approximately 120 grams for a dedicated battery that will last around half an hour. This would bring our system away from the optimal configuration. In our analysis, this energy would better be taken from the main battery and the impact on the flight time, when compared with consumption coming from the motors, is negligible.

The rest of the components are responsible for bringing power to the different locations, regulating voltage levels for those sensors operating at different voltages and monitoring current consumption for the battery monitoring functionality of our autopilot.

Two key design decisions are worth highlighting. Firstly, the complete set of sensors described in the next section are connected through an independently powered USB hub. This ensures all power needs are within limits. Secondly, the intensity required from the LED system may depend on the environment. In our design, we have foreseen the possibility of regulating the intensity of the LEDs placed on the front (these LEDs will face the darkness of the sewer), first manually, but potentially automatically in the future implementation. In the current design, this is achieved by an actuated regulator that allows a wide voltage range which in our design, controls the intensity of the LED illumination. The current values are 10.8V, consuming a total of 0.6A/h. The LEDs that light the sides and top of the platform are much less power-consuming (0.1A all of them) and have their own internal regulator to produce the maximum light. See section 3.2 for a detailed explanation on the design of the LEDs.

3.2 Sensor equipment

In this section we describe the sensor equipment mounted on the ARSI platform. The embedded sensors are grouped into two categories: navigation and inspection sensors.

3.2.1 Navigation sensors

One of the requirements for this project is that the robotic platform developed should provide a high level of autonomy in order to self-resolve operator orders and facilitate navigation in the sewers. In this section we give detailed information about the **navigation sensors** included in the ARSI platform in order to provide this autonomy.

3.2.1.1 Inertial Navigation System (INS)

An INS groups together motion and rotation sensors to provide a system able to build a continuous estimate of the velocity, orientation and position of a mobile platform. Such systems are used on many types of vehicles including planes, ships, and mobile robots.

Figure 10: 3DR Pixhawk unit

On the ARSI platform these core sensors are bundled in the 3DR Pixhawk unit (see Figure 10), a low-cost lightweight autopilot extending the functionality of a standard INS. Using its open-source PX4 firmware, Pixhawk is a powerful autopilot able to execute high-level waypoint-based missions, as well as low-level control requests (e.g. velocity or attitude requests). Details about the use of the PX4 Autopilot are given in section 3.3 – Motion Planning.

The Pixhawk hardware unit combines the following sensors:

- A 3-axis gyroscope (pitch, roll and yaw) for attitude control;
- A 3-axis accelerometer: for velocity control and position estimation;
- A magnetometer for heading estimation;
- A high-resolution MEMS pressure sensor for altitude control.

3.2.1.2 Laser scanner

Figure 11: Hokuyo UST-20LX laser scanner

The ARSI platform will be equipped with a Hokuyo UST-20LX unit, a high-resolution, wide-angle 2D laser scanner with the following characteristics:

- Long range (20m)
- Wide-angle (270 degrees)
- Lightweight (130g)
- Resistant to vibration and shock
- IP65 rating making it resistant to dust and water

Hokuyo sensors are widely used in the robotics community, which means that drivers, processing tools and support are widely available.

This sensor was chosen mainly for its ability to operate in environments with poor illuminations and a lack of distinctive visual features. Navigation techniques using imaging cameras, such as visual odometry, rely on the presence of robust visual features in the environments which are unlikely to be present or consistent in sewer tunnels. Another advantage of using laser is that it can be used both for navigation and obstacle avoidance (see details in section 3.3 – Localization).

3.2.2 Inspection sensors

Like in most large cities, the sewers in Barcelona are inspected by human operators through the means of routine visual inspections. The primary goal of these inspections is to reduce the risk of collapse and floods, and to optimise the cost of renewing facilities. In particular, this involves ensuring that there are no obstructions to the flow of wastewater, and that any cracks or fissures on the walls are detected and repaired so they don't weaken the structural integrity of the sewer.

If autonomous systems are to become a viable alternative to the current inspections, they must be able to collect sensor data and provide post-processing tools allowing operators to achieve the level of coverage and guarantee the same level of integrity of the sewers.

3.2.2.1 Video cameras

Since visual inspection is the primary aspect of the work currently carried out by human operators, it is critical that the ARSI system should be able to collect high-quality imagery of the sewers during autonomous inspections. Structural defects can occur on the sewer walls, ceiling and basin, although special attention should be paid to the basin, where most of the damage is found due to the flow of wastewater and entries from side pipes.

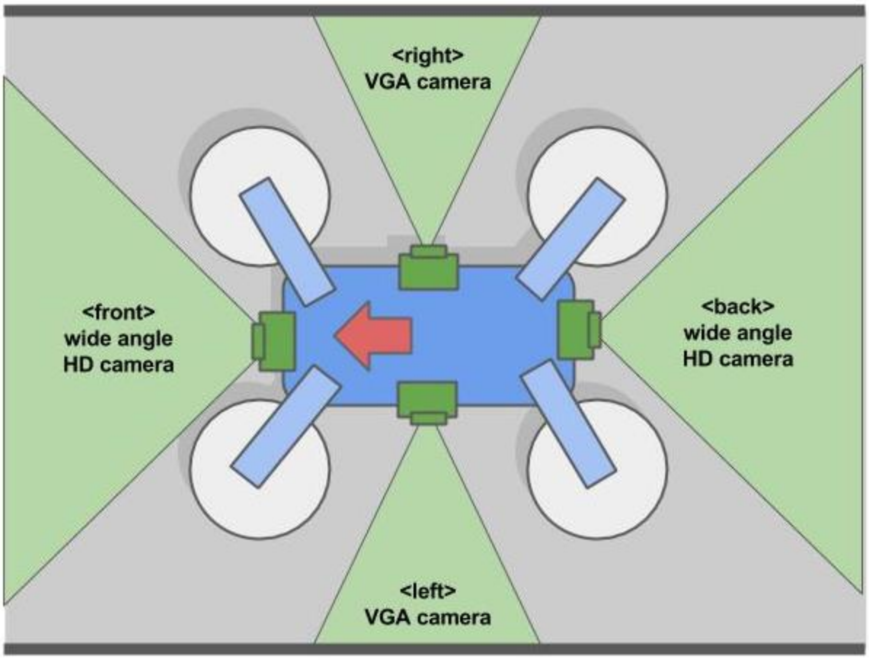


Figure 12: Mounting of the 4 cameras on the ARSI platform

The ARSI platform carries 4 cameras as shown in Figure 12, all equipped with wide-angle "fisheye" lenses:

- Two grayscale VGA cameras (640x480) cameras are mounted on each side of the platform, to record close-range video of the sewer walls where structural defects are often found.
- Two HD (1200x800) cameras are mounted at the front and rear of the platform, providing wide-angle views of the vehicle surroundings, including the sewer ground and ceiling.

Figure 13 illustrates how the front and rear will be mounted on the final design[1] to provide coverage of the sewer ground and ceiling, by taking advantage of the wide fields of view provided by the fisheye lenses. These cameras will be the primary viewpoints used by pilots to operate the ARSI platform, since it can move both forwards and backwards.

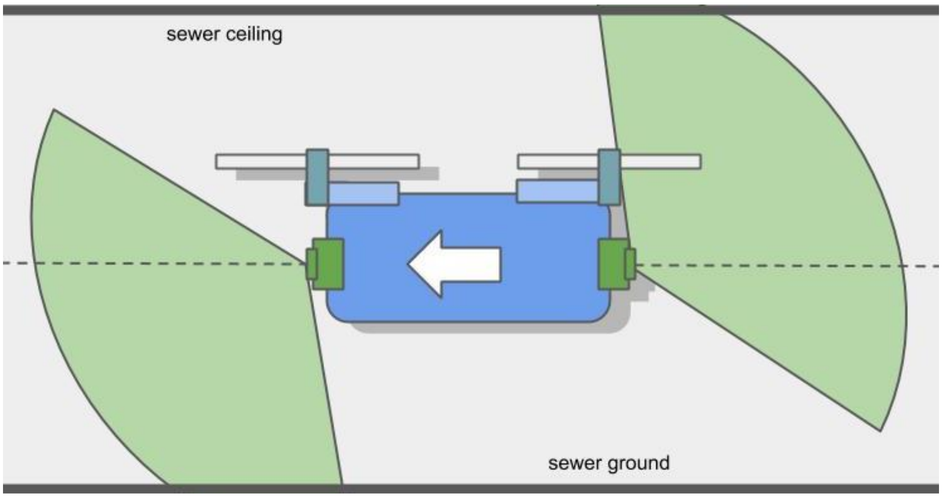


Figure 13: Mounting of the front and rear cameras

After careful evaluation, the camera model selected is the uEye UI-3251LE. It was selected for its image quality, low weight, and relatively low cost.

Choice of inspection parameters: speed and camera rates

Inspection parameters, such as vehicle speed and camera rates, must be chosen carefully in order to meet the project brief requirements in terms of video data collection.

As show in Figure 14, the length D of the section of wall covered by a camera is given by the following formula:

$$D = 2 \times d \times \tan \alpha$$

where d is the distance from the camera to the wall, and α is half the camera field of view.

[1] Due to Budget constraints only the front camera follows this configuration. On the current version the rear camera is actually on the top.

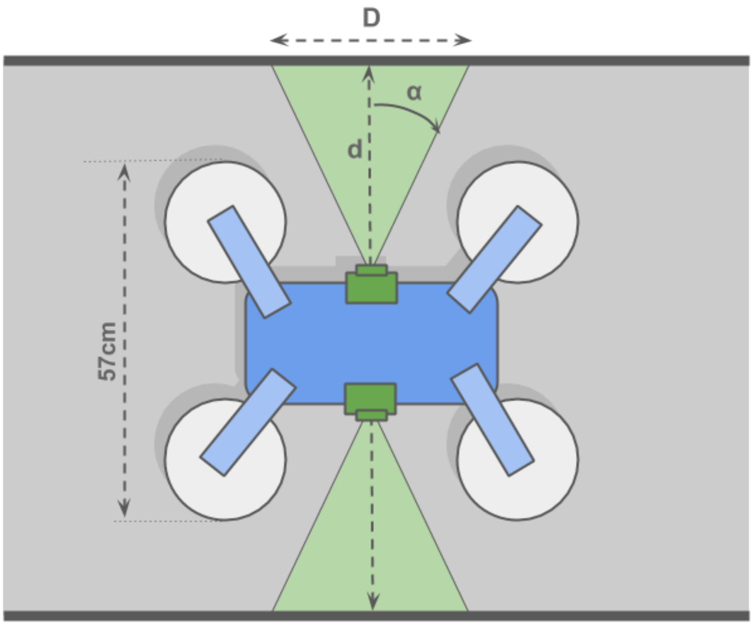


Figure 14: Coverage given inspection distance (d) and camera field of view (α)

Under normal conditions we can assume the following:

- $d \sim 30cm$ (vehicle navigates at the centre of the tunnel)
- the camera lens is chosen so that $\alpha = 30°$
- therefore $D = \sim 35cm$

The main configurable aspects of the inspections carried out using the ARSI platform are the camera capture rate and the inspection speed: both need to be chosen to maximize overlap between consecutive video frames, in order to provide maximum coverage of potential defects.

Using a typical inspection speed of **0.5 m/s** and a camera capture rate of **5Hz**, the displacement between images is 10 cm, resulting in a 70% overlap between frames, ensuring that defects are visible in at least 3 consecutive images.

3.2.2.2 LED lights design

The scene covered by each camera needs to be lit by LEDs, so that consistent illumination is provided in an otherwise obscure environment. Camera illumination is critical since they will provide the visual information for defect inspection, as well as images streamed to the operator on the surface.

We have selected two CREE XLamp 1590 lm LED lights to be placed by each side of the camera at the front. These LEDs work at 12V ensuring that 4-cell batteries can power them easily. Several color temperatures have been tested; we have assessed experimentally in situ that a color temperature of 6500K achieves the best results in terms of image definition and contrast in scene features.

These LEDs meet the trade-off required between the light needed to illuminate the sewer and the constraints on weight and size imposed by the platform. Therefore the amount of light they produce will be regulated to save power and avoid overheating or the need of heat sinks.

The LEDs will be powered at 10.8V consuming a total of 0.6A/h. Each CREE LED will be mounted in a star PCB, which makes them easier to handle and helps dissipate heat.

The requirements on power for the cameras of the sides are less challenging, since experiments have shown that the walls and the ceiling will be very close to the platform and reflectance phenomena occur. For this function we have selected the extremely small and light VOLO LEDs which provide a satisfactory lux performance with very little power consumption.

The configuration of the VOLO LEDs with respect to the cameras is shown in Figure 15.

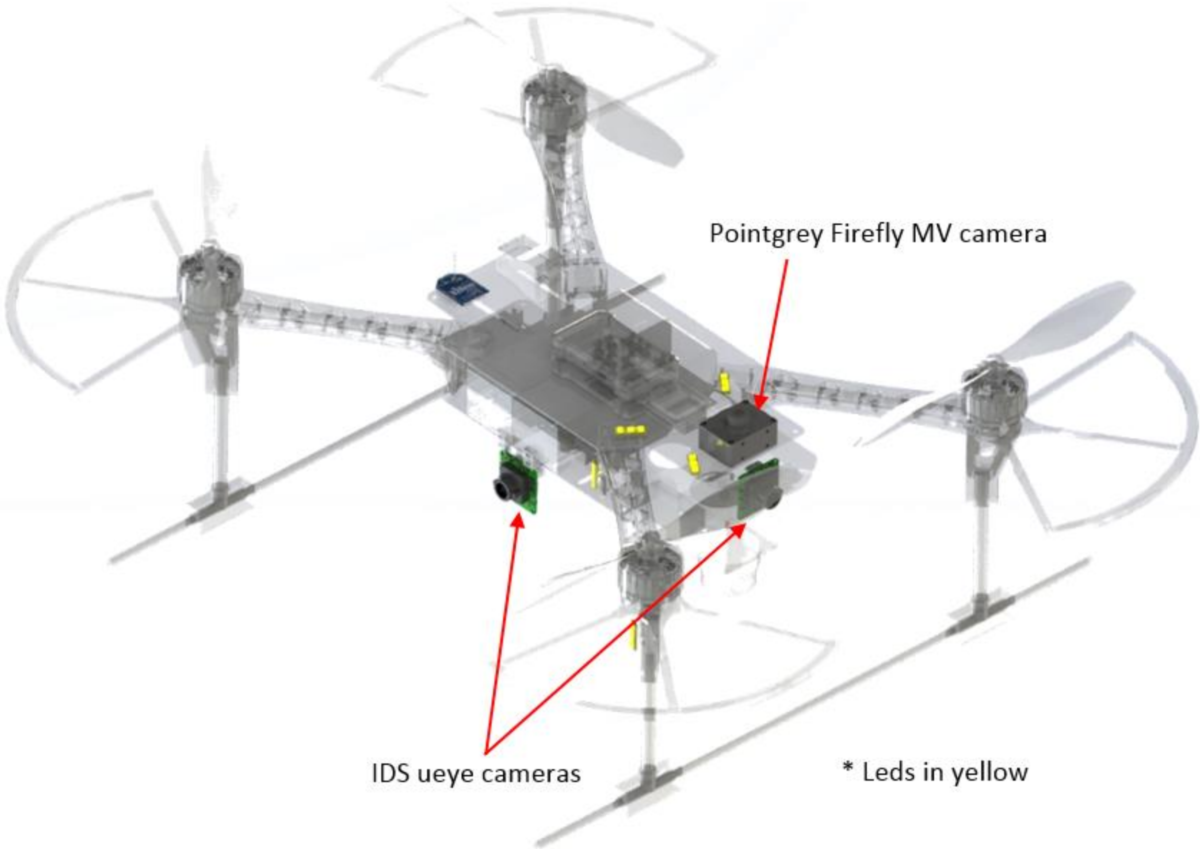


Figure 15 : VOLO LEDs (in yellow) and visual cameras

3.2.2.3 Air quality sensor

Sewer networks are a very challenging environment to work in for many reasons, including high humidity, slippery areas, and concentration of toxic gases. One of the objectives of this project is to develop an inspection system able to operate remotely in these conditions, in order to improve efficiency as well as the health and safety of sewer workers.

As explained in the Concept of Operations section, the ARSI platform is operated remotely from the surface, which means that inspection teams do not have to spend extended periods of time inside the sewer network. The ARSI system is equipped with an air analysis sensor able to estimate the concentrations of several gases, including toxic gases such as hydrogen sulphide.

The ARSI aerial vehicle is designed as a plug-and-play system where new sensors can be easily integrated as long as the overall payload weight stays within the platform specifications. In order to demonstrate this flexibility, a sensor to analyse the composition of the air inside the sewers was integrated and evaluated during Phase 1 of this project.

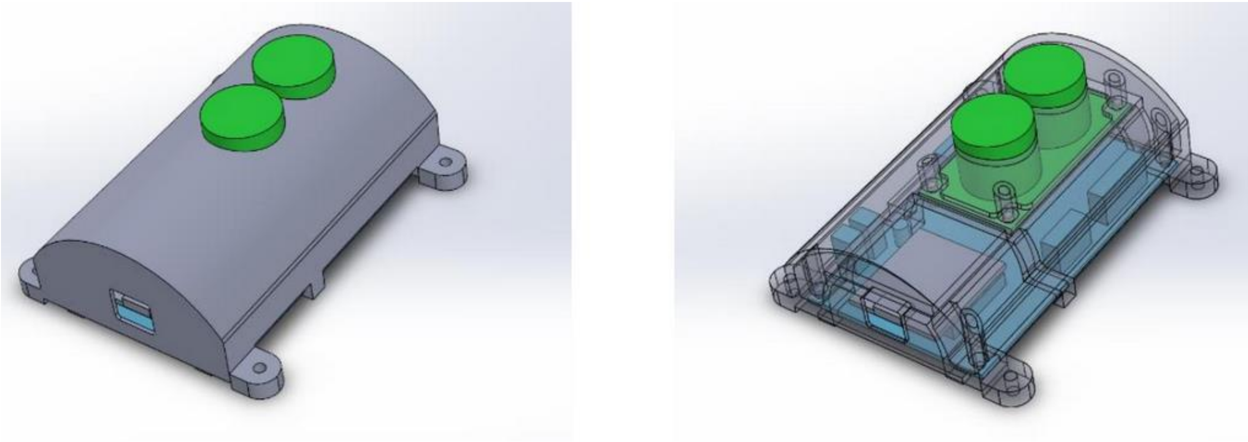


Figure 16 : ARSI air monitoring sensor

The sensor, provided by the company Envira Sostenible, is able to monitor temperature and humidity as well as levels of Carbon Monoxide (CO) and Hydrogen Sulphide (H_2S). Future versions will also be able to monitor Sulphur Dioxide (SO_2), Nitrogen Monoxide (NO) and Nitrogen Dioxide (NO_2)

As inspections are being performed, the ARSI platform collects regular air samples and stores the results in the mission logs. These air samples can then be georeferenced against a GIS system to produce a map of the concentration levels of different gases of interest. This map can be very useful for sewer inspection teams in order to plan their inspections safely, and to take appropriate measures in the event of high concentrations of dangerous gases.

3.2.2.4 Laser scanner

The laser sensor described above is used both as a navigation and inspection sensor, since laser scans collected during an inspection can be post-processed to build a geometric model of the sewers. This reconstruction task is carried out in the post-processing phase, as it requires the vehicle trajectory computed using the algorithms described in section 3.3.1 – Robot localization.

Note that due to payload weight limitations, the ARSI platform can only carry one laser sensor, so that the generated models only contain 2D information. However models containing height information can be produced using the ability of aerial platforms to vary both their altitude and pitch, as shown in Figure 17.

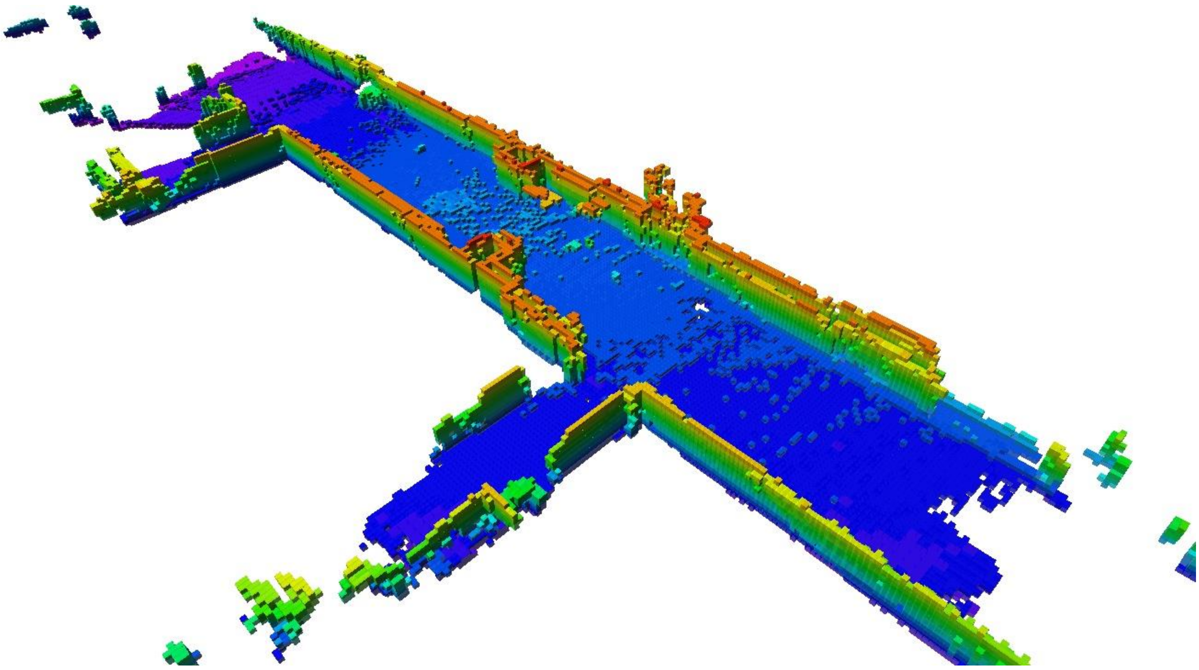


Figure 17: 3D visualization of a 2D model built from laser data

As shown in Figure 18, the 4 cameras mounted on the ARSI platforms have significant overlap thanks to the wide angle (~ 180 degrees) provided by the fisheye lenses. Using these overlaps, we can in theory apply the principles of stereo vision for 3D reconstruction: if a visual feature is seen in two or more calibrated cameras, then it is possible to estimate its 3D position with respect to the fixed frame where the cameras are mounted (see Figure 19).

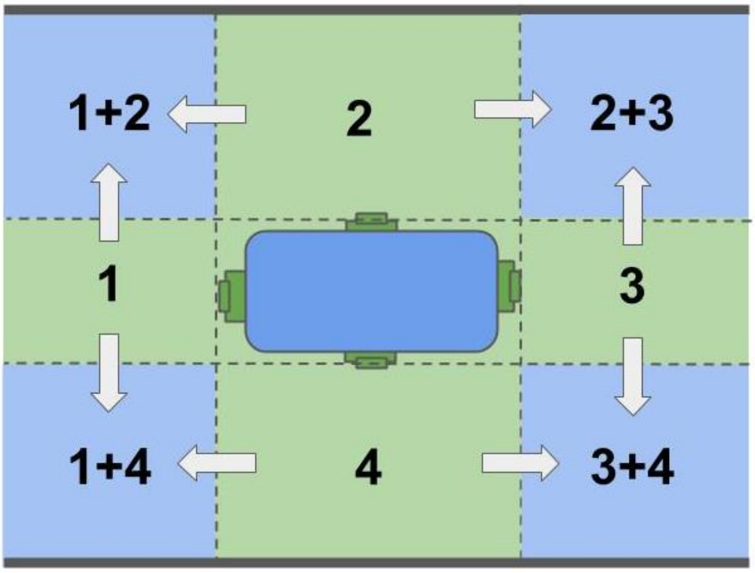


Figure 18: Overlap between the 4 wide-angle cameras (numbered 1 to 4)

The accuracy of this 3D position depends on the calibration of the cameras, the model of the distortion caused by the fisheye lenses, as well as the accuracy of the feature matching. This approach is widely used in outdoors environments, where many such features can be seen, to build 3D models of the surroundings for many purposes, including detection and navigation.

In most real-world applications, visual features are also tracked across images and over time to build more robust estimations of their position.

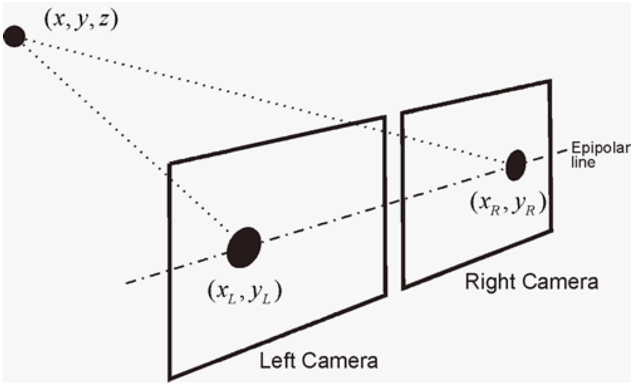


Figure 19: 3D position (x,y,z) calculated from two correspondences (X_L, Y_L) and (X_R, Y_R) in a stereo configuration

In our application, such 3D features would allow us to augment the 2D model built using laser data into a 3D one. However typical sewer tunnels do not exhibit many recognizable visual features, and their detection is made more complex by the lack of illumination. On the other hand, sewer tunnels present advantages in that they are man-made, controlled environments whose shape and profile is accurately known based on the type of tunnel sections. Based on this information, we intent to investigate this approach in phase II of this project, in order to evaluate the quantity of features available for 3D reconstruction and the quality of the 3D models produced.

3.2.3 Processing hardware

In order to process and store all the data generated by these sensors, the ARSI platform carries an Odroid XU4 embedded PC. This model was selected primarily for its low cost and weight (60g) as well as its high-speed Ethernet and USB 3.0 connectivity.

The Odroid XU4 also provides slots for flash storage, and will use a high-speed 64GB eMMC memory card for sensor data storage. The Odroid PC runs all our ROS sensor drivers and embedded modules for data processing, storage, as well as the dynamic detection and navigation algorithms described in section 3.3.2.

Note that the 3DR Pixhawk unit also contains its own dedicated PC to run the PX4 autopilot software and execute high-level control commands such as auto-takeoff and landing, waypoint following, velocity requests, etc. It also includes a Kalman Filter for pose estimation.

3.3 Localization and motion planning

Navigation, either autonomous or semi-autonomous, is the most challenging competence of an aerial robot. The **localization** module estimates the robot state, typically defined as position, velocity and attitude (PVA) relative to an external reference frame. This enables the **motion control** module to compute the required outputs to achieve a desired motion, goal or trajectory.

3.3.1 Robot localization

Robot localization is not only needed for the operation itself. The reconstruction of the trajectory is also required to geo-reference observations against the map of the sewer network, allowing information to be recorded and inspection teams to efficiently plan further inspection visits. These observations may include for instance structural defects or gas measurements.

Global positioning sensors such as a Global Positioning System (GPS) are unfortunately unavailable in the sewer system. Therefore, the position and trajectory of the ARSI aerial vehicle cannot be directly measured. It can only be estimated using onboard sensor data captured during flight.

Most localization techniques for mobile robots work by fusing motion information provided by Inertial Measurement Units (IMU) with external correction sources such as GPS. In an Inertial Navigation Systems (INS), position is estimated by a double integration of inertial measurements (i.e. accelerations and angular rates) and, therefore, inherent measurements errors, such as noise and bias, inevitably accumulate causing the position estimation to drift exponentially. In **unaided inertial** position estimation, where an IMU is used as a stand-alone INS without assistance of external sensors, even the highest grade unit shows an inherent drift.

The following formula [1] provides a maximum static horizontal position error E and will serve as a reference for a later analysis:

$$E = 0.5 \times 9.81 \times \frac{E_{acc}}{1000} \times T^2$$

Where E_{acc} is the accelerometer bias error in mg, and T the elapsed time in seconds.

The following table illustrates the expected drift for each IMU grade.

Table 4: Horizontal position error table for Inertial Standalone (unaided)

	Accelerometer Bias Error	Horizontal Position Error [m]			
Grade	**[mg]**	**1s**	**10s**	**60s**	**1hr**
Navigation	0.025	0.13 mm	12 mm	0.44 mm	1.6 km
Tactical	0.3	1.5 mm	150 mm	5.3 m	19 km
Industrial	3	15 mm	1.5 m	53 m	190 km
Automotive	125	620 mm	60 m	2.2 km	7900 km

IMU measurements provide a continuous and accurate motion measurement in the short term, but the position solution drifts over time. It is therefore clear that INS needs to be aided by external sources to bound or even remove the accumulated errors in any robotics application, including ARSI. GPS provides an ideal complement to inertials, since it provides absolute position measurements, less accurate but with bounded errors, therefore, drift-free. The traditional techniques to fuse both sensors relies on probabilistic localization algorithms such as, for example, Kalman Filters.

In the absence of GPS, exteroceptive sensors, such as monocular or stereo cameras, laser scanners and rangefinders, are typically used as secondary sensors. These sensors cannot provide a direct measurement of position but there are different techniques to locate the robot on the environment that exploit data coming from this type of sensors. Sensor-based localization has received the greatest research attention in the past decade with significant advances. In terms of algorithms, in synthesis, we want to differentiate between two large categories:

- Map-based or correlation-based algorithms use the previous estimate of the robot location and the current sensor data (i.e. an image or a laser scan), to compare against the expected measurement on an a-priori model of the workspace (i.e. a map). They generally estimate the location that minimizes a certain metric representing an error. Monte-Carlo localization based on maps are an example of this category.
- Feature-based algorithms use the sensors to observe features on the environment (points, corners, lines, etc.), and use the change in range and orientation to these features to derive motion information directly. They generally estimate motion (displacement and rotation rather than position). Examples are any visual or laser odometry algorithms.

Map-based algorithms are therefore capable to locate the robot with respect to a reference map and automatically get rid of the drift. They are in general multi-modal (carrying out simultaneously several position beliefs) and sudden corrections may imply jumps on the estimate of the location over the map. Furthermore, they are capable to recover from severe drifts.

Feature-based algorithms, on the other hand, do not need a priori knowledge of the environment. They are typically dead-reckoning solutions that integrate motion estimates over time, and therefore can accumulate drift. These are unimodal (single belief), and without external aid, they do not recover from severe drifts. They are commonly used in aid of the inertial navigation in two possible integration strategies: loosely coupled (position domain) or tightly coupled (measurement domain). In these cases, a prediction of the state is done using only inertial measurements, while the correction is achieved by processing the sensor data to either compute displacement or impose constraint equations. Any difference between predicted and measured motions can be considered an error in the estimate and therefore removed from the solution.

3.3.1.1 Sewer characteristics and challenges

While the task of locating oneself accurately in a sewer gallery would already be very difficult for a human, it becomes extremely difficult for a mobile robot with relatively cheap sensors and strict weight constraints. Sewer are made of galleries connected together into a network, generally mirroring the road network on the surface. Each gallery has a specific section type, which defines its dimensions and shape (see examples below).

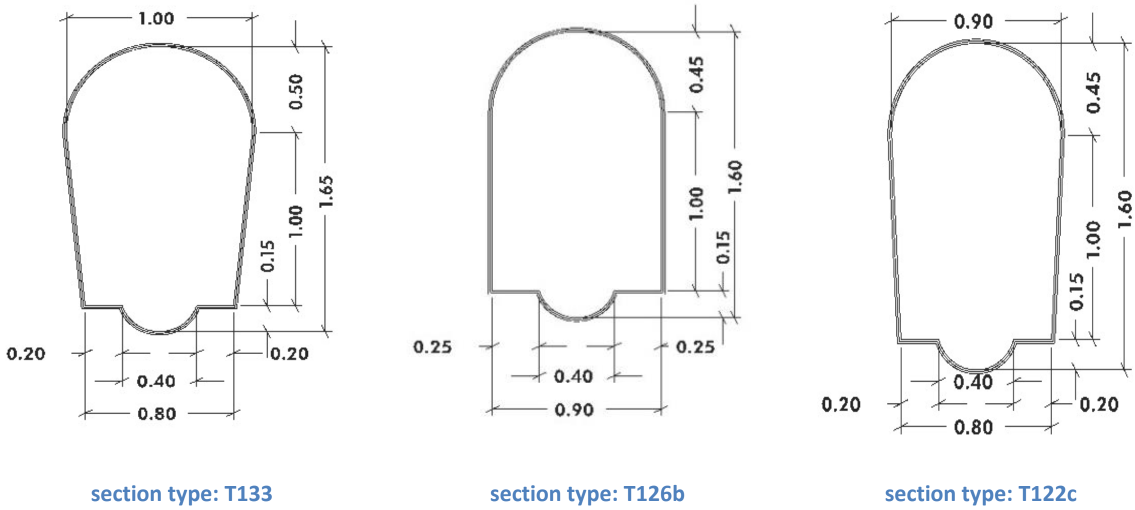


Figure 20: Examples of sewer sections

The main challenge for localization in the sewers is that galleries are typically featureless environments: they exhibit very few visual or physical landmarks. Some of these features may be used to temporarily estimate motion, but would not be reliable enough to completely estimate the location along the tunnel unambiguously. Additionally, most sewers are not illuminated, so our drone must either be able to operate in darkness or be equipped with artificial illumination, making the use of visual features even more challenging.

Sewers, on the other hand, are man-made highly structured environments. Structural elements such as walls, openings, ceiling and floor are easily detected with scanning sensors. The change of distance and bearing to these features can be obtained with laser scanners and rangefinders at different instants. A position estimate based only on these measurements is not possible, but this information may be used on a tight integration filter, therefore working on the measurement domain, to correct the drift of the inertial **local** position estimate. For example, lateral distance to the walls, which are known to be static, can be used to impose a constraint on the inertial drift along this axis, improving the performance by means of laser-aided inertial navigation.

Typical sewer gallery

Intersection with clear corner feature (in red)

Figure 21: Examples of features

Finally, sewer intersections exhibit the strongest features, typically corners, which can also be easily detected using sensors such as 2D lasers. These detections allow a **relative** estimation of the vehicle position (i.e. distance to the feature). Another important aspect of these intersections is that they can almost always be identified unambiguously on the map (i.e. globally), based on their topology and previous location estimates of the vehicle. Bifurcations therefore provide accurate **global** position information. Of course, this information is only available in specific areas of the sewer.

3.3.1.2 Proposed localization method

Given these constraints, an **accurate real-time** localization method in the sewer system is extremely dependant on the location along the sewer and the characteristics of the surroundings. Therefore, the control strategy cannot rely on a position estimate to implement a cascade control with position, velocity and attitude control loops, which is the common approach, for instance, in outdoor aerial robots. Instead, ARSI shall be based on **reactive navigation,** where sensor data (measurements) are used to close the control loop and keep the platform safe during the inspection. This will be described in later sections.

Our approach for localization stems from the observation that different phases of the inspection require different performances and solutions. Our solution is thus made of the combination of complementary techniques:

- A **continuous local estimator,** a feature-based inertial localization method serves as dynamic estimator (velocity and attitude). This solution exploits the accuracy of inertials in the short term. It also estimates position but, even aided with secondary sensors, it may show some drift. This is overcomed by the use of reactive navigation which constantly keeps the platform away from collisions. This estimator does not require a reference map, and therefore ensures continuity even in areas without enough information on the map. This allows constant supervision of the mission by an operator.

- An **online discrete global estimator,** a real-time map-based localization method will locate the robot on the operational map and correct the drift of the local estimation in certain areas, for instance, near intersections. In these areas is where high-level decisions require a more reliable position estimate, for instance to decide which gallery should be followed.
- A **full discrete global estimator,** an offline map-based localization method. After the mission, the entire data set is available and can be processed to optimize the accuracy of each estimate. This method is equivalent to the previous one, but in this case, data capture before and after a given time instant can be used to improve the estimation. This method serves to maximize the accuracy of the geo-referencing of the defects, and may also be improved with user inputs in the form of control points.

The following diagram illustrates the solution:

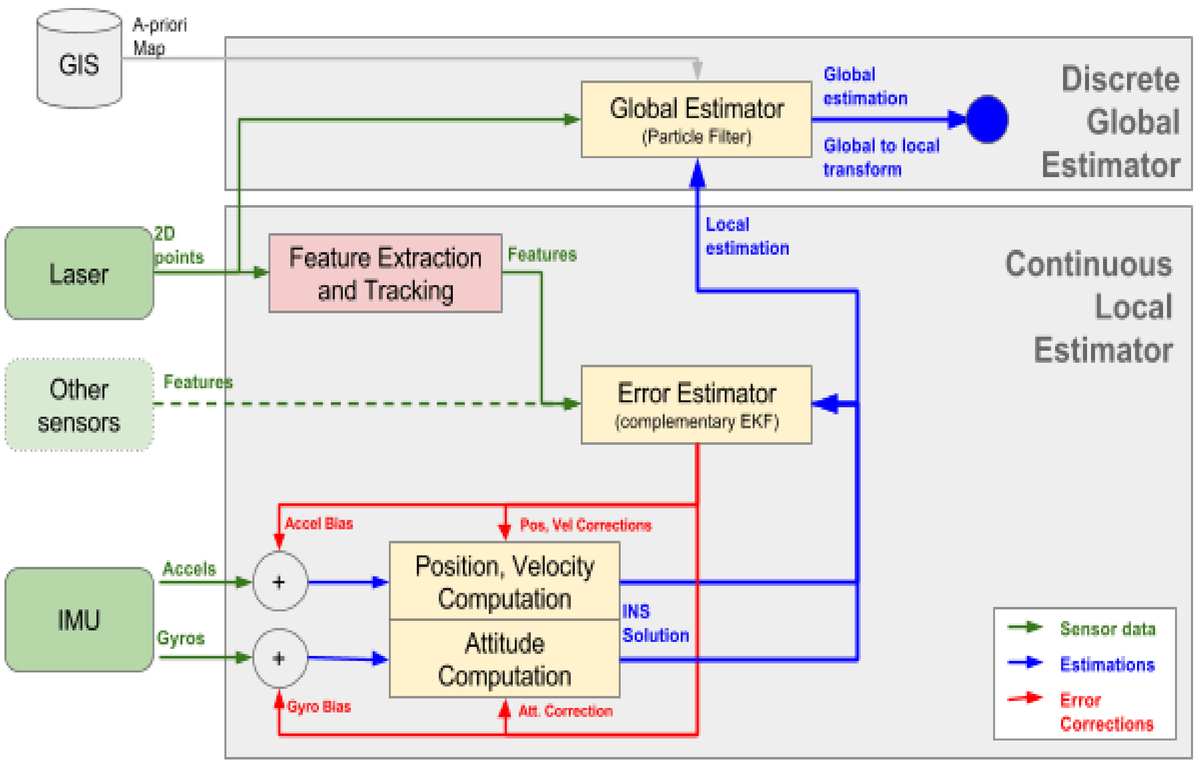


Figure 22: Integration strategy for the local and global estimators

3.3.1.3 Continuous local estimator

Our local estimator relies on an IMU as the core sensor as it is self-contained and, therefore, does not depend on any external characteristics. INS algorithms have been well documented [2] and there are several reference implementations to build upon.

Raw measurements such as angular rate ω_b and accelerations f_b are computed to obtain the current position, velocity and attitude (see Figure 23).

Given the constraints of the operational environments described above, the integration with secondary sensors must be done on the measurement domain. Our local estimator will implement a complementary Extended Kalman Filter (EKF). A complementary filter, also referred to as “error-state” filter, estimates errors rather than absolute values. It is therefore extremely suited for our purpose since, in order to use secondary sensors, we need to derive measurement equations that relate sensors and the state vector. This mathematical derivation becomes much easier for most of the exteroceptive sensors when the filter is estimating errors instead of absolute positions or velocities.

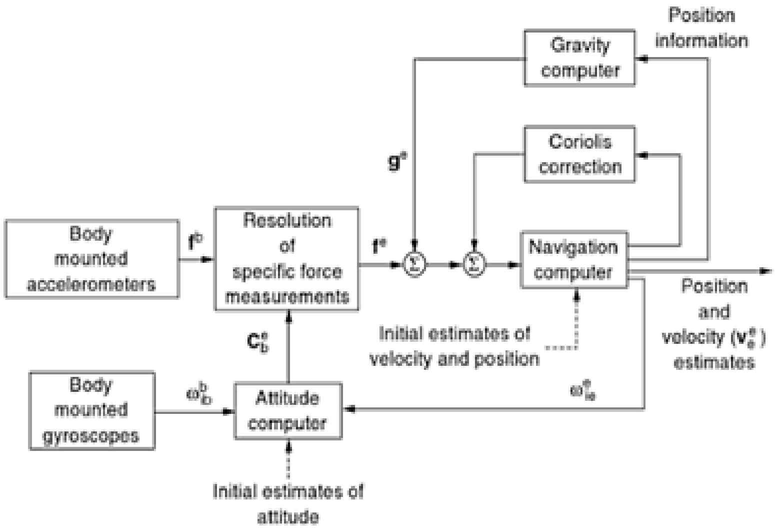


Figure 23: Inertial strap-down navigation algorithm

The objective of this estimator is to individually exploit the sparse characteristics available on the sewers to periodically calibrate the INS errors and remove them from the INS computation. To remove these errors, they have to be estimated with the support of secondary sensors.

The use of most secondary sensors follows a similar approach:

- Features are extracted from the data (lines, points, etc.)
- Features are associated (tracked) across consecutive samples
- INS outputs are used to predict (synthesize) the expected changes in the range and orientation to the features.
- The difference between prediction and observation is used to estimate the error in the INS.

This algorithm, referred to as “tight integration” is illustrated in Figure 24.

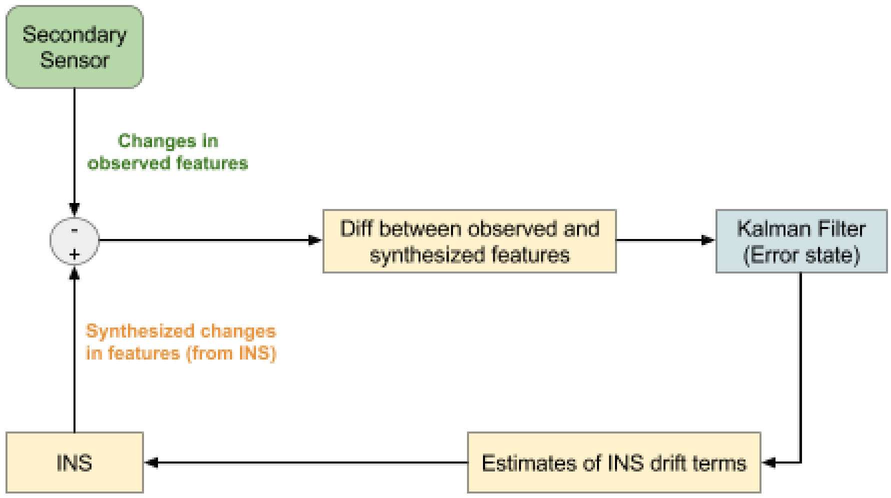


Figure 24: General aided inertial tight integration scheme

As shown in the diagram above, these error must be removed from the INS solution. Therefore, the vector state X of the complementary filter contains the main sources of error for the INS:

- δr: position error
- δv: velocity error
- $\delta \varphi$: tilt or mis-orientation error
- $\delta \omega$: gyro bias
- δf: accelerometer bias

The filtered INS outputs are also used to compensate for motion, in particular to compensate for tilt on the sensors measurements. For instance, on a 1D range finder or a 2D laser scan, the current estimate of the platform attitude is taken into account to rotate the measurement and align it with the localization coordinates frame.

The Kalman equations, including system modelling, error propagation, Kalman gains, etc, are well documented on the scientific literature. This estimator builds upon previous development at Eurecat [4][5], therefore, they are not detailed in this deliverable. The added value of our estimator relies on how to integrate, as measurements, the differences between synthesized and observed features.

This filter could easily integrate several secondary sensors by extending the measurement vector and measurement functions. The following lines described the approach for the specific case of a 2D laser. Other secondary sensors could be rangefinders, more 2D lasers, 3D LIDARs or even cameras.

3.3.1.3.1 Laser-based motion estimation

A 2D laser scanner is typically employed to detect features in man-made environments. It provides a polar scan of distances to objects for a specific angular range. Two type of features will be extracted from the scan and used for localization purposes: lines and corners.

The walls of the sewer will be seen as two parallel lines on both sides of the sensor. These lines will be repeatable across multiple scans which facilitates feature tracking. There exist several procedures which are computationally efficient to extract lines from laser scans.

For line-based motion estimation, we rely on the Normal Point of a line, defined by the perpendicular intersection of the scanned line and the sensor, as shown in Figure 25.

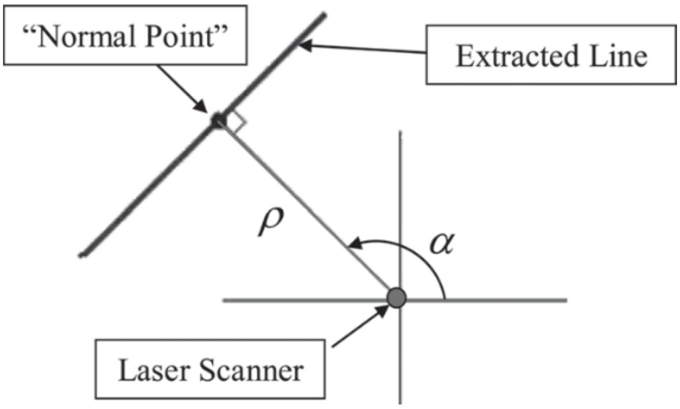


Figure 25: Line representation using the normal point

A normal point is defined by its polar coordinates: range ρ and angle α. Changes in the perceived location of the normal point are used to compute the displacement of the robot.

Figure 26 shows the changes in the range and angle to a single line caused by robot motion, where (x_n, y_n) represent the body frames at different time instants, ρ_n is the polar range and α_n the polar angle.

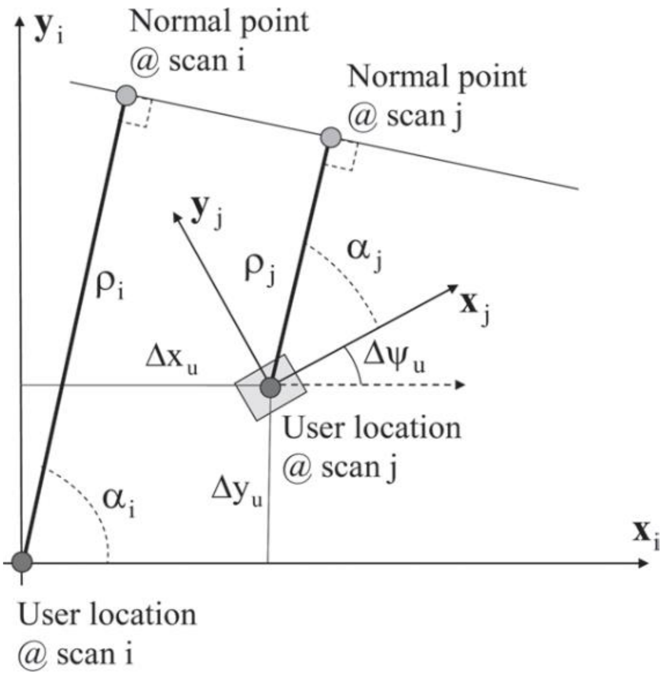


Figure 26: Changes in line parameters due to robot motion

Our objective is to relate the robot displacement $\Delta R_u = [\Delta x_u, \Delta y_u]$ and its change of heading $\Delta\varphi_u$ to the change of polar parameters ρ_n and α_n of the extracted line.

Changes of position and orientation can actually be computed independently.

Let's first focus on the position changes. For every single line, the following equations represents the linear relation given an estimation of the displacement ΔR_u:

$$\Delta x_u \cdot cos(\alpha_i) + \Delta y_u \cdot sin(\alpha_i) = \rho_i - \rho_j = \Delta\rho$$

We can therefore now use the INS estimation of motion, $\Delta R_{u,INS} = [\Delta x_{u,INS}, \Delta y_{u,INS}]$ to synthesize the expected changes in the range to the normal point: $\Delta\rho_{INS}$.

The actual measurement z_ρ to be included in the Kalman filter for every extracted line is the difference between the observed and synthesized change of range to a normal point induced by the robot motion (Figure 27):

$$z_\rho = \Delta\rho_{laser} - \Delta\rho_{INS}$$

Every line, extracted and tracked on the laser data will provide an independent measurement to correct position.

Regarding the estimation of rotation, since the walls are assumed to be static, a change on the angle to the normal point shall be due to a rotation of the robot. Therefore, for a single line:

$$\Delta\varphi_u = \alpha_i - \alpha_j$$

Similar to the previous exercise, the change of angle estimated from the angle to normal points can be compared against the rotation based on inertial. One line may be sufficient to correctly estimate the rotation between two time instants. The measurement in this case is:

$$z_\varphi = \Delta\varphi_{laser} - \Delta\varphi_{INS}$$

which is again the difference between the observed and synthesized change of angle to a normal point induced by the robot motion.

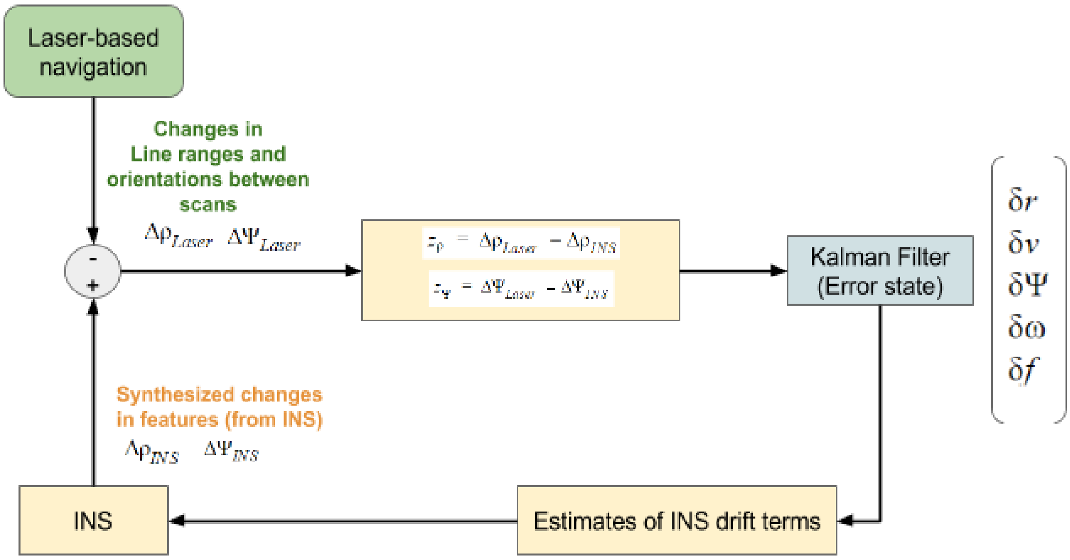


Figure 27: Laser-aided inertial tight integration scheme

To finalize the integration into the filter, we need to derive the entry h of the measurement matrix H for each of this measurements. H relates measurements with the error state of the complementary filter.

The mathematical approach consists in developing expressions relating measurements and motion; separates the motion into the ideal motion and an error term, and assumes that ideal measurements correspond to ideal motions and, therefore, any other error can be related to the error state of our filter, which is what we want to estimate. This process is detailed in [3].

The following equations give examples of the rows derived for the previous measurements for displacement and rotation and how they can be used for measurement equation (matrix H) to correct position and attitude:

$$h_{\rho,Laser} = \begin{bmatrix} n_i^T C_{i,n}^b & 0_{1x3} & 0_{1x3} & 0_{1x3} & 0_{1x3} \end{bmatrix}$$

$$h_{\Psi,Laser\_lines} = \begin{bmatrix} 0_{1x3} & 0_{1x3} & (C_{j,n}^b C_{i,b}^n n_i \times) & 0_{1x3} & 0_{1x3} \end{bmatrix}$$

Where n_i represents the normal vector to the line and $C_{i,n}^b$ represents the rotation from local to body frame, both at time instant i. However, these details may vary depending on the final implementation of the complementary filter and features selected.

Every feature extracted from the laser will represent an independent measurement for the filter in order to improve the estimate, therefore, the dimension of both the measurement vector and the measurement matrix need to be managed, increasing and decreasing its size. This overhead in memory management and computation is typically a limitation, but it suits perfectly the localization in sewers where the number of features will be low and the implementation can be easily optimized.

Lines in sewers should provide sufficient information to contain the **transversal and rotational** drift on the inertial, and also partial corrections on longitudinal. Similarly, bifurcations and side opening will be seen as corners on the laser scan. A corner, or a point, can be used to navigate similarly to the use of line normal points described above. If any of these characteristics are within laser range, these point features should provide sufficient information to contain the **longitudinal** drift.

3.3.1.3.2 Other secondary sensors

This filter can potentially integrate very easily other secondary sensors to complement laser-based corrections. For each specific new sensor a new row on the measurement vector and measurement matrix will be added. Therefore, assuming an adequate mathematical derivation of the relation between changes on the sensor measurement and the inertial-based predictions of these changes, the same filter can incorporate multi-sensors corrections. A 1D rangefinder facing forwards, sideways or downwards could easily be incorporated if required.

Furthermore, the team at Eurecat has previous experience on the use of communication signal fading waveform to localize a robot in pipes [9]. Given the results obtained in this first phase, described in D2.2, an RF-based localization systems relative to the RF transmitters[21][22] may be also implemented in combination with the localization described here to reset the accumulated errors.

3.3.1.4 Discrete global estimator

The aim of the “discrete” localization algorithms capability of the ARSI system is to produce improved estimates of the vehicle position at times when specific events occurred, for instance when structural defects were detected. Unlike continuous localization, discrete localization uses both local information collected by the onboard sensors and global information recorded in the GIS of the sewer network.

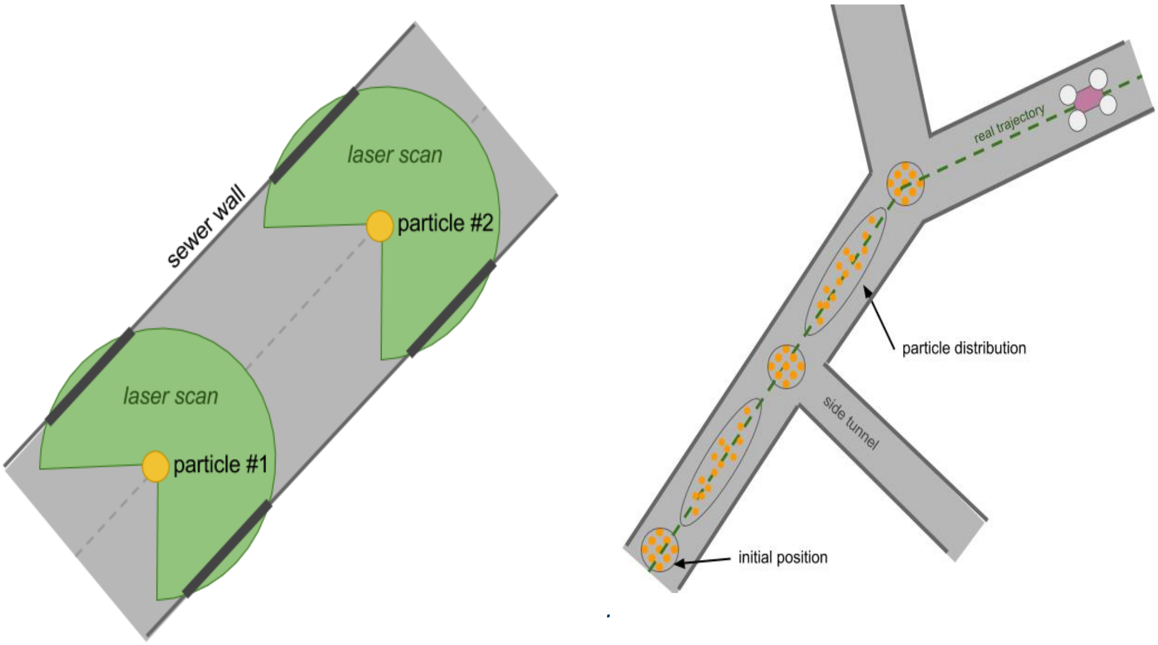
The key idea behind this module is that topological features such as bifurcations provide accurate and unambiguous positional information.

We use a probabilistic algorithm called Particle Filter to handle this variability in the positional error. Particle Filters model this error by generating a large number of hypotheses (“particles”) for the real location of the mobile robot. Each “particle” represents a possible vehicle pose, based on an initial state, previous observations, and information about the measurement noise of the sensors. In our case, observations are provided by the laser sensor, chosen mainly for its ability to detect structural features (eg. corners) even in dark environments. Each particle has an associated weight, which quantifies its likelihood of representing the real vehicle position. The general idea of particle filters is to identify the most likely particles based on how much support they have from the data collected by the embedded sensors.

Our particle filter implements the following steps:

- Build a 2D model of the sewer area to be inspected, using the GIS provided and the dimensions of each type of sewer section.
- Generate N random particles (hypotheses) based on the initial vehicle location and estimated error. Initially, all particles are equally likely and therefore have the same weight.
- At each iteration:
    - Move each particle to follow the trajectory of the vehicle estimated using the INS solution (which is known to drift rapidly).
    - At each particle location, generate a simulated laser scan using the 3D model of the network as though it was the real vehicle.
        - Match this simulated scan against that acquired by the real laser sensor at that moment. Produce a matching score, which will be higher for good matches.
        - Update the weight of each particle to be the latest matching score, and normalize all weights.
    - Resample the particles based on their weight:
        - Particles with low weights (low likelihood) are discarded, as their hypothesis is not supported by real data.
        - New particles are generated randomly around those with higher weights, in order to refine the position estimation in the most likely areas.
- After a termination criteria is reached (eg. number of iterations, spread of the particles, etc.), one or several positions are estimated from clusters of the most likely particles

The figure below illustrates how two distinct particles in a tunnel would generate nearly identical scans due to the lack of features, and are therefore equally likely matches for the real vehicle location. This longitudinal ambiguity will cause the particle distribution to spread along the tunnel. However, in locations such as intersections where structural features are visible, the ambiguity disappears and the particle distribution becomes compact again, providing a much more accurate estimate of the vehicle location.



Ambiguity between particles in a featureless tunnel

Evolution of the particle distribution during a tunnel inspection

Figure 28: Description of the particle filter performance along a tunnel

The high-accuracy position estimates achieved at intersections act as "virtual GPS" fixes, in the sense that they provide an absolute position (from the GIS) which, unlike the INS solution, doesn't vary with time. These fixes allow us to bind the error drift from the INS, and to interpolate the location of defects detected in sewer galleries using the fixes achieved at each intersection.

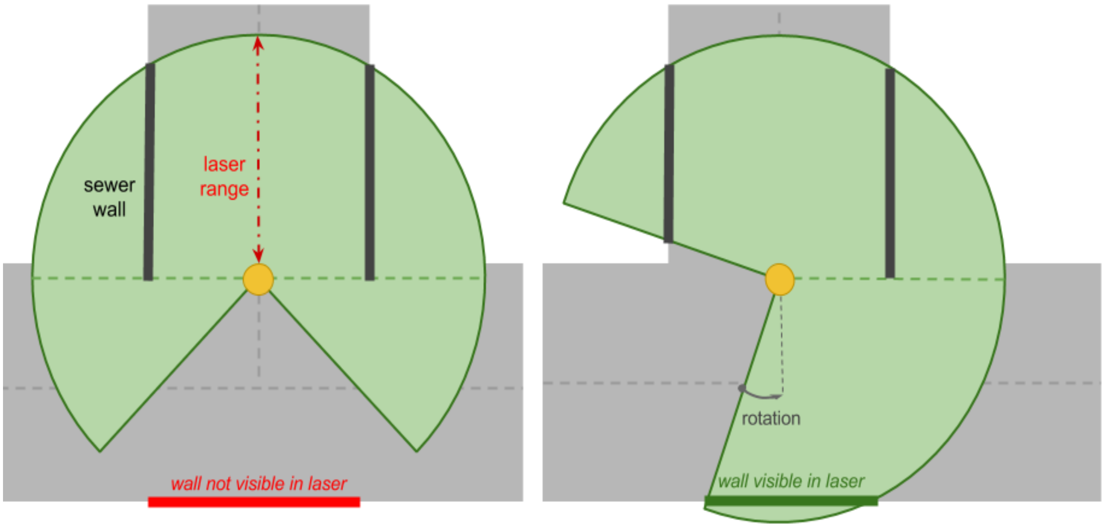
3.3.1.4.1 Localization improvements

An analysis of the particular case of the sewer network of Barcelona leads to a key observation: most sewer galleries are linear. If humans were to travel in a truly featureless tunnel, they would not be able to localize themselves with good accuracy. However, if they were able to measure the distance from their location to the start of the tunnel, then they would always know exactly where they are.

The fact that the large majority of sewer tunnels are linear allows us to follow the same idea. Using a ranging sensor such as a laser, we can measure our distance to the previous or next intersection, provided that it is within range of our sensor. This information largely eliminates the ambiguity in the longitudinal direction depicted above, and therefore, can be used in the particle filter to dramatically improve the position estimate.

Our platform is equipped with a laser sensor with a detection range of 20m, and a maximum field of view of 270 degrees. This means that in most sewer galleries our system can observe the end of the tunnel from a distance of 20m, allowing the particle filter to calculate a position fix. A 360 degrees field of view would allow us to double this range to 40m, since the previous intersection would be visible for 20m after the inspection starts, and the next intersection would be visible from 20m away (see picture below). Ideally we would like to use the full laser range both in front and behind the moving platform, but most lasers have a blind spot looking directly behind the vehicle trajectory. One solution to this problem is to rotate the sensor on the vehicle body as depicted on the diagram below, allowing us to use the full 40m range with only a small reduction of the forward-looking field of view needed for wall detection and obstacle avoidance. Note that due to the very short distance between the laser and the sewer walls (typically <60cm) increasing the angle of the laser only causes a small reduction of the area used for wall detection:

- rotation=10 degrees: reduction=11cm,
- rotation=20 degrees: reduction=22cm.



Standard laser configuration facing forward. Notice the blind spot at the back of the vehicle

Rotated configuration, giving the laser full range in along the vehicle trajectory

Figure 29: Description of the two possible laser mounting schemes

Another option is to use a lightweight range-finder sensor mounted directly behind the platform. The **LIDAR-Lite 2** for example, has a range of 40m and weighs only 35g. In either configurations, the particle filter can use the full 40m range provided by the laser sensor, or around 60m combining two sensors. Either way, this range reduces the area without fixes on the average 75m length of featureless galleries, meaning that our system is theoretically able to calculate an absolute estimate at most locations in the sewer network.

3.3.1.4.2 Online vs Full solution

The sensor data obtained after a specific instant of time also contain information about the current location of the platform. Based on this observation, a modification of the global localization algorithm will allow for a global optimisation of the different estimates to improve accuracy by using a-priori and a-posteriori data combined.

Furthermore, an operator may know the location of a feature which is not included in the GIS, with respect to another location which is indeed represented in the GIS. The user will be allowed to manually annotate the location of specific features on the data log with the support of the inspection software. This new input will be incorporated as a virtual fix to optimise the overall performance of the full global localization.

Another advantage of the full solution is that future inspection may choose to rely on previous optimised results. When an inspection team is re-visiting a certain area, the information of the GIS, which may be partially incomplete or inaccurate, may be enhanced by artefacts included in the previous inspections, or even corrections which are not yet reflected on the map.

This method serves to maximize the accuracy of the geo-referencing of the defects.

3.3.1.5 Coordinate Frames

Our estimators follow the ROS recommendations on coordinate frames for mobile platforms:

Map: The coordinate frame called "map" is a world fixed frame, with its Z-axis pointing upwards. The pose of the mobile platform relative to the map frame does not significantly drift over time, thanks to our global estimator. The map frame is not continuous, meaning that the pose of the platform can change in discrete jumps at any time. In a typical setup, a localization component constantly re-computes the robot pose in the map frame based on sensor observations, therefore eliminating drift, but causing discrete jumps, therefore, it is a poor reference frame for control.

Odom: In our case we would refer to Odom as Local. The coordinate frame called odom is a world-fixed frame. The pose of a mobile platform in the odom frame can drift over time, without any bounds. This drift makes the odom frame useless as a long-term global reference. However, the pose of a robot in the odom frame is guaranteed to be continuous, meaning that the pose of a mobile platform in the odom frame always evolves in a smooth way, without discrete jumps. In a typical setup the odom frame is computed based on an odometry source, such as wheel odometry, visual odometry or an inertia measurement unit. The odom or local frame is useful for control as an accurate, short-term local reference, but drift makes it a poor frame for long-term reference.

Base_link: The coordinate frame called base_link is rigidly attached to the mobile robot base.

Relationship between Frames: The standard ROS recommendation for coordinate frames attachment is as follows: map → odom → base_link. The map frame is the parent of odom, and odom is the parent of base_link. Following these definitions:

- the **global estimator** will publish the robot position in the **map frame**, and it is also responsible to publish the transformation between the map and the odom frame.
- the **local estimator** will publish the robot position in the **odom frame** and it is also responsible to publish the transformation between odom and base_link frames.

3.3.1.6 Expected solution accuracy

The expected error of the combined solution is difficult to estimate without further experimentation on the real scenario. There are no significant examples on localization on sewers on the literature that could provide a background to refer to. Therefore, this section aims at analysing our design and initial datasets in order to provide two indications: the upper bound of the expected error describing the worst-case, and an educated guess based on examples from the state of the art addressing similar problems in order to extrapolate our nominal performance.

According to our proposed solution, the identified sources of errors are:

- Errors associated to the sensors: IMU bias and noise, laser accuracy, etc.
- Performance of the feature extraction and matching algorithm of the local estimator
- Accuracy on the GIS
- Performance of the matching algorithm of the PF

An analysis of the sewer network of the city of Barcelona shows that the distance between major intersections is approximately 150 m in average. However, having a closer look at the GIS data of Barcelona provided by BCASA, we estimate that the average distance between two intersections (primary or secondary) is around 75m. According to the laser characteristics described in the section above, our platform will be able to detect objects 20m in front and behind the drone, providing 40m detection range.

Let's therefore define three different phases of the operations:

- Open space (pure unaided inertial): worst continuous case
- Long galleries with sparse features (inertial + laser features corrections): nominal continuous case and worse discrete case.
- Intersections: nominal discrete case

3.3.1.6.1 Accuracy of the local estimator

Based on the ARSI localization strategy, and assuming that the global particle filter can obtain a position fix for each intersection described on the GIS, the distance that the local estimator needs to coast on sensor-based localization, without support from the map, is 35 m.

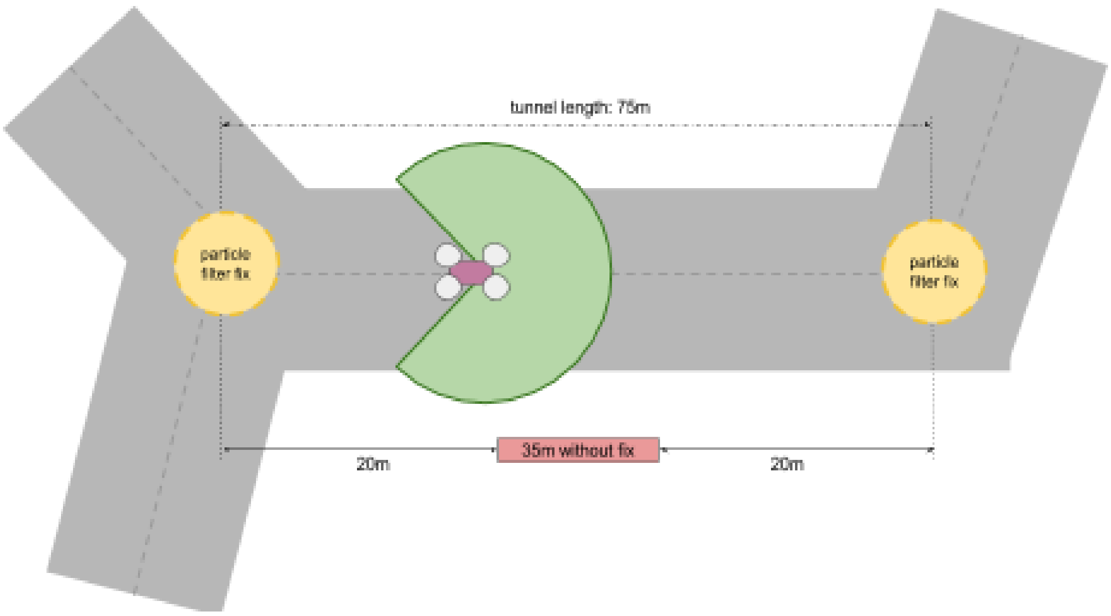


Figure 30: Laser detection range and impact on the localization along the sewer

Let's firstly focus on the areas without any physical characteristics to be used for localization. Based on the formula to estimate the unaided inertial drift used before, assuming a nominal speed of 1 m/s during the flight along the 35 m, an industrial grade INS will drift **18m** in this time, without corrections from secondary sensors. This figure represents the **worst case in an unrealistic scenario where no walls, opening or bifurcations could be detected**.

(1) Worst case local expected error =18 m

As a remark, a navigation grade IMU would only drift 0.15 m on the same distance. However, the focus of the ARSI project is to achieve equivalent results with lower-cost sensors, such as the industrial grade units (approx. 400€). This will be achieved by exploiting the combination of multiple sensors and techniques for this specific environment.

According to the preliminary tests on different sewers, we expect to have some side openings to be used as extra features on the local estimator, together with the detection of the walls. Previous works on tight coupling of laser scanners and inertial measurements, for instance, have evaluated a similar approach to localization in corridors with promising results of 1.1% error of the distance travelled. Assuming that we obtain similar performance, this will lead to an error of **0.38 m** for this case. This would reflect the accumulated error (drift) with respect to the latest fix or correction, which would be at the beginning of the gallery, as defined by the intersection on the GIS. We are aware that the challenges present in sewers are different to those in corridors, but there are many similarities that let us extrapolate the expected error for a large portion of the sewer network. This figure represents the **nominal case where enough laser features should be sparsely available within laser range during inspections.**

(2) Nominal case local expected error =0.38 m

3.3.1.6.2 Accuracy of the global estimator

A previous work on particle filter localization [23] has focused on the evaluation of the performance of an algorithm similar to our global estimator along a pure corridor. This represents the worst case scenario for this technique, where no intersections are detectable. The paper analysed a reference implementation of a particle filter using laser-map matching only (i.e. gmapping), without support from inertials or local estimators. However, it proposed an improvement based on active navigation consisting of inducing a zig-zag trajectory to the robot to increase observability across both axis. A drone naturally excites all axes since it is a free flying, highly coupled, rigid body, which should lead us to similar improvements of performance. Furthermore, in our case we enhanced the matching algorithms with an inertial and local estimation which should also reduce the uncertainty of the different beliefs. Therefore, **the worst case for the global localization where we are navigating along pure corridors is:**

(3) Worst case global expected error =5 m

Another example of related work, where a member of Eurecat team was involved, has shown the feasibility of these techniques for accurate localization in tunnel-like featureless environment [21]. These works use signal-based ranging instead of laser scanning and provide a promising average error of 1 m. with respect to the ground truth. Our expected error is computed with respect to the reference map, therefore, adding the expected accuracy of the map, we consider than **the nominal case for expected error represented by the areas where enough information of the map will allow global localization is:**

(4) Nominal case global expected error =2 m

These two expected errors for the global localization refer to the online approach, where only a-priori sensor data is used to localize the system. For the case of the offline solution, where the entire dataset is available to estimate the location of a specific detection or measurement, both a-priori and a-posteriori data can be used. A global optimization technique will allow improving this expected error.

3.3.2 Reactive Navigation and Collision Avoidance

As described in the previous section, given the constraints that the environment poses to perform an accurate localization, the motion control of the system will be completely reactive. The **reactive navigation** component of the ARSI system is designed to allow our aerial platform to carry out inspection of the sewer network with minimal pilot intervention. It builds upon the Pixhawk Autopilot, extending the built-in flight modes, such as altitude control, with sewer-specific functionality. The control law will use sensor data to close the loop at low level, avoiding collisions with the environment. The primary sensor used for perception is a 2D laser scanner to detect structural features such as walls and corners in the sewer galleries.

The ARSI system currently implements 2 sewer-specific flight modes:

- Tunnel Follow
- Hover

These modes are based on complementary approaches that should enable a reliable pilot-centered operation under any of circumstances expected on the sewer system.

3.3.2.1 Piloting the ARSI system

Most commercial drone platforms include an Autopilot, which uses information provided by the embedded sensors (see Navigation Sensors section) to automatically handle certain aspects of the vehicle control, for example the vehicle attitude (roll and pitch) or the altitude over the ground. The Pixhawk Autopilot used in the ARSI system implements several built-in flight modes designed to help pilots execute simple flights with minimum intervention. The most useful modes in the sewer network (where GPS is not available) are Auto-TakeOff, Auto-Landing and Altitude Control. Pilots can easily change between modes using switches on the Remote Controller (RC) or the control station software. Some RC remotes can also notify pilots of alarms, either by vibrating, emitting a sound, or by flashing light. These alarms can be used to notify the pilot that a flight mode is not available, for instance, in the event of loss of GPS when performing an autonomous mission outdoors. If the selected mode becomes unavailable, the Pixhawk Autopilot always defaults to a safe mode, for instance, the Altitude Control mode.T

Figure 31: Typical RC controller for aerial drone

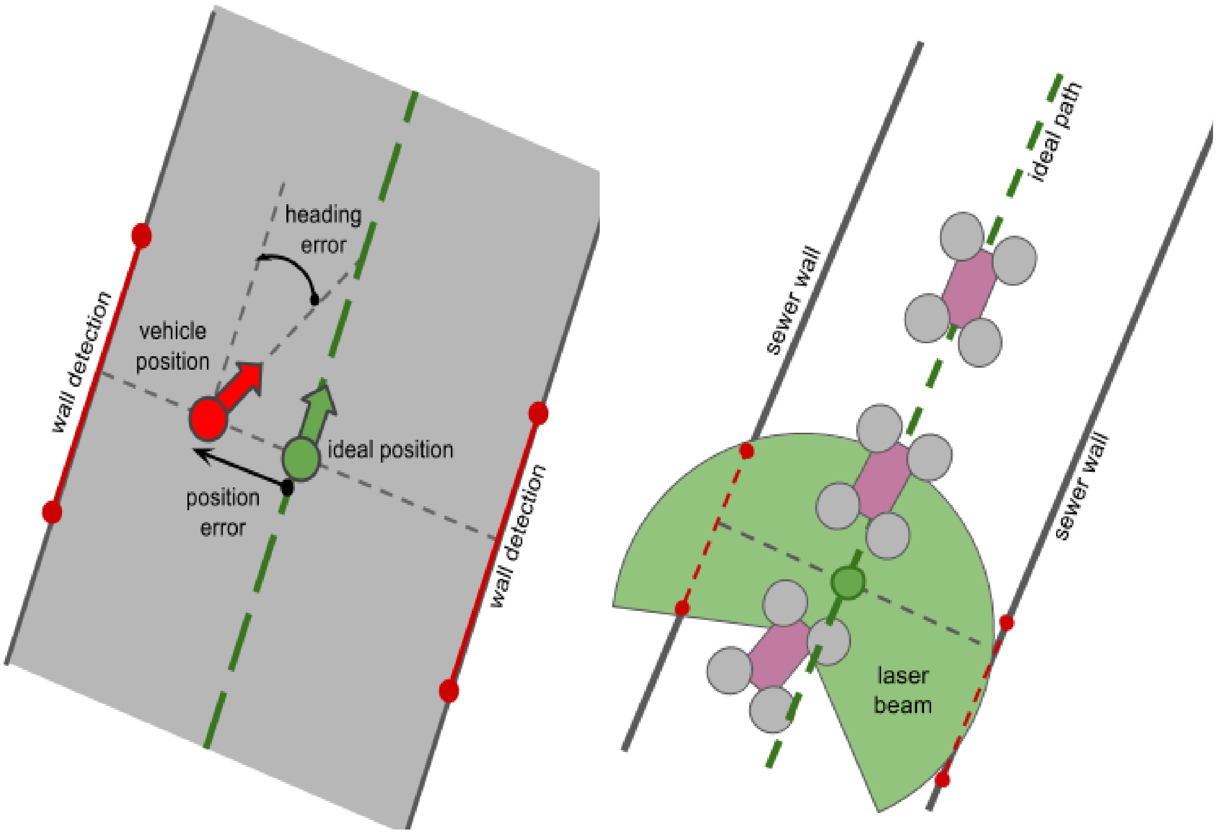
ARSI will integrate a RC into its communications and Remote Station systems. This gives constant and complete control over the vehicle to the pilot. The ARSI system also implements sewer-specific flight modes, which can be used in the exact same way as the built-in Pixhawk modes. These flight modes are designed to help pilots perform inspections in complex conditions with very little visibility and margin of error, but they always rely on the operator making decisions, in particular when deciding which flight mode to use. Pilots can easily switch between the different modes based on the video feedback received throughout the mission, and remote alarms are used to warn them if the selected mode isn't possible given the surroundings of the vehicle.

The following sections will describe in detail these sewer-specific flight modes.

3.3.2.2 Tunnel Follow flight mode

The Tunnel Follow mode is designed to facilitate inspections of sewer galleries, where the narrow space, low visibility, turbulences and possible air currents make manual flight very challenging. In this flight mode, pilots can focus on the quality of the inspection, while the ARSI system keeps itself travelling along a gallery, safe and away from collisions.

In Tunnel Follow mode, the ARSI embedded software processes laser data to detect the sewer walls. From these detections, the software calculates the distance and orientation of the walls relative to the platform, from which the lateral and heading errors with respect to its intended trajectory can be derived (see below).



Errors calculation **Trajectory correction**

Figure 32: Laser based trajectory control

Based on these errors, a simple controller will compute low level requests (roll, pitch and yaw rate) and issue them to the Pixhawk Autopilot stabilizer (attitude controller), in order to direct the vehicle along the tunnel. This trajectory correction can be performed at appropriate rates (5 to 10 Hz depending on the available onboard processing power) so that the system can smoothly adapt to changes in direction or curves in the tunnels.

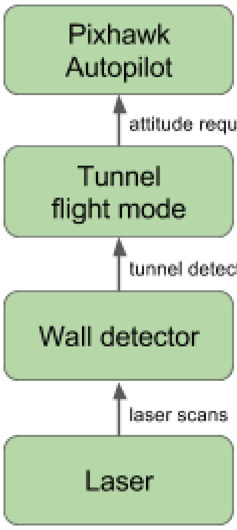


Figure 33: Components of the Tunnel Follow flight mode

The Concept of Operations for ARSI requires that users must have direct control over the vehicle during inspections, including being able to issue commands such as "stop" or "observe this specific area". Using the Tunnel flight mode pilots can control the inspection speed, and in particular they can slow down in front of a point of interest to collect high-quality imagery for further inspection. If no speed input is provided by the pilot, the software automatically returns to the base inspection speed specified during mission planning.

This mode is particularly suited to travel along long galleries. When the system arrives to the next bifurcation, it will automatically stop and wait for user inputs. The user will be able to select which gallery the system should follow. The RC stick will mapped to the different options: stick to the left wall, stick to the right wall or go ahead (if applicable). This setup solves most of the expected situations in "Y"-shape and 2+"-shape bifurcations. Alternatively, the operator can switch to continue with the inspection in any of the other modes (Hover or altitude).

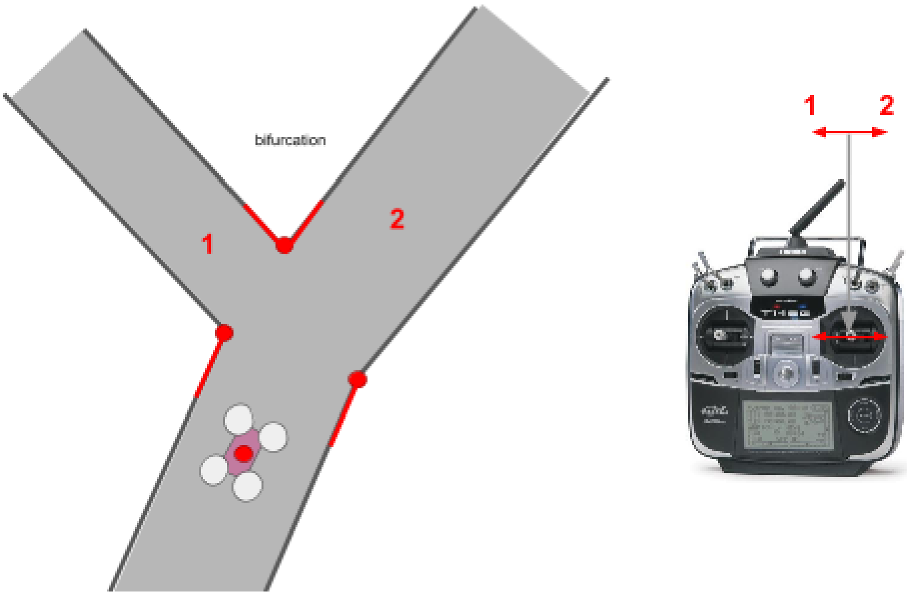


Figure 34: User trajectory selection on V-shape bifurcations of the Tunnel Follow flight mode

3.3.2.3 Hover flight mode

The Hover mode is designed to facilitate detailed inspections of a specific location where accurate and comprehensive data is required. This mode is particularly suited for intersections and inspection of specific assets.

It is only available when enough features are within laser range, for instance, in front of a clear corner, when the platform is at the intersection between several sewer galleries. The operator can switch to “Hover” flight mode, in which the system automatically controls position so that the drone remains stationary without any pilot interaction. If the mode is unavailable, due to a low number of features, the pilot is notified via the RC controller that the Autopilot is about to return to its default mode (typically Altitude Control).

In Hover mode, the pilot can optionally control the heading of the vehicle, for example to carry out a 360 degrees observation of a given location, or to make a decision as to which gallery should be inspected next based on the mission plan. Likewise, the operator can manually override this mode by using the control stick on the RC. In Hover mode, a minimum safety distance to obstacle is active, preventing the pilot to fly into collisions. As soon as the stick is released, the Hover mode is engaged again.

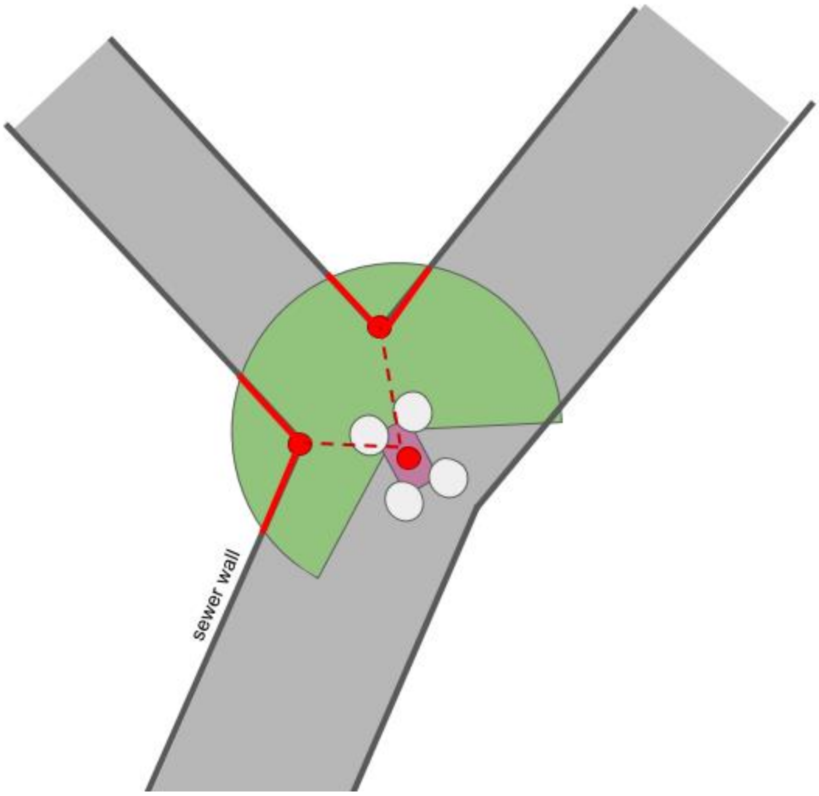


Figure 35: Hover mode at sewer intersection

The Hover flight mode relies on scan-matching to generate control requests and keep the vehicle stationary. Scan-matching algorithms are designed to estimate the positional and angular offsets between two 2D scans (typically laser scans) captured from a moving platform. We used the Canonical Scan [10] which gave excellent results in our simulation tests. A first “reference” scan is stored when the pilot enters Hover mode, and successive scans are matched against the reference, providing an estimation of the positional and angular errors from the hover location selected by the pilot. These errors are then used to generate attitude requests to the Autopilot, as previously described in the Tunnel Follow mode section.

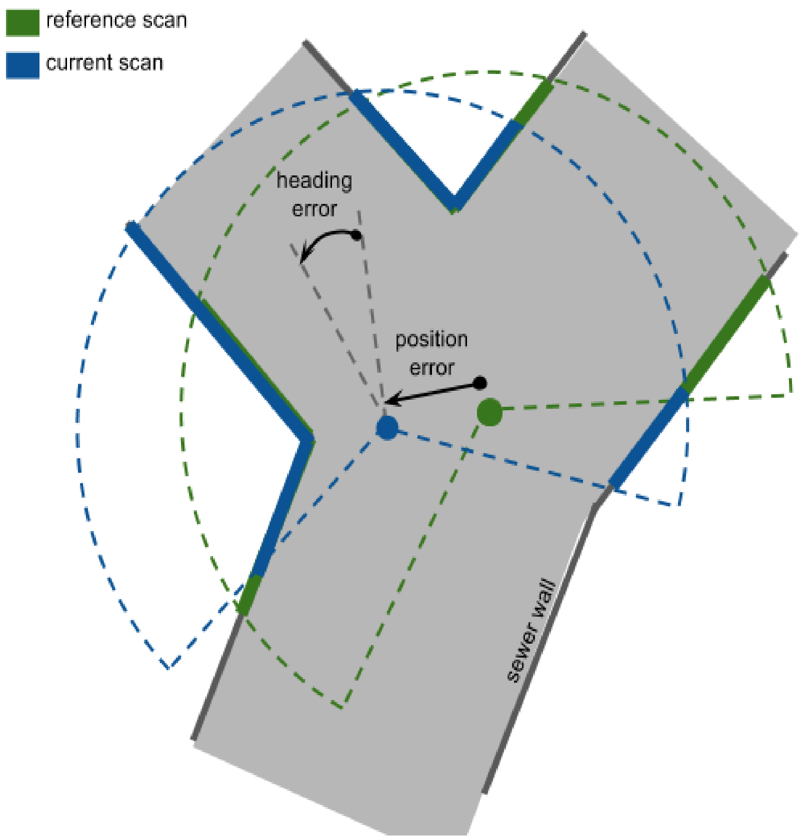


Figure 36: Error estimation using scan matching

3.3.2.4 Collision avoidance

ARSI sewer-specific modes implement a guarded-motion strategy. The use of reactive navigation based on laser data ensures that the control of the system does not collide with the infrastructure. Large objects such as walls, intersections, etc. will be easily detected on the 2D scans which makes the system collision free under nominal circumstances.

More complex objects, not detectable on the longitudinal slice provided by a horizontal 2D laser scanner, are more difficult to detect. ARSI system is also equipped with passive propeller protection, making the platform tolerant to soft hits with the surroundings. However, during the second and third phase of the project the consortium will explore different alternatives to detect obstacles on the camera systems. This experience builds upon previous experiences of the team.

3.3.2.5 Faults and emergencies

All robotic systems are susceptible to faults, either from hardware components, or sensors, or onboard software modules. The ARSI Concept of Operations will aim to minimize the risk of faults by implementing thorough safety procedures:

- **Hardware & sensor faults**:
    - Regular platform visual checks, maintenance and cleaning;
    - Maintenance protocols to replace components such as motors, propellers before the end of their specified lifetime;
    - Pre-flight checks.
- **Software faults**:
    - Software development processes (version control, code reviewing, unit testing)
    - Use of simulation to validate all changes to onboard software and algorithms.

Despite all these measures, faults are inevitable especially in harsh environments such as sewers where water and dust can damage equipment after repeated usage. In order to manage this risk, dedicated embedded software will be developed to monitor all aspects of the ARSI platform during flight: battery levels, autopilot status, health of sensor drivers, unexpected obstacles detected in laser data, etc.

A severity will be assigned to each possible faults, and all will be reported to the operator via the ARSI Remote Station. The risk associated with each fault will also be evaluated by the ARSI consortium and the operators, so that an appropriate procedure can be determined. For example, a fault with the air monitoring system might not be considered severe enough to require an inspection to be interrupted. On the other hand, a fault with the laser sensor would likely require a mission abort, since without laser possible obstacles cannot be detected and the integrity of the platform is therefore at risk. In this specific situation, the pilot might decide either to bring the ARSI platform back to its starting point, or to land it immediately to avoid further damage to the sensor payload.

Emergency behaviours will be implemented to handle exceptional cases where faults prevent the operator from remotely piloting the ARSI platform, like failures in the video drivers or in the streaming of video data back to the Remote Station. The most important emergency behaviour is auto-landing, where the ARSI platform will automatically land and disarm itself at its current location where it can then be recovered by inspection teams. The Pixhawk PX4 firmware already implements several such emergency behaviours, including auto-landing if battery levels fall below a predetermined threshold. Since PX4 is open-source, we will be able to include additional ARSI-specific behaviours which will need to be discussed and agreed with the operational teams.

3.4 Sensor information recording

In this section we describe the tools used to record the data acquired by the sensors of the platform and the processes, devices and hardware selected to this end. The data usage for storage and video streaming is also outlined.

3.4.1 Data format

All sensor data is recorded using the open-source Robotic Operating System (ROS) data exchange pipeline, where all sensor samples (video frames, laser scans, air monitoring samples, etc.) are stored in a log file (ROS “bag”) as a timestamped message. ROS is distributed freely under very permissive BSD open license that allows for reuse in commercial and closed-source products.

ROS open-source drivers are readily available for many commercial sensors, including those currently integrated on the ARSI platform. Integrating new sensors in the future (e.g. air or water monitoring sensors) only requires a relatively small amount of work to develop a new driver, before it is fully integrated to the rest of the system.

ROS is widely used in the robotics community, both in research and commercial environments. It comes by default with an array of free tools for visualization, monitoring and analysis. RVIZ for example is a plugin-based 3D visualization tool which we built on in our design for the ARSI Remote Station (see section 3.6). ROS also comes with built-in support for image compression pipelines, which are extremely useful when streaming video over Wi-Fi (see below).

Using the localization algorithms described in section 3.3, we use sensor data collected during an inspection to compute an estimate of the vehicle trajectory. Since all data samples in a ROS bag are timestamped, they can be matched against this trajectory to interpolate their position. After an inspection is completed, ROS bags will be post-processed to estimate the absolute positions of the defects and areas of interest flagged either by operators or by the automatic defect detection algorithms developed for ARSI.

Specific plugins will be developed to export the geo-referenced inspection data generated by ARSI into formats suitable for the end-users (GIS files, DRACMA uploads, etc.).

3.4.2 Data storage

Table 5 below lists the main ROS messages stored in a typical **10-minutes** long ARSI inspection log. It shows that a typical ARSI **uncompressed** inspection log would require around **7.6 GB** of storage space. In practice, the size of mission logs is reduced by compressing all video data produced by the 4 cameras. We use lossless PNG compression, so that this process has no negative effect on the quality of the imagery used for inspection purposes.

Even with a "worst-case" compression ratio of 1:2, the total mission log size drops to around **4 GB**. Since the ARSI aerial platform carries a high-speed 64GB eMMC memory card, we see that an inspection team can comfortably run over 10 missions in a day before having to download the data and clear the memory card. Note also that eMMC cards of larger capacity are already commercially available.

Table 5: ROS messages in an ARSI mission bag

Type	***ROS message***	***Size (bytes)***	***Frequency***	***Mission total***
Laser scan	`sensor_msgs::LaserScan`	4KB	10Hz	26MB
2x VGA image (640x480)	`sensor_msgs::Image`	2x 900KB	5Hz	1.8GB
2x HD image (1200x800)	`Sensor_msgs::Image`	2x 780KB	5Hz	5.8GB
Air monitoring sample	`diagnostic_msgs::Diagnostic`	1KB	0.2Hz	120KB
IMU measurement	`sensor_msgs::Imu`	0.3KB	30Hz	5MB
Mavros meta-data	`mavros_msgs::State`	0.1KB	10Hz	600KB
			Total	**~7.6 GB**

ARSI mission data will be stored and archived on a dedicated server, while relevant information (camera stills, operator comments, etc.) are uploaded to the DRACMA database for analysis and reporting (see section 3.6 –Remote station).

3.4.3 Video streaming

In order to allow operators to pilot the ARSI platform from the surface, live video data is broadcast from the vehicle to the Remote Station over Wi-Fi. This functionality is built into the ROS pipeline: the Remote Station can display any ROS message generated on the platform by subscribing to the relevant "topic" (message).

Operators can subscribe to any video streams broadcast by the ARSI platform directly from the Remote Station using standard RVIZ plugins. Normally the operator will only require the video stream from the wide-angle front camera, to visualize the vehicle surroundings. Video data will be streamed in JPEG format at a rate of 10Hz and in VGA resolution (640x480). This amounts to less than ~3 Mb/s of data being transferred, which is well within the limits of our Wi-Fi communications system (see section 3.5 – Communications).

3.5 Communications

This section describes how the problem of the communications between the ARSI aerial vehicle and the Remote Station in the sewer was addressed and solved. Firstly, the challenge of the problem is described. As a result of a study of the problem and of the available technologies, our solution is described. Our procedure aims at optimising the range provided by our communications system and the autonomy of the batteries.

3.5.1 Challenge

To provide radio coverage in tunnel-like environments (tunnels, mines), two main methods are used: the leaky feeder, based on the use of radiating cables, and systems based on the natural propagation of radio-waves.

Owing to the high cost of leaky-feeder installations and the fact that they are susceptible to damage and failure, the natural propagation system is preferred in many applications. Wireless propagation in these environments is described as strongly multipath, and if the wavelength of the signal is much smaller than the tunnel cross section, tunnels act as an oversized dielectric waveguide. In this case, the attenuation per unit length is low enough to allow communications over a range of up to several kilometers.

However, the signal is affected by strong fading phenomena, as has been studied by many authors [12][13][14]. Figure 37 below shows an example of these periodic fadings in the received signal power obtained inside a 4 km tunnel, after displacing the receiver up to 4 km from a fixed transmitter [11].

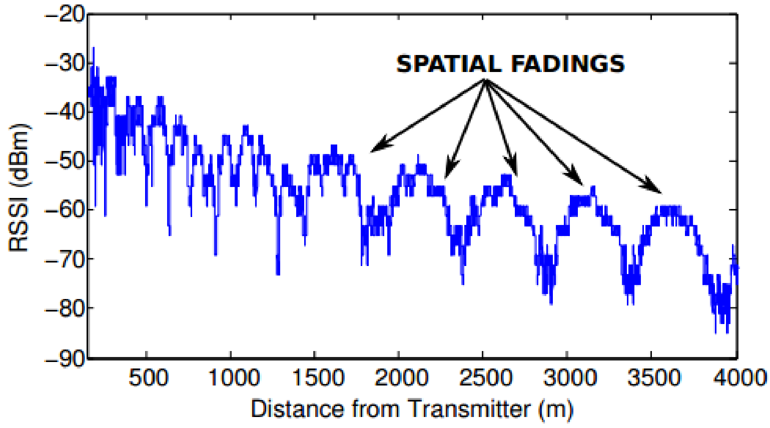


Figure 37: Measured Received Power at 2.4 GHz inside a tunnel. The transmitter was kept fixed close to the entrance of the tunnel and the receiver was displaced along 4 km from the transmitter [11]

The environment that a sewer creates for telecommunications is challenging to say the least. Wired communications are not feasible given the aerial nature of our platform. Moreover, the multiple ground obstacles (corners, changes of level, water, etc.) present in sewers result in wired communications being impractical for almost any type of mobile platform.

In the domain of wireless communications, only very low frequency signal travels without impediment in the underground. However, only high frequency waves provide the bandwidth and link performance necessary to meet the video and data streaming requirements of this project.

3.5.2 Behaviour of waves in the sewer

Despite this very challenging environment, an analysis of the behaviour of electromagnetic waves in confined spaces helped us build our solution for wireless communication between the ARSI vehicle and the Remote Station.

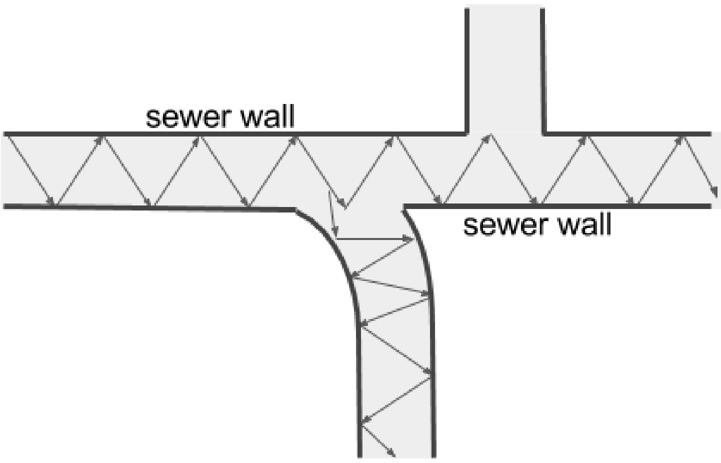


Figure 38: Waveguide effect of the sewer on high frequency electromagnetic waves

Our experiments (see ARSI deliverable D2.2) have shown that the combination of high-frequency signal and reduced dimensions of the sewer tunnels causes waves to keep “ricocheting” on the walls as shown in Figure 38. This **multi-path** phenomenon channels the waves and points them along the longitudinal axis of the tunnel. Wireless propagation in these environments can therefore be described as strongly multipath, and if the wavelength of the signal is much smaller than the tunnel cross section, sewer tunnels effectively act as oversized dielectric **waveguides**.

The waveguide effect of the sewer over the waves renders the use of directional antennae impractical: the directionality would be here a drawback, since it would only cover one side of the antenna, whereas an omnidirectional antenna covers both sides (see Figure **39**).

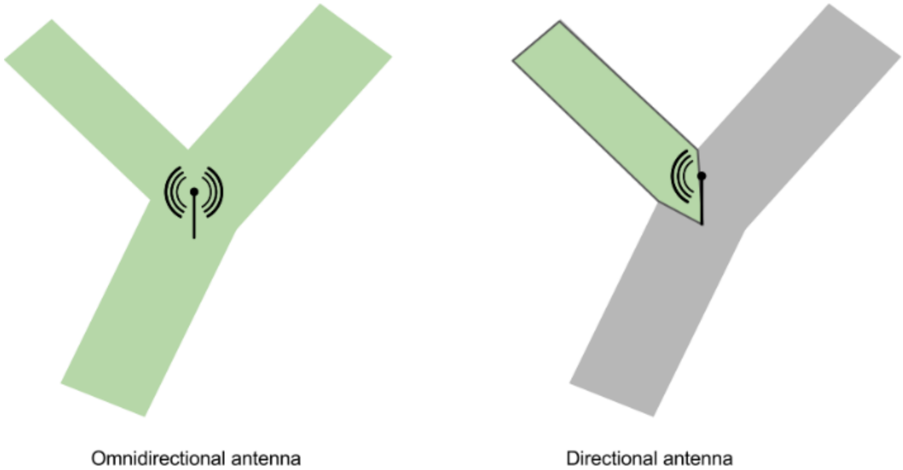


Figure 39: Range of field in the sewer of omnidirectional and directional antennae.

3.5.3 Solution and methodology

Our experimental results have confirmed that sewer tunnels act as a waveguide for Wi-Fi signal (see ARSI deliverable D2.2). In straight stretches of tunnels, Wi-Fi signal travels for hundreds of meters with very little attenuation.

In our experiments we paid close attention to the attenuation at bifurcations in the sewer network. While sharp turns (90 degrees or more) result in a nearly complete loss of Wi-Fi signal, we observed that **shallow turns also act as waveguides** and that Wi-Fi signal keeps propagating for large distances after.

This is a crucial observation because the topology of sewer networks is specifically designed to merge sewage water flows and direct them towards evacuation points. This topology is shown clearly in Figure 40 below which depicts a section of the Barcelona sewer network (in green) in the Eixample area where the ARSI evaluation will take place.

Figure 40: Wi-Fi propagation (in red) in Barcelona sewer tunnels (in green)

The key to our methodology is to **position our Wi-Fi emitter at locations where the generated signal range will be maximal based on the topology of the network**. In Figure 40, the red line models which sewer tunnels would be within Wi-Fi coverage given the location of the emitter. We can see that from this location, the Wi-Fi signal travelling south only encounters bifurcations with sharp angles, therefore none of the tunnels in the side streets (Corsega and Rosselló in this example) would be within Wi-Fi range for an inspection using the ARSI platform.

If on the other hand the Wi-Fi emitter is placed at the location shown in Figure 41, then the Wi-Fi signal propagating North encounters much more favourable bifurcations; and we can see that many side tunnels are now within Wi-Fi range. Note that while these examples where generated using a simple computer model for signal propagation, our various tests in the Barcelona sewers have confirmed this phenomenon (see deliverable D2.2).

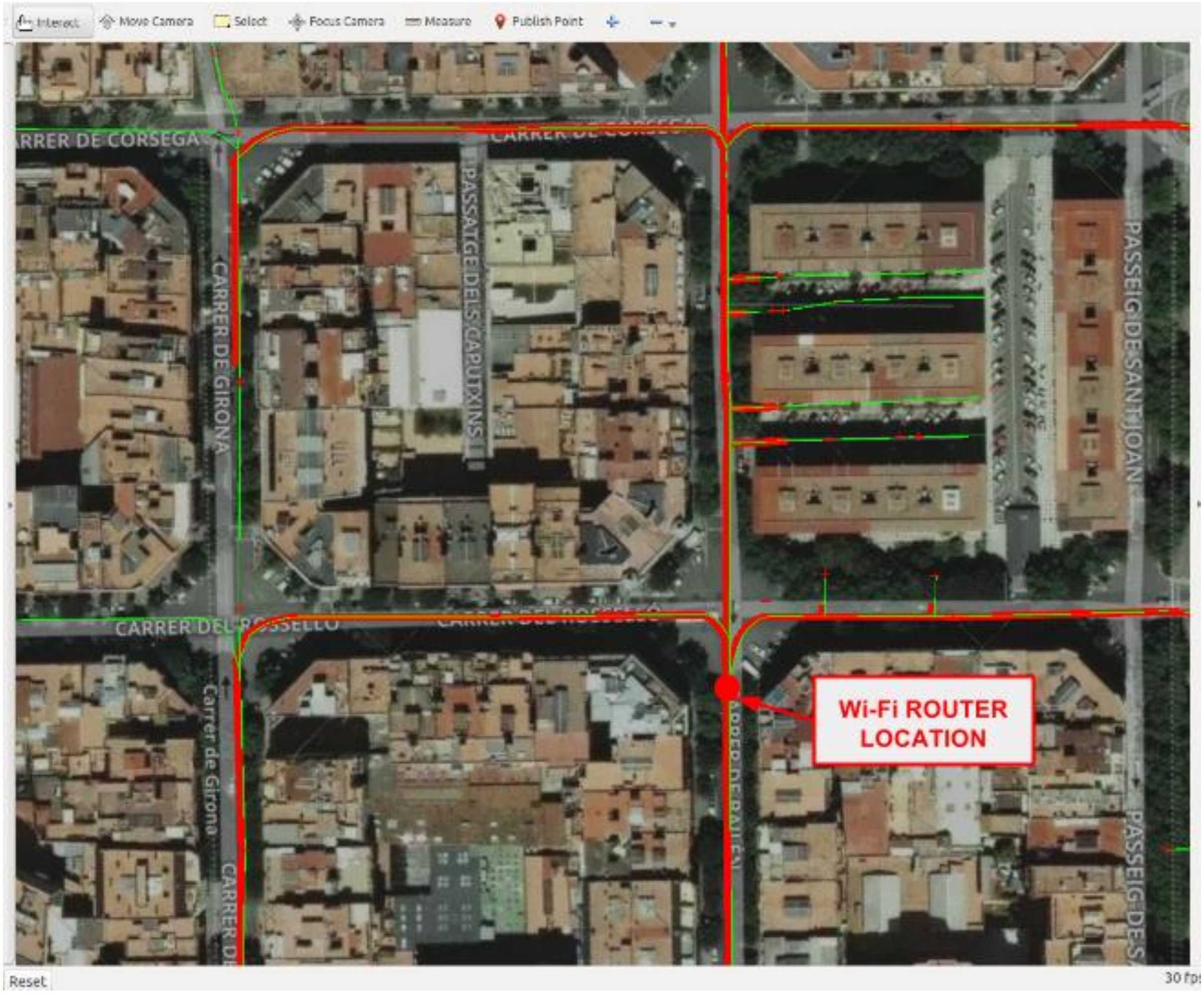


Figure 41: Improved Wi-Fi coverage (in red)
after taking sewer network topology (in green) into account

Using careful placement of the Wi-Fi emitter, we estimate that this behaviour of the signal allows us to cover more than 500 metres in total, which is **more than the range current batteries can provide** for our aerial platform for our nominal inspection speed of 0.5 m/s. This observation shows that careful inspection planning can effectively ensure full Wi-Fi coverage throughout missions using a single emitter, and that the real limiting factor for ARSI in terms of inspection range is in fact the battery life.

The operational methodology for ARSI missions described in section 4 was designed specifically with these considerations in mind. Inspection are planned by selecting optimal entry points into the sewers where the ARSI platform and a Wi-Fi router can be deployed to maximize both inspection and communications coverage. Specific planning tools (see section 3.6.1 – DRACMA platform) were also designed to assist operators in this relatively complex task, and to generate efficient inspection campaigns for the ARSI aerial platform.

3.5.4 Equipment

The communications system designed by ARSI is based on the latest Wi-Fi technologies (standard IEEE 802.11/ac) to maximise the link strength between emitter and receiver. The equipment used to address the problem of communications is based on off-the-shelf Wi-Fi devices. The use of ARSI deployable communications equipment guarantees the compatibility of communications protocols and standards across platforms.

The equipment currently deployed is:

- Linksys WRT 1900ACS router: equipped with double core at 1.6GHz and 512 MB of RAM, it provides up to 1300Mbps of link performance at 5GHz. It has 4 high-performance external antennae and beamforming technology to optimise both the range and the signal that arrives to the receiver. In addition, the firmware is open-source, which enables researchers to potentially modify and adjust it to the specifications of the project. The router will be powered using a LIPO battery and connected via Ethernet from the sewer to the Remote Station at the surface.

- ALFA AWUS036AC 802.11ac wireless adapter to be plugged on the ARSI aerial platform. It has a link performance of 867 Mbps at 5GHz, and a high-sensitivity antenna.

3.6 Remote station

The ARSI Remote Station is an extensive software infrastructure designed to complement our aerial inspection system. The role of this system is to facilitate operation and maximize efficiency at each stage of the inspection process:

- During inspection planning
- During mission execution
- During post-mission data analysis
- During report generation

3.6.1 DRACMA platform

Planning and scheduling inspections in a sewer network as large as that of Barcelona is a hugely complex task. Inspection service providers such as our partners FCC must ensure comprehensive and efficient coverage of the sewer networks, taking into account many parameters such as personnel safety, minimal disruption to the road traffic, weather alarms, history of structural defects, etc.

In order to facilitate this complex task, FCC have developed a proprietary cloud-based platform called DRACMA (Drainage Resource Administration and Cleaning Management). The general DRACMA architecture is shown in Figure 42 below. The platform offers extensive functionality including:

- Planning of inspections using detailed maps and GIS data of the sewer network;
- Management of inspection teams and schedules;
- Inspection reporting on the ground using the dedicated Dracma Mobile Android app;
- Cloud-based management of inspection data and report generation.

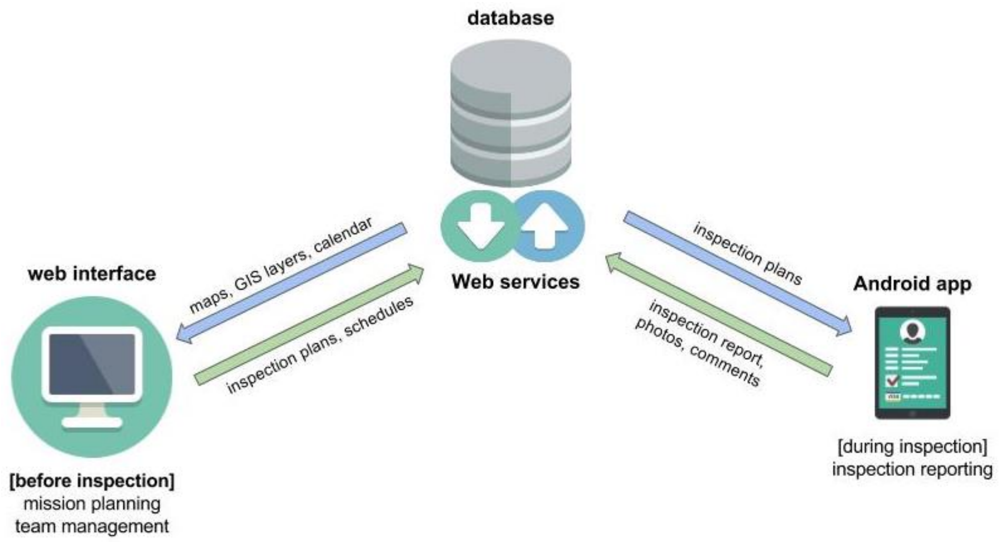


Figure 42: FCC DRACMA architecture

DRACMA will be extremely useful to plan and manage sewer inspections carried out with the ARSI aerial platform. While DRACMA isn't an intrinsic part of the ECHORD PDTI project, FCC are willing to participate in a tight integration between their proprietary platform and ARSI, in order to reuse functionality, avoid duplication, and reduce development costs. This approach also allows for a smoother transition for FCC teams who are already using DRACMA when they start using ARSI to carry out inspections.

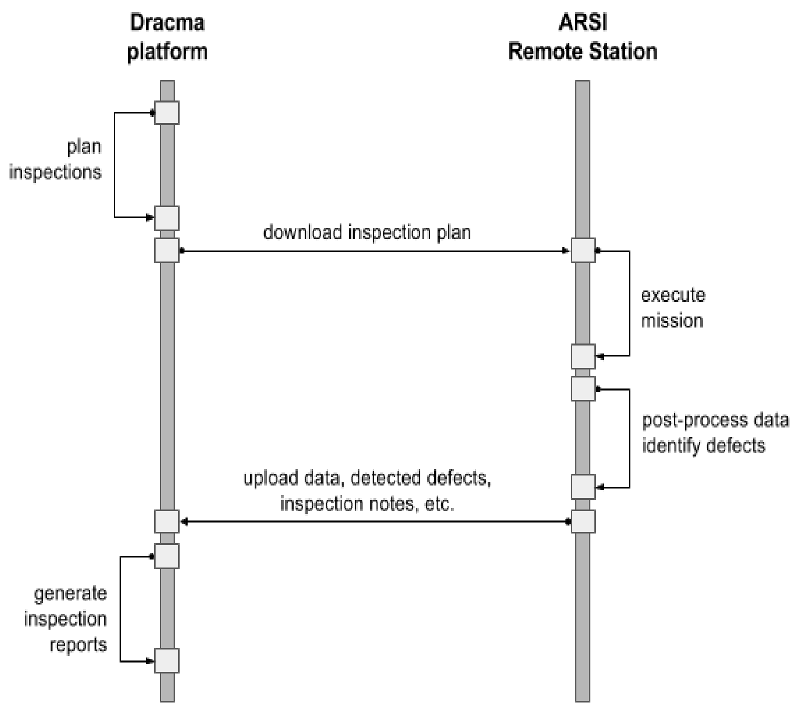


Figure 43: Integration between DRACMA and ARSI

The sequence diagram above illustrates the integration between DRACMA and ARSI at each step of the inspection process. Inspections are planned on DRACMA using maps and other GIS resources as well as the ARSI plugin (see details below). All inspection plans are stored in the cloud; specific plans for a given date can then be downloaded by inspection teams on the ARSI Remote Station in order to help pilots carry out their tasks.

After one or more inspections have been carried out, sensor data collected by the ARSI platform is analysed using the Remote Station, to detect possible structural defects in the sewer network. All potential defects, along with relevant sensor data (photos, air samples, possibly video, etc.) and inspection notes can then be uploaded to DRACMA. This information can then be used to generate inspection reports, or to plan specific structural inspections in order to address the detected defects.

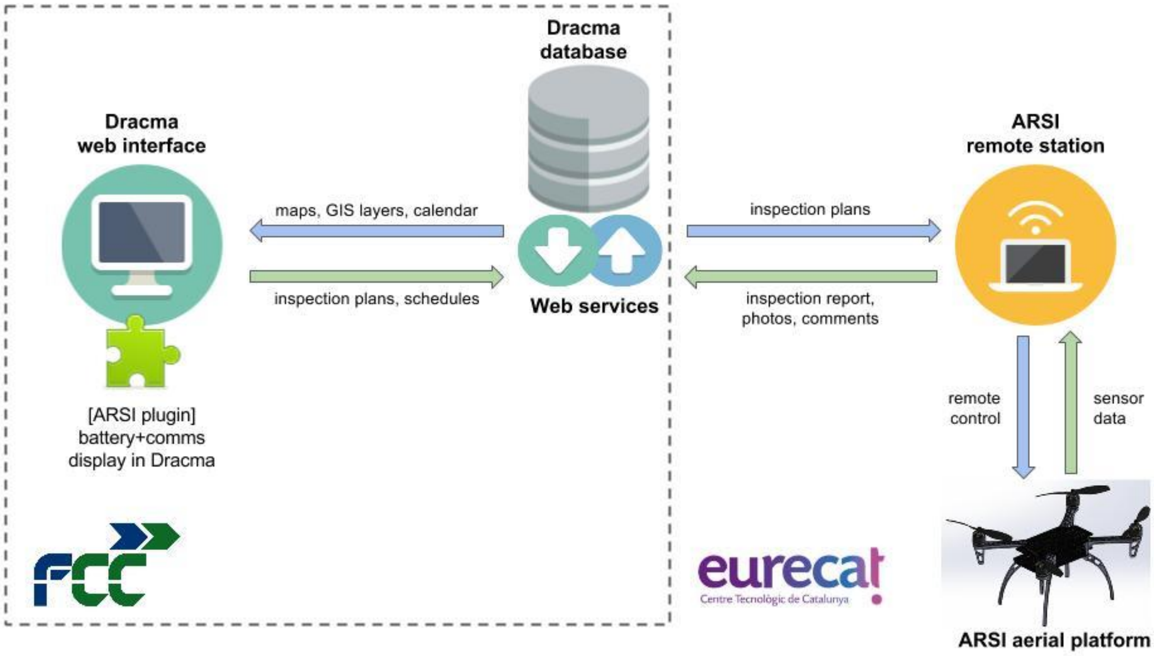


Figure 44: Integration between DRACMA and ARSI

3.6.2 Mission planning

Inspections are planned in DRACMA by selecting a series of sewer sections using detailed map and GIS data, which together form an inspection. Traditional teams will then inspect each of the specified sections, monitoring for potential structural defects or obstacles to the flow of sewage water.

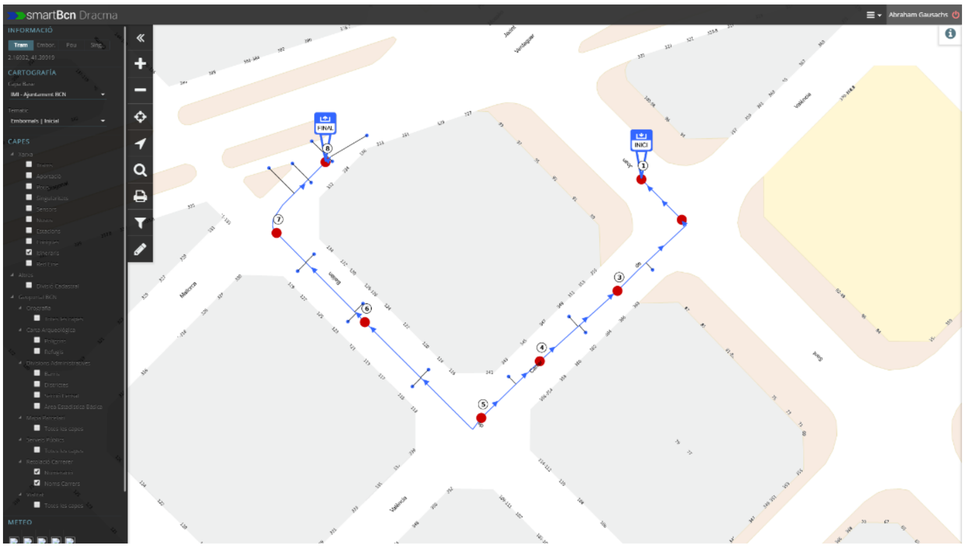


Figure 45: Mission planning using DRACMA (FCC)

The DRACMA user interface allows users to get detailed information about each section (dimensions, section type, etc.) or any other element of the sewer network. DRACMA also allows users to manage inspection teams using a calendar where missions can be assigned based on availability, previous tasks, inspection reports, etc.

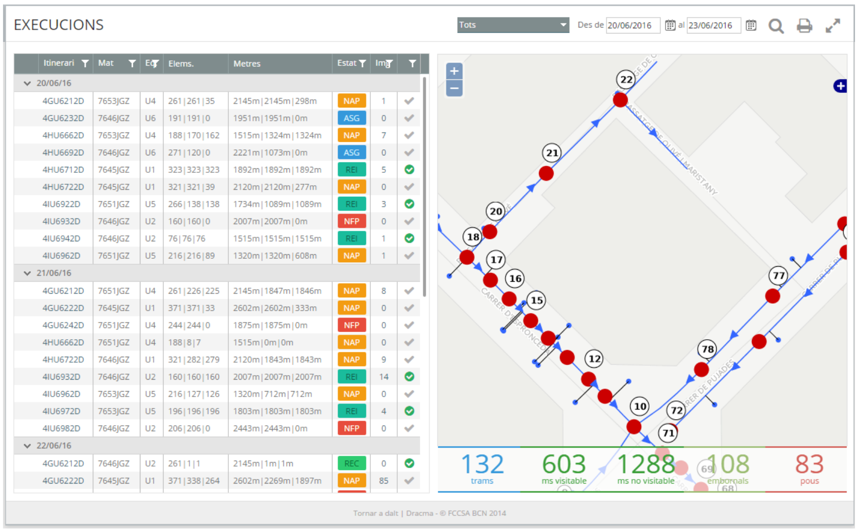


Figure 46: Inspection details and history display in DRACMA (FCC)

Planning inspections for the ARSI platform is slightly more complex than for traditional teams, as battery life and Wi-Fi communications range must be taken into account. Due to their weight and size limitations, aerial drones have relatively short battery lives in comparison with ground or maritime robots, typically between 10 and 20 minutes depending on the platform size and sensor payload. While this limitation is largely compensated by aerial platforms' faster operating speeds and navigability, it does imply that batteries must be changed frequently, which requires suitable access points for the inspection staff.

Additionally, planning of ARSI missions must take Wi-Fi communications into account, to ensure that the platform always operates within range of the Remote Station. As described in the Communications section, sewer tunnels, under certain conditions, may be a favourable environment when it comes to propagating Wi-Fi signal, due both to the shape of the tunnels and the topology of the network. But this depends largely on the route planned.

It is however difficult for a human operator to combine all this information and estimate the area in which the ARSI platform can operate given a specific entry point (a specific manhole from the GIS). In order to facilitate this task, we developed a plugin specifically for DRACMA to visualize both the battery range of the ARSI platform and a model of the Wi-Fi propagation from that point. Using this plugin, users can select a valid landing point meeting these limitations as well as external constraints such as disruption to road traffic, etc.

Once both deployment and recovery points have been selected on the map, ARSI missions can be created by selecting all sections within battery and Wi-Fi range between them. Due to the relatively short battery life of the ARSI aerial platform, missions must be planned to maximize inspection time and minimize logistics for redeployment. Together, DRACMA and the ARSI plugin make it easy for users to plan a series of connected inspection missions using convenient deployment and recovery points.

3.6.3 Mission execution

At the centre of the ARSI software infrastructure is the Remote Station, a support system for mission execution installed on a dust- and humidity-resistant rugged laptop that operators can take onsite during inspections.

3.6.3.1 Platform health plugin

Plugin to monitor and display all relevant platform status and health information. Alerts users of any fault or emergency: low battery, sensor fault, etc. While the inspection mission is running, the plugin monitors vehicle status (flight mode, arming status, etc.) and health information (battery level, sensor faults, etc.) broadcast by the Pixhawk autopilot via the Mavlink protocol. This information is converted into ROS messages by the Mavros (Mavlink/ROS) open-source interface, so that it can be displayed in RVIZ and used by any other ROS component.

Any fault or alert is flagged with the corresponding severity, so that pilots can decide whether to continue or abort the mission.

3.6.3.2 Pre-flight checks plugin

Pre-flight checks should be performed before each inspection carried out using the ARSI platform, to ensure the safety of the human personnel as well as the integrity of the aerial platform. While certain tasks will need to be carried out by operators (visual inspection of the airframe, checking flight perimeter and take-off zone, etc.), a Remote Station plugin will also be developed to facilitate this task and support inspection teams.

The plugin will monitor ROS and in particular Mavros traffic from the ARSI aerial platform to validate the following elements:

- A Wi-Fi link to the aerial platform is available and provides sufficient bandwidth;
- Batteries are connected and report sufficient levels to execute an inspection;
- Thrust requests are issued to the motor to validate their response;
- The Pixhawk Autopilot is connected and reports a valid state;
- All sensors are present, drivers are in valid states and data can accessed.

3.6.3.3 Remote control plugin

Converts commands from the USB remote control used by pilots at the surface into high-level Autopilot commands sent over Wi-Fi to the Pixhawk unit mounted on the ARSI vehicle. This plugin produces a result identical to that of a standard LoS (line of sight) remote control.

In order to avoid bandwidth shortages, remote control commands will be isolated on a reserved and safe TCP connection, separate from that used to transfer other data such as video streams.

3.6.3.4 Video display

RVIZ natively comes with a plugin for image or live video display. The Remote Station uses various instances of this plugin to display video streams from different cameras mounted on the ARSI platform. The ROS data capture system is able to compress video on-the-fly in order to adapt to the data bandwidth of the communications system.

3.6.3.5 Compass display

Displays the current absolute vehicle heading as a compass overlay in the RVIZ 3D window.

3.6.3.6 Battery display

Displays the current battery charge as an overlay in the RVIZ 3D window. This plugins is designed to inform pilots of the battery status at all times.

3.6.3.7 GIS overlay plugin

Plugin to display GIS data of the sewer network provided by the users. The plugin supports standard formats such as AutoCAD DXF and Postgres database as used in DRACMA (see Figure 47). Note that remote GIS data (e.g. from a remote database) is downloaded locally so that the Remote Station can be operated without an internet connection.

3.6.3.8 Map overlay plugin

Plugin to display various map overlays of the area from external sources such as Google Maps, Mapbox and OpenStreetMap (see figure below) which provide high-resolution raster, vector and satellite maps of the globe from sources such as NASA. The map overlay plugin will also be able to connect to Web Map Services (WMS) such as those offered by the City of Barcelona which include the design the sewer network.

Multiple maps can be displayed at various resolutions, in order to aid inspection teams in their tasks. Note that mapping data downloaded from the web is cached, so that the Remote Station can be operated without an internet connection.

3.6.3.9 DRACMA mission plugin

Plugin to retrieve a specific inspection plan from DRACMA and display it on the GIS/map overlay to help pilots prepare their flight.

Requests to DRACMA are implemented over the same Web Services as those already used by the tablets FCC staff carry with them during inspections.

3.6.3.10 Battery and Wi-Fi range display

Plugin to display the both battery and Wi-Fi range from any given point selected on the map, taking into account the topology of the sewer network (see section 3.5 – Communications). This plugin is useful to verify that a given mission plan is safe to execute based on battery life and Wi-Fi coverage from the deployment point.

3.6.3.11 Air monitor plugin

Plugin to display output from Envira air monitoring sensor. Alerts users of any dangerous level during the mission. In its current version, the reports levels of Hydrogen Sulphide (H_2S) and Carbon Monoxide (CO) readings as well as temperature and humidity.

3.6.4 Core functionality

The core functionality of the Remote Station is as follows:

- Piloting the drone from the surface to carry out sewer inspections,
- Visualizing video data from the drone to record possible structural defects,
- Monitoring the health of the ARSI aerial drone.

Following the Concept of Operations described in section 4, the ARSI platform is operated from the surface over a Wi-Fi link, primarily using visual feedback from the video cameras mounted on the vehicle. The Remote Station provides functionality to display video feeds from one or several camera, depending on the bandwidth available. As detailed in section 3.2 – Sensor equipment, the camera mounted at the front of the vehicle is a HD camera with a fisheye lens with a 180 degrees viewing angle to provide maximum awareness of the surroundings to the pilots.

Control commands are passed from a USB remote connected to the Remote Station to the aerial platform over Wi-Fi. Note that it is critical for pilots to keep the ARSI platform within Wi-Fi range of the Remote Station, or connection to the platform will be lost. This is achieved by planning inspections carefully using the ARSI plugin for DRACMA, and using conservative estimates of the Wi-Fi range. Note that the ARSI platforms monitors the health of the Wi-Fi connection to the Remote Station as a safety measure: if a loss of connection is detected, the platform **automatically lands** and needs to be physically recovered. Such an event is highly unlikely however, as tests have shown that the Wi-Fi range in the sewers is vastly superior to that of the platform batteries (see section 3.5 – Communications).

Pilots can choose which control mode they want to operate in, either low-level manual modes or the high-level sewer-specific modes as described in section XX. The choice is made directly from the Remote Control where a button allows pilots to switch between modes, and retain total control over the platform in case of emergencies. Semi-autonomous modes such as “Tunnel” mode are designed to minimize the work of the pilots and only require them to monitor progress and optionally control speed, for example if a defect or anomaly is observed in the video streams.

3.6.5 Software design

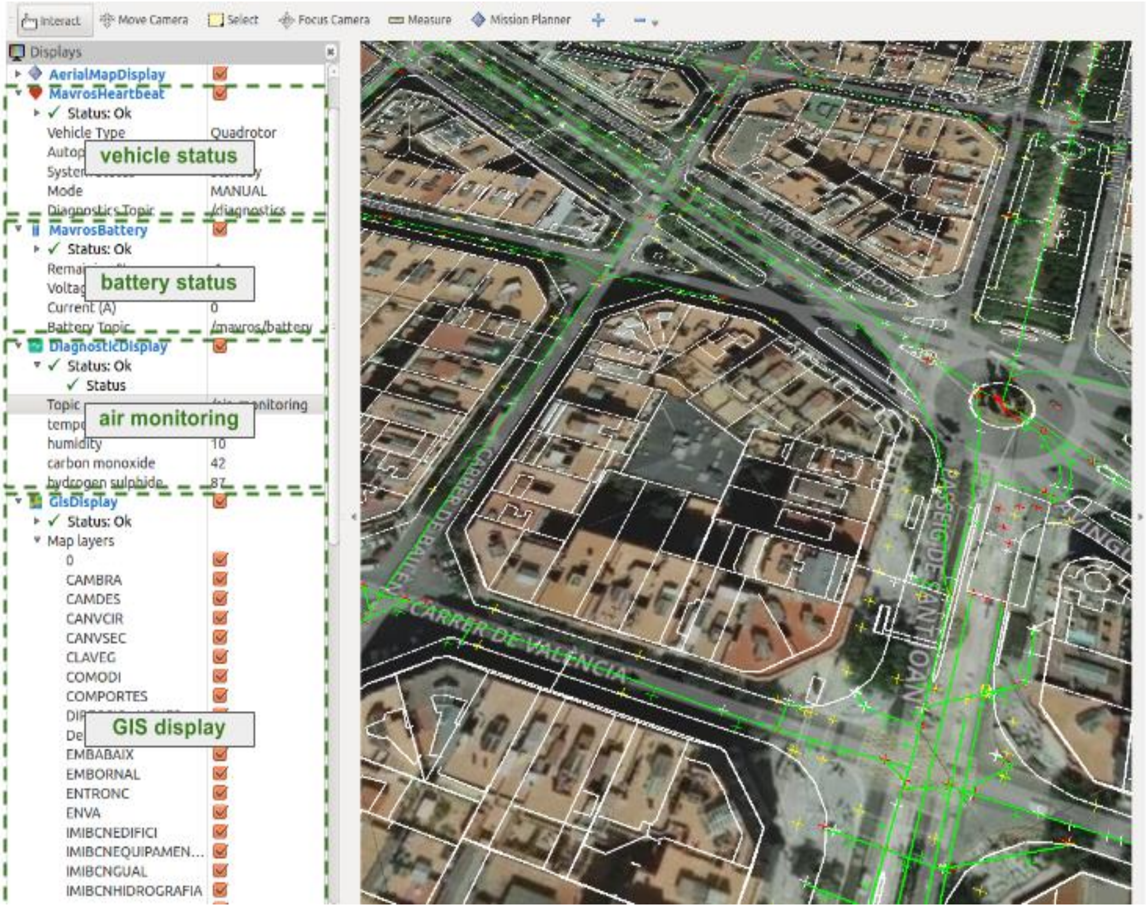


Figure 47: User Interface of the ARSI Remote Platform

Since the embedded navigation and sensor system on the ARSI platform are based on the Robotic Operating System (ROS, see section 3.4.1 – Data format), it follows that the Remote Station must also be ROS-compatible in order to receive live sensor data from the platform during inspections.

ROS distributions include a number of open-source and free utility tools, in particular RVIZ for 3D visualization of sensor data (odometry, laser, etc.), and RQT for sensor data replaying and analysis. Both RVIZ and RQT follow a plugin-based architecture, which makes them highly configurable and extendable. Many plugins are provided as part of the ROS distribution, and many more have been developed by the ROS open-source community.

The approach chosen for the design of the Remote Station is to reuse and extend the existing ROS tools, in order to focus the development effort on functionality specific to the ARSI platform instead of re-implementing an entire user interface. As shown in the figure above, the ARSI Remote Station is comprised of the RVIZ user interface augmented with a number of standard or custom ROS plugins such as video display, 3D map and GIS layers, vehicle status, Wi-Fi connection monitor, etc.

3.6.6 Post-mission analysis

Additional plugins will be developed to allow users to post-process and review sensor data after an inspection has been completed using the ARSI system.

3.6.6.1 Localization plugin

The most important step in the post-mission analysis process is to accurately geo-reference information collected during an inspection against the maps and GIS of the sewer network. This is achieved using the localization algorithm described in section 3.3.1, which will be implemented as a standalone executable able to process ARSI mission logs in the form of a ROS “bag” file containing readings from the core navigation sensors (see section 3.2.1).

This localization executable will build an estimate of the vehicle track and update the mission logs with timestamped vehicle positions throughout an inspection. Using this information, it becomes possible to geo-reference any entry in the mission log (sensor reading, detected defect, etc.) by interpolating its timestamp against the vehicle track.

3.6.6.2 Inspection quality plugin

This plugin will review the mission. Once an estimate of the vehicle track has been computed, it will be compared against the planned mission. The objective of this plugin is to ensure coverage and corrected of the executed mission, compared against the a-priori plan. This plugin will show the following:

- Percentage of mission accomplished
- Quality of the inspection: this tool will analyse the log and ensure that the inspection was performed according to the quality criteria (maximum velocity, maximum heading deviation from target, valid altitude, etc.)
- Display of the coverage on the map
- Time
- Energy consumed and batter left at the end of the mission
- Alerts from the air monitoring component
- Any incident or deviation from the plan

3.6.6.3 Video tagging plugin

One of the key tasks during a sewer inspection is to spot and report all structural defects, which are currently reported with the following characteristics:

- ID of sewer section and nearest node (from GIS)
- Distance from node nearest node
- Circular reference (see Figure 48 below)
- Dimensions
- Comments

A plugin will be developed allowing operators to manually review video data from all 4 cameras mounted on the ARSI platform, and to tag all images in which defects or points of interest can be seen. Tagging is done simply by selecting an area in the image with an optional comment. The plugin then uses external information such as extrinsic and intrinsic calibration of all cameras as well as the vehicle track to calculate all the fields required to identify and locate the point of interest. This information is then sent to DRACMA using a Web Service interface, so that inspection records produced by the ARSI platform can be seamlessly integrated in the existing data management infrastructure, and used by all inspection teams.

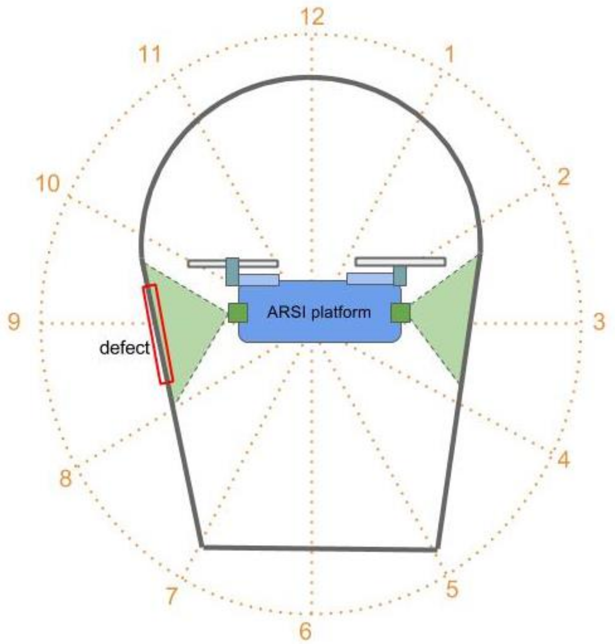


Figure 48: Circular reference for structural inspection reporting

3.6.6.4 Defect detection plugin

A plugin will be developed to assist operators in the post-mission analysis phase of the inspections, to process video data collected by the ARSI platform during inspections and automatically detect possible structural defects on the sewer walls.

Our algorithm for automatic detection will build on the extensive research available in the field of automated defect inspection and condition assessment of tunnels and civil infrastructure [15][16]. A wide range of image processing techniques have been investigated to detect failures on constructions: feature-based and model-based methods have been applied to crack detection [20], and pattern-based methods and 3D reconstruction [18] have been proved useful when searching for crack failures, since volumes and gaps can be measured with these techniques. Perhaps the most promising field in this area is the approach taken by machine learning [17] and the emergent area of deep learning, which allows a software system to be trained to identify and classify a pattern in a given environment, and then it can learn to find this pattern in a dataset.

We intend to make the most of Eurecat's extensive experience in 3D reconstruction and deep learning to develop a system which will assist the operator in the reporting of defects in the sewer. The plugin will post-process inspection data and produce a list of possible defect candidates. Special effort will be made in preventing the system from producing false negatives (actual defects classified as non-relevant by the system).

In our proposed Concept of Operations (see section 4), several inspections will be executed every day, before all sensor data is post-processed back at base to report all possible structural defects in the sewers. While our automated algorithm can be extremely useful to filter through large amounts of data, it is clear that human supervision will be required to determine which defects require further intervention by the inspections teams. An intuitive user interface will be developed to facilitate this task allowing experts to review all candidates produced by the automatic algorithm and eliminate all invalid or irrelevant detections, so that real defects can be investigated further.

3.6.6.5 Structural reconstruction plugin

A plugin will also be developed to reference laser data collected during an inspection against the vehicle track, to build a geometrical model of the sewers. As detailed in section 3.2.2 – Inspection sensors, we will investigate strategies to augment the 2D models generated using laser data in order to produce 3D reconstructions of the sewer tunnels.

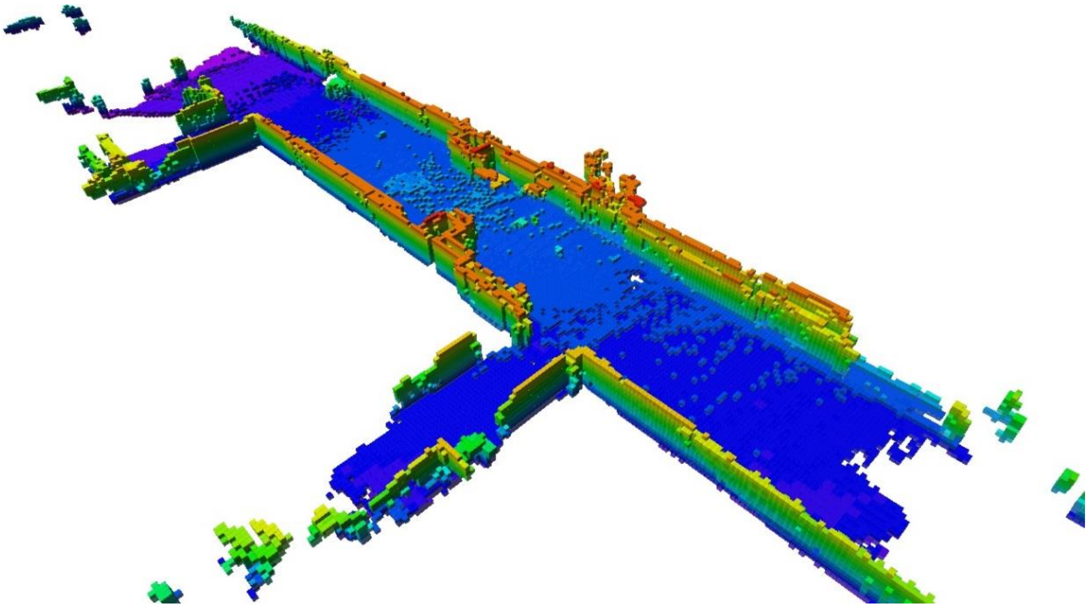


Figure 49: 3D visualization of a 2D map built from laser data

4 Logistics and Operations

In this section we describe the logistics and methodology required to carry out inspections using the ARSI system. Our methodology was designed to meet the main objectives of this ECHORD ++ PDTI project: increase the productivity of the inspection teams by optimizing human resources, while minimizing the safety risks for the staff.

An analysis of the current structure of Barcelona sewer network served as basis for the later definition of the basic navigation and inspection criteria for the ARSI solution and the identification of the required equipment to comply with current safety legislation (see Annex B). Barcelona sewer network shows a level of complexity, extension and variability of conditions that makes possible the extrapolation of the assumptions and decisions made here to any other city and sewer system.

4.1 Minimum criteria for drone-based inspection

As described in the Challenge brief document (v. 29/12/2014), sewer networks are currently classified into Visitable, Semi-visitable and Non-visitable, according to their dimensions in height, width or diameter. The dimension defines how easy and safe is for sewer inspection staff to access and work. Staff is only allowed to enter Visitable sewers. The minimum width which is considered safe, therefore visitable, is considered 60cm. Likewise, the minimum height is 150cm. Semi-visitable sewers can only be accessed under some strict exceptions.

In the case of ARSI, these concepts translate into an equivalent classification for the case of inspections with drones. Therefore, ARSI consortium divides the network into three different types, according to their height (H) and width (W) and the navigability of the solution:

- **Navigable**: if H ≥ 80cm and W ≥ 80cm
- **Semi-navigable**: if H ≥ 60cm and W ≥ 70cm
- **Non-navigable**: if H < 60cm and W < 70cm

ARSI solution targets the Navigable sewers. From the analysis of Barcelona sewer, a **39%** of the network belong to this group, which leads to near **600km** of inspection that could be inspected with a drone, which is already a considerable achievement. Semi-navigable sections (23%, 370km) present some additional challenges to the navigation of the platform. For instance, some sections present a variable width, such as the T111 which shows a minimum width of 60cm at the bottom and 90cm at the top. ARSI will attempt the inspection of some of the sewers in this group, but it will require further analysis, specific for each type of section. Non-navigable sewers (37%, 574km) are completely discarded for drone-based inspections. The following table summarizes this classification:

Table 6: Classification of sewer based on the definition of drone navigability

	Number of sections	Meters	%
NAVIGABLE	26,279	597.400,68	39%
SEMI-NAVIGABLE	14,398	370.236,05	24%
NON-NAVIGABLE	27,956	574.925,32	37%
TOTAL	**68,633**	**1.542.562,05**	**100%**

4.2 Current methodology

Structural sewer inspections are currently carried out by brigades of 4 people: 2 skilled inspection staff and 2 surface staff (typically 1 peon and a driver equipped with a van). Throughout inspections, these teams must follow strict health and safety guidelines, in particular:

a) Inspection staff deployed inside the sewers must always work in pairs;
b) Inspection staff must carry protective equipment and specialized sensors to monitor toxic or flammable gases;
c) Entry into the sewers (manholes) must be clearly marked and protected. This is particularly important when entries are on roads and crossroads, and occasionally this might require interrupting traffic.
d) Manholes at both ends of a section being inspected must be open from the surface to ensure sufficient air flow.
e) Manholes at both ends must be guarded by surface staff, to provide support in the event of an emergency evacuation.

These regulations, while critical to ensure the safety and wellbeing of the inspection staff, imply that inspection brigades must be composed of at least 4 people: 2 inspection staff and 2 surface staff. Additionally, surface staff must follow the inspection officers, opening and closing manholes for each section being inspected, to meet safety guidelines d) and e) listed above.

4.3 ARSI methodology

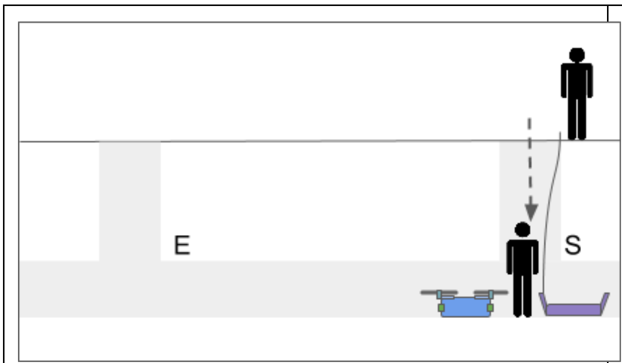
4.3.1 General approach

The key innovation of our technology is that the ARSI platform is **operated from the surface**, using our Remote Station and the Wi-Fi communication solution described in section 0 – Communications. Table 7 below describes the general approach for operating the ARSI system.

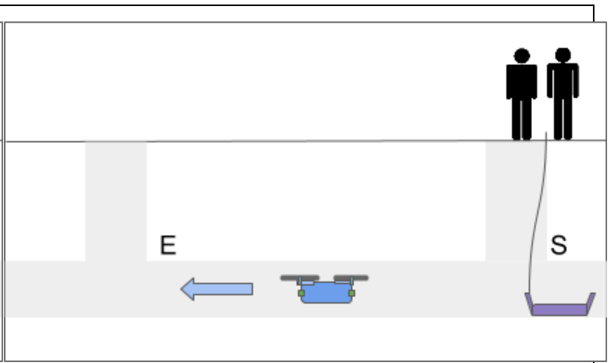
Table 7: General approach for inspection using ARSI

Task		***Description***
(0)	**Mission planning in DRACMA**	Inspections are planned in advance using DRACMA and the ARSI plugin, as described in section 3.6 – Remote Station. Inspection plans are downloaded on the Remote Station and viewed on a map or GIS to facilitate execution.
(1)	**Travel to inspection site**	Inspection brigades travel onsite with all necessary equipment, including the ARSI platform, remote control, and Remote Station. Based on the inspection plan, the relevant entry point into the sewers is opened and secured.
(2)	**ARSI platform set-up**	One team member enters the sewers with the ARSI platform, and a Wi-Fi communication device. The ARSI platform is placed in the nearest sewer section, and a new battery placed and connected. The Wi-Fi device is placed directly next to the ARSI platform and connected with an Ethernet cable to the Remote Station at the surface.
(3)	**Pre-flight checks**	The team member exits the sewer, and verifies that a connection to the ARSI platform was established from the Remote Station. Pre-flight checks are performed: battery check, sensor checks, etc.

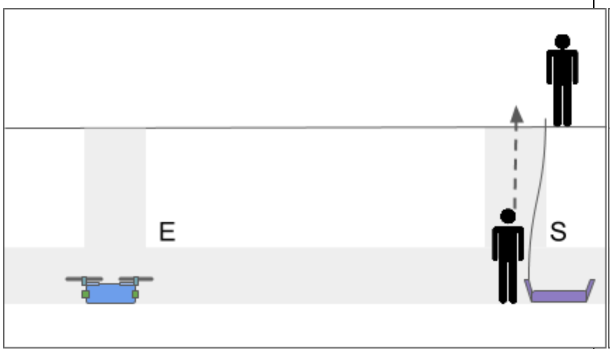
(4)	**Mission execution**	The pilot executes the inspection based on the mission plan downloaded from DRACMA, using video feedback from the Remote Station, and lands the ARSI platform at the specified location chosen to be easily accessible from the surface.
(5)	**Equipment recovery**	A team member enters the sewers at the start location to retrieve the Wi-Fi router, and the team packs the Remote Station and remote control.
	Next mission	Both team members travel to the landing point, and repeat the process from step (1) to execute the next inspection.
(6)	**Data analysis**	Sensor data (video, laser, air monitoring, etc.) is downloaded from the ARSI vehicle onto the Remote Station and analysed using dedicated tools (see section 3.6 – Remote Station). Possible structural defects are recorded, and uploaded to DRACMA along with any other relevant information.



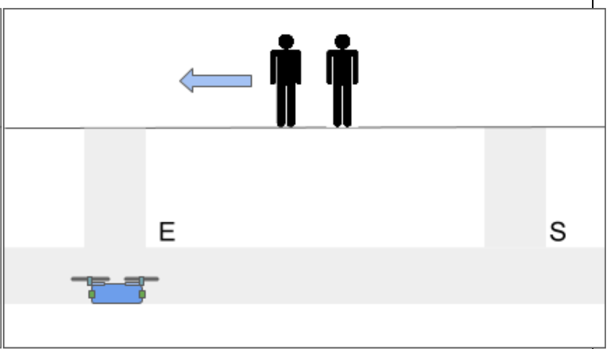
ARSI platform set-up



Mission execution



Equipment recovery



Travel to landing site for next mission

The main advantage of our approach is that only 2 team members are required in each brigade, thus significantly reducing the operating costs (see section 5 – Business plan). Moreover, inspection teams only need to spend very short amounts of time inside the sewers to deploy the ARSI system, which dramatically reduces the human risks.

Three guidelines should be followed when planning missions with this operational method:

- Missions should be planned in DRACMA so that they follow each other: the end/landing point of the first coincides with the start/take-off point of the second. This guideline maximizes productivity, since the landing site is used as the equipment setup location.
- Entry points (mission start/end) should be chosen to be as easy of access as possible, in order to minimize the time inspection staff need to spend inside the sewers.
- Missions should be planned to maximize coverage given the battery life of the ARSI platform, and the Wi-Fi coverage. The DRACMA plugin described in section 3.6 – Remote Station was designed specifically for this purpose.

4.3.2 Coverage

Given an estimated battery life of 10 minutes and an inspection speed of 0.5 m/s, we obtain an inspection range of 300 meters. Table 8 lists the estimated durations for each step of the modus operandi described in previous sections, given sufficient training and practice.

This would give us an estimated inspection rate of **300 meters per hour**, or 2.4 km per 8h day. Taking into account the time needed for data analysis, we obtain a conservative number of **2km per day**. This shows that our system would yield a significantly larger coverage than current inspection teams. Note however that this inspection rate does not take post-processing of data into account.

Table 8: Total duration of an inspection using ARSI

Step	*Task*	*Duration (mins)*
(1)	Travel to inspection site	20’
(2)	ARSI platform set-up	10’
(3)	Pre-flight checks	5’
(4)	Mission execution	15’
(5)	Equipment recovery	10’
	Total per mission	**1h**
(6)	Data analysis (per day)	1h

Note also that both the battery life and the inspection speed used in this estimation are conservative values. The analysis and flight tests carried out in Phase 1 of this project suggest that an autonomy between 15 and 20 minutes could realistically be achieved with this platform by the end of Phase 2.

Figure 50 provides a visual representation of the timeline for a full day of work by an ARSI inspection team: while inspection steps (2) to (5) are carried out on-site and repeated for each flight, mission planning and data analysis can be performed back at base and all at once by specialized inspection staff, in order to increase productivity.

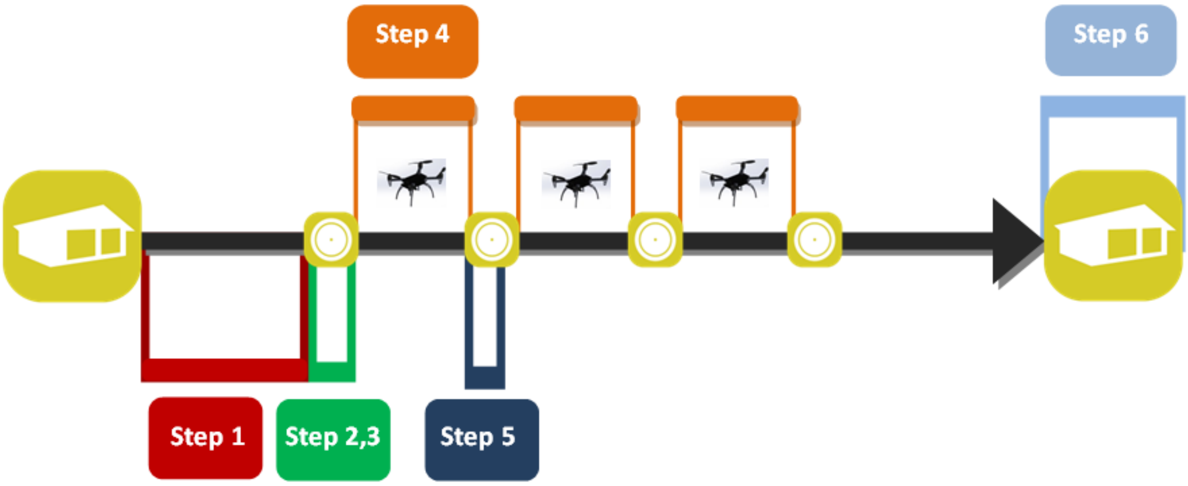


Figure 50: Various steps of an inspection day using the ARSI system

The inspection speed of our aerial platform is only limited by the performance of our semi-autonomous flight modes, as well as training and skills of the pilot. Since we have not been able to evaluate either in Phase 1, we do not want to overestimate the capabilities of the system. However we believe that inspection speeds around 1 m/s are realistic.

Using these more optimistic estimates for battery life and inspection speed, we hope to significantly improve on our inspection coverage, possibly even doubling the 300m/h figure used above. However given that our system is still a prototype, we prefer to be prudent and avoid overestimating our capabilities.

4.3.3 Logistics and equipment

Table 9 below lists all the equipment and training required for a team to carry out an inspection using the ARSI platform. All specific safety equipment required for inspection brigade members is listed in Annex B.

Table 9: Logistics required for an ARSI inspection

STRUCTURAL INSPECTION	ARSI Inspection team with 2 technicians Red Visitable > 80 cm		
HUMAN RESOURCES	**Operators**	**Category**	**Qualifications**
	1	Oficial	- Work in confined spaces - First Aid - Use of gas detector - Efficient driving - Health and Safety training - Working at height - Environmental awareness - Use of harness, tripod - UAV training - ARSI training
	1	Operator	
EQUIPMENT on the SURFACE	**Vehicle**		
	Van with 4m³ of available volume with machinery integrated		

	Signalling and crew protection	**Auxiliar tools and hardware**
	Fences and protection grids of manholes	Polyvalent barrow for opening manhole lids
	Traffic signs, cones.	Auxiliar tools
	Tripod, fall-arresters device	
EQUIPMENT in the SEWER	**Inspection devices**	**Management and communication devices**
	ARSI aerial platform	Mobile phone
	ARSI Remote Station	ARSI deployable communications
	Lithium batteries for drone & router	Ethernet cables
	USB remote control	

4.3.4 Mission planning and deployment

It has been aforementioned that there are three key elements to take into account when planning an inspection using the ARSI system:

- Battery life and Wi-Fi coverage in the sewers
- Access to the platform at the start and end points.
- Synchronisation with DRACMA

Since the ARSI platform is piloted from the surface, all communications between the Remote Station and the platform, including the pilot commands issued via the USB controller (see section 3.6 – Remote Station) are transmitted over the Wi-Fi communications link. It is therefore critical that the ARSI platform should always remain within Wi-Fi range throughout an inspection, and within the vehicle range estimation based on the battery life and inspection speeds.

As detailed in section 0 – Communications, the Wi-Fi range inside the sewers largely depends on their topology, and in particular the shape of the connections between the galleries. Smooth curves tend to carry Wi-Fi signal with little attenuation; while sharp turns act as barriers where virtually all signal is lost. The ARSI plugin for DRACMA (see section 3.6 – Remote Station) was designed specifically to help inspection staff by modelling Wi-Fi propagation using the GIS data provided.

Using DRACMA and the ARSI plugin, operators can easily plan a series of ARSI-specific inspections, where start and end points should coincide in order to replace batteries and set-up the Wi-Fi router. All inspections are uploaded into the DRACMA database, and can be accessed at any time by inspection teams on the ground, using the ARSI remote station as well as the DRACMA Android app for tablets.

It should be noted that missions are scheduled according to a criterion of compactness, i.e. on one session, a squad should cover a convex area of the sewer so that redundant inspection sessions are avoided. This criterion is illustrated on figure 29.

Figure 51: Compactness criterion combined with Wi-Fi coverage. All the manholes of the street selected should be inspected in the same mission. The coverage of the communications (highlighted in red) should therefore cover the whole street.

4.3.5 Adoption and continuous improvement

The methodology described in this section is central to the ARSI system, because without a sound operational methodology even the most advanced aerial platforms or software systems will not produce the desired results. Developing an efficient, safe and environmentally sound methodology for sewer inspection is an extremely complex task because so many factors come into play: human factors, health and safety regulations, training for new types of equipment, environmental regulations, changes in team routines, etc.

It is clear that the adoption of this new system will take time, and that improvements and adaptations to our suggested methodology will be required. In future phases of this project we hope to take advantage of the deep field knowledge and experience available in our consortium, in particular through our partners FCC, to carry out a careful operational analysis and obtain performance values of all the parameters that directly or indirectly affect the daily life of the service. The theoretical performance figures given in previous sections will need to be validated against empirical evidence when the ARSI system has been fully developed and real inspections can be carried out.

The objective will always be to provide the best possible service to our customers, and the highest possible quality of inspection data, while striving to maximize safety, efficiency and productivity.

4.3.6 Additional considerations on mission execution

One of the major advantages of using an aerial platform for sewer inspection is that unlike most ground robots, it is very easy to transport and deploy.

The ARSI platform weighs around 3kg (see section 3 – Aerial Platform) and is small enough to fit through standard manholes. It can be carried down inside the sewers by a single person, or moved down using a simple basket and pulley in areas where sewers are deeper underground and harder to access.

Thanks to its adapted landing gear, the ARSI platform can be positioned in the middle of any sewer tunnel, as it can take-off and land from anywhere as long as sewer water depth and current are within specifications (see section 3 – Aerial platform). Thanks to a careful design, the platform provides easy access to the batteries, so that changing and connecting batteries can be accomplished in a few seconds.

Finally, the Wi-Fi router should be set up where convenient near the platform. Like all electric components of the ARSI system the router is protected from water using a hydrophobic coating. The router has its own battery, although it does not need to be changed at each mission like that of the ARSI platform. Since the Wi-Fi device is always connected to the Remote Station, a Power over Ethernet (PoE) solution will be investigated in Phase II in order to facilitate operations.

5 Economic feasibility and business plan

This section justifies the social interest and economic viability of ARSI project and defines the potential business model and exploitation plan for every member of ARSI consortium which compose a real and complete value chain able to bring research to the market.

The section is structured as follows:

- Market overview and interest of inspection and maintenance robotics
- Description of ARSI exploitable results and IP distribution
- Business model and exploitation plan, including a description of ARSI value chain
- Economic viability for the companies and institutions involved, including economic prospects

5.1 Market overview and interest in Inspection and Maintenance Robotics

The interest of robotics technology for inspection and maintenance applications is growing rapidly through different industrial sectors such as petrochemical, off-shore, power and nuclear plants and civil infrastructures. The cost of inspection and repair tasks of infrastructure keep growing vastly and incessantly due to the ageing of infrastructure and with the gradual expansion of distributed installations. This reality can be addressed by robotic technology in order to procure automated, reliable and cost-effective solutions that will not only reduce costs, but will also minimize risks to personnel and asset safety. With all, the coming decade will probably witness the rapid expansion of inspection robots. Key market drivers for that to be a reality are:

- Growing interest in robotics not only by US and European countries but also by emerging countries.
- Potential for improved coverage of large areas thanks to technical improvements.
- Increase in quality of monitoring data and regularity of monitoring due to lower cost per task.
- Reduction of total operational costs with respect to existing manned solutions.
- Increasing acceptance of robotics technology.

According to a new market research report on the “Mobile Robots market by Environment, Component, Application and Geography – Global Forecast to 2020” by Markets and Markets[2], the global mobile robots market was valued at USD 4,438.9 Million in 2014 and it is expected to reach USD 10,605.4 Million by 2020, at an estimated CAGR of 16.31% between 2015 and 2020. The professional service sector constituted the largest application for the mobile robots market in 2014 and it is expected to continue to grow at a significant rate because of the increasing applications, such as logistics, inspection & maintenance, telepresence and field robots across the globe. The market for these applications is expected to grow at a significant rate during the forecast period, because of the increasing adoption of the mobile robots due to the decline in the prices of several robotics components such as sensors, actuators, and others. Furthermore, these systems have been able to overcome the difficulties faced by humans in saving costs and time apart from avoiding danger in several applications.

[2] Markets and Markets http://www.marketsandmarkets.com/PressReleases/mobile-robots.asp

More specifically, for inspection and maintenance robots, the International Federation of Robotics (IFR) estimates that 4.000 units will be sold in the period of 2015-2018[3]. However, this is recommended by the IFR Statistical Department to be seen as a trend concerning market direction rather than actual and precise sales forecast.

5.1.1 ECHORD++ PDTI Urban Challenge use case: Sewer network inspection

Sewer inspections require many humans to work in risky and unhealthy conditions. Introducing a robotics solution in this process aims at reducing the labour risks, improving the precision of sewer inspections and optimizing sewer cleaning resources of the city, not only in terms of economic expenses but also in terms of water required for the cleaning process and of machinery needed. For ECHORD++ the city of Barcelona will provide its sewer network as use-case and test site.

In many points of the sewer network the terrain is highly irregular and with obstacles. The presence of significant levels of liquid waste and litter, produced by the collection of residual and pluvial waters, limit the operability of terrestrial vehicles and frequently, a cleaning of the sewer is necessary previous to an inspection with one such vehicle.

The ARSI consortium plans to tackle the pipelines and galleries inspection using an unmanned aerial vehicle (UAV), quadrotor type, endowed with sensors for its autonomous navigation along the network, collecting data for its inspection. The aerial option avoids the mobility constraints that suffer the vehicles that should advance along paths having steps, steep drops and even objects like the own domestic waste or elements dragged by pluvial waters.

5.1.2 Expected impact

While the expected impacts identified during the proposal stage are still valid and targeted by ARSI project, the Phase I of ECHORD++ Urban Challenge allowed the consortium to be more specific with respect to the economic, social and scientific-technological impacts.

Economic impact: This impact is deeply discussed in section *5.4 Economic viability for every institution involved* showing great commercial opportunities for the actors involved and high efficiencies up to 43,2% reduction in cost with respect to current sewer inspection methods.

Social impact: The solution has proven to be valid for the improvement of working conditions of inspection staff, frequently exposed at risky and unhealthy situations. FCC, a service company currently offering sewer inspection services worldwide has validated the technical approach for its inspection brigades, whose operational and logistics requirements are described in section 4 – Logistics and Operations.

Scientific-Technical impact: Phase I has established the grounds for ARSI consortium to be able to efficiently achieve significant step changes in a number of technologies such as localization and navigation in harsh environments, precise control of aerial platforms in confined spaces and inspection techniques in low visibility conditions.

With all, and according to the Robotics 2020 Multi-Annual Roadmap Release B 03/12/2015[4] published by SPARC - *The partnership for Robotics in Europe*, ARSI will contribute to the achievement of at least 3 out of the 6 envisioned prioritized targets for the Inspection and

[3] http://www.ifr.org/service-robots/statistics/
[4] https://eu-robotics.net/cms/upload//H2020_Robotics_Multi-Annual_Roadmap_ICT-2016.pdf

Robotics sub-domain (see section 2.6.3.2 of the Sub-Domain Inspection and Maintenance, section 2.6.3), namely:

Priority	Target	ARSI contribution
1	Move People away from hazardous spaces to safe areas by 50%	ARSI solution prevents brigades for accessing unhealthy and risky areas. Additionally, where ARSI solution will be used, this will require brigades of 2 operators, instead of the current 4-members brigades needed for inspection.
4	Coherent standards for robotic deployments	An operations procedure has been defined for the deployment and user of ARSI solution by a worldwide inspection service company.
5	Step Change in data and information management	ARSI proposes a holistic way of integrating sensor data into an existing information management systems, facilitating market uptake of project results. The designed ARSI remote station adapts formats to make it compatible with DRACMA, FCC's own planning platform.

5.2 ARSI exploitable results and IP Rights management

Despite the large number of robots currently available for pipe inspection, there is no system on the market suitable for sewer networks inspection. Sewer networks characteristics in terms of the different type of sizes, spaces and surfaces to inspect need of bigger and more agile robots compared to pipeline robots. Additionally, pipelines robots, and current inspection robots in general, are always remotely operated and include low levels of autonomy in their operations. On the other hand, a sewer inspection robot will have to have certain levels of autonomy in order to cover higher distances of the network, facilitate operators tasks such as navigation and inspection and make it commercially feasible to become a real business opportunity.

5.2.1 Definition of ARSI exploitable results

ARSI technical developments and contributions seek to fill that commercial gap with the achievement of the following results, already deeply described in section 3 – Solution design.

- An aerial quadrotor platform
- A customized sensor configuration
- An advanced navigation and inspection system
- A remote station for ARSI system operations
- A customized integration of the collected data to an existing information management software

5.2.1.1 Aerial quadrotor platform

An aerial quadrotor platform designed specifically for the strict operational requirements of sewer inspection based on a custom-made carbon body and landing gear with commercial components, including propeller protection, as described in section 3.1 – Aerial platform. The platform was designed, built and tested by SimTech Design and Eurecat.

5.2.1.2 Customized sensor configuration

The strict weight limitations of an aerial platform in general impacts the type and number of sensors that can be included as payload. On the other hand, the performance level required to ensure the feasibility and quality of the inspection operations represent a tough challenge given the later premise. Therefore, as can be deducted from section 3.2, ARSI platform and sensor configuration, and possible future modifications to adapt the platform to other sewer network particularities, require of expert knowledge on platform operations and sensor configuration to provide a feasible solution. Eurecat is contributing with this knowledge in the framework of ARSI project.

5.2.1.3 Advanced navigation and inspection system

The advanced navigation solution makes use of the customized sensor configuration to provide high levels of autonomy so that the platform can self-resolve operators orders and facilitate navigation and inspection tasks in the sewers. As described in section 3.3, the navigation solution is represented by a combination of methods and software implementations which fuse different data sources to obtain a robust navigation functionality, all embedded into a powerful processing core. This module provides, on one hand, a set of pilot-centered flight modes which enables reliable operations under any of the circumstances expected during the sewer inspection tasks, and, on the other hand, it implements an autonomous inspection mode which automatically generates a combination of the previous flight modes which will be executed under the supervision of the operator as long as there is no unexpected events detected or human intervention.

5.2.1.4 Remote Station for the system operations

The ARSI Remote Station is a software package designed to facilitate platform operations and maximize efficiency during all the stages of the inspection tasks (planning, mission execution, data analysis and reporting). As described in section 3.6, the remote station is composed by a set of plugins and monitoring displays that provides full visibility and control of the platform operations and the necessary visualization tools to plan, analyze and report the collected data.

5.2.1.5 Customization for integration with existing software: DRACMA use case

DRACMA (Drainage Resource Administration and Cleaning Management) is a proprietary cloud-based platform owned by FCC used to plan inspections, to represent data on a GIS, to manage inspection resources and teams, to analyze data and to generate reports. In order to maximize end user uptake of ARSI project results, Eurecat has developed a plugin for the integration of the Remote Station inputs and outputs into DRACMA. This plugin takes into account ARSI platform information such as battery life, communication range, size limitations, etc. in order to plan inspection tasks and report and analyze ARSI collected data. While the Remote Station does not need any additional software to plan ARSI inspection or report data, the integration with existing end user platform significantly reduces market entry barriers, minimizes training needs and ease user acceptance. Therefore, it is expected that this service will be of high value in future commercial opportunities to integrate ARSI system with other existing platforms.

5.2.1.6 ARSI sewer inspection system

Finally, the integrated combination of the previous results into a unique and innovative system represents the main commercial result of ARSI project, the ARSI inspection system.

5.2.2 IP Rights Management

According to the results described above and the involvement of each participant in the design activities carried out during Phase I, but also during the envisaged involvement in Phases II and III, the agreed IPR framework for the protection and exploitation of the project results is detailed in the table below:

#	Project results	IPR protection	Owners & Involved partners
1	Quadrotor platform inspection system for sewer networks	Patent	SD, EUT
2	Advanced navigation system for confined environments (Software)	Copyright	EUT
3	Structural inspection and sewer monitoring system (Software)	Copyright (under discussion)	EUT, IBAK
4	Remote station for platform operations and data analysis	Copyright	EUT
5	Customized integration with existing information managements software (DRACMA use case)	Copyright (under discussion)	EUT, FCC
6	ARSI sewer inspection system	Patent	IBAK, FCC, SD, EUT

In order to properly assess the patent options of the identified results, a thorough patentability study, updating and complementing the analysis made at the proposal stage, should be made during the early stages of Phase II, when the design is approved, to define specific IP protections strategies for the results.

5.2.2.1 Clarification of DRACMA Background use within and after the project

As described in *Attachment 1 - Background IPR included* of the Consortium Agreement (CA), DRACMA is an FCC's Background asset to which access rights are granted during the project with no limitations or conditions for implementation and on a royalty-free basis. On the other hand, as indicated in the CA, the access to this background beyond the project during the exploitation phase could be provided by FCC, if required, under fair and reasonable conditions still to be determined.

As indicated in section 5.2.1.5, the customization of the system to DRACMA it is recognized by the consortium to bring great market value to the project as a professional tool developed by an inspection company such as FCC, facilitating market uptake and reducing entry barriers. However, DRACMA is not a background needed for the use of ARSI project results as the remote station provides the required operational and reporting functionalities on a standalone basis. Therefore, regarding the future exploitation of the system, the remote station could be adapted to other existing information management systems when required by the end user, as it was done for DRACMA, on a contract basis.

5.3 Business model and exploitation plan

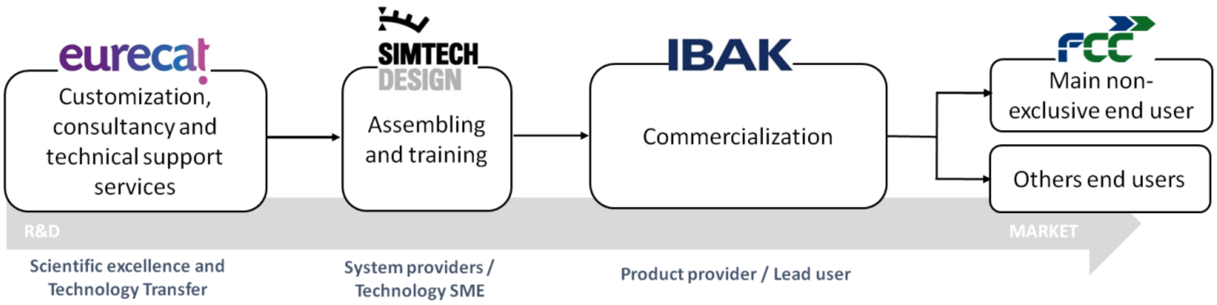
Additionally to an excellent set of technical results, a clear route to market strategy is needed to hit the market. Therefore, ARSI members have defined a clear value chain that sets the commercial client-provider relationships among the consortium in order to define an appropriate business model to satisfy early market demands. While this value chain is based on the current exploitation interests expressed by the partners (see table below), it is recognized that it may change along the first years of the commercialization based on market needs, industrialization requirements, changes on exploitation interests or the entry of new actors.

The business model will be based on the following exploitation interests indicated by the partners:

Partner	Exploitation interest
SIMTECH	Design and manufacturing of platforms, training and technical consultancy.
Eurecat	Technology transfer (licensing, etc.), technical consultancy and customization services.
IBAK	Commercialization of innovative sewer inspection systems.
FCC	Early access on innovative products on advantageous economic conditions.

5.3.1 Value chain

Based on the expressed exploitation interest and the discussions during the ECHORD++ PDTI Phase I - Solution Design, the consortium defined the following value chain:



5.3.2 Business model and Exploitation plan

According to the defined ARSI exploitable results, the agreed IPR distribution and value chain, the following products and services are defined by partner:

EURECAT			
# - Product/Service	***Origin***	***Commercialization***	***Revenues from***
1 - Advanced navigation and inspection system and Remote Station integrated in ARSI inspection system	Results #2,#3, #4	Price per unit sold (License)	SIMTECH (IBAK sales)

2 - Technical support to platform manufacturing and validation	Results #1 and Background	Price per hour	SIMTECH
3 - Upgrades of ARSI inspection system (navigation and inspection system and remote station)	Results #2, #3, #4 and Background	Price per unit sold (License)	SIMTECH (IBAK sales)

SIMTECH			
# - Product/Service	Origin	Pricing method	Revenues from
4 - ARSI sewer inspection system and technical support (helpdesk, training)	Result #5 and Background	Price per unit sold	IBAK

IBAK			
Product/Service	Origin	Pricing method	Revenues from
5 - ARSI sewer inspection system and technical support	Results #5	Price per unit sold	FCC and other end users

FCC			
Product/Service	Origin	Pricing method	Revenues from
9 - Use of ARSI inspection system in their inspection service contracts*	Result #5	Price per service	Public Entity

(*) By using ARSI sewer inspection system, FCC (and other service companies, end users) will be able to significantly reduce the cost of the inspection service (see section 5.4.5), hence, obtaining higher profit per service offered.

5.4 Economic viability for every institution involved

Based on the products and services and the business model defined in the previous section, we describe and quantify the commercial opportunity for each institution involved that makes the ARSI project an economically viable market opportunity.

Assumptions, commercial estimations and other market considerations are indicated, where applicable, based on the market knowledge and expertise of every partners.

5.4.1 Sales forecast

As described in the market overview (section 5.1) by different market studies, sales in the sector of professional robotics, and specifically inspection and maintenance robots, are expected to growth double digit in the following years. The International Federation of Robotics (IFR) prudently estimates that 4.000 units will be sold by 2018.

On the other hand, a commercial prototype of the ARSI inspection system is expected to reach TRL7 (maybe up to TRL8) by mid-2018. Then, it is estimated that a time-to-market of approximately 6 months will be needed for product certification and achieving a ready-to-sell product. Therefore, by 2019 ARSI inspection system may hit the market.

Therefore, based on the market reports estimations, the commercialization experience of IBAK and the current sales of IBAK's robots, the following sales prospects where estimated during the first 5 years of commercialization, from 2019 to 2023:

	2019	2020	2021	2022	2023
Units	30	45	65	90	120

Based on this estimation, the following sections present the economic viability of ARSI project by institution involved according to the value chain defined (from left to right).

5.4.2 For the Research Institute - EURECAT

EURECAT will have benefits from the exploitation of the following products and services:

- (Result #1) Navigation and inspection system sold to SimTech Design for platform manufacturing at an estimated price per unit of 1.750€. The total profit will indirectly depends on the ARSI system units sold by IBAK.
- (Result #4) ARSI Remote Station sold to SimTech Design for platform operations at an estimated price of 2.500€. The total profit will indirectly depends on the ARSI system units sold by IBAK.
- Technical support for manufacturing and validation to SimTech Design. At least during the first five years it is expected that Eurecat will contribute with its expertise on platform development for the product manufacturing and validation. The estimated price of this service is of 1.200€ per ARSI unit produced.
- Navigation and inspection system upgrades. It is expected that as of the third year of exploitation, upgrades of the navigation and inspection system will be released by Eurecat based on the customers feedback. It will be sold as a license of a new software to SimTech Design and the estimated price of the upgrades is of 300€ per unit sold.

The following table present the estimated economic prospects for Eurecat:

Figures in €	Year 1	Year 2	Year 3	Year 4	Year 5
Revenues	163.500	245.250	375.250	525.000	706.500
- R#1 - ARSI inspection system (navigation and inspection system and remote station)	127.500	191.250	276.250	382.500	510.000
- R#2 - Technical support to platform manufacturing and validation	36.000	54.000	78.000	108.000	144.000
- Upgrades of ARSI inspection system	0	0	21.000	34.500	52.500
Cost of goods	-57.225	-85.838 €	-131.338	-183.750	-247.275
Gross margin	269.775	404.662	619.162	866.250	1.165.725
Operating costs	-67.444	-101.166	-154.791	-216.563	-291.431
Net income	202.331	303.497	464.372	649.688	874.294
Accumulated income	202.331	505.828	970.200	1.619.887	2.494.181

The estimations shows that ARSI could potentially represent a business of an accumulated 2.5M€ profit for Eurecat in 5 years time after the end of the project

5.4.3 Economic viability for the SME - SimTech Design

The following table presents a cost breakdown of the aerial robot and platform. The breakdown includes materials, manpower and maintenance costs as well as the cost for the products and services provided by Eurecat:

Materials costs	
Platform costs	**1.220 €**
Frame (arms, plates, landing gear and protection)	200 €
Motors	250 €
Propellers	10 €
ESCs	160 €
Battery	100 €
Navigation and inspection system (provided by Eurecat)	1750 €
Electronics (converters, LEDs, power distribution board)	150 €
Payload costs	**6.067 €**
Onboard PC	125 €
Laser	3.000 €
LEDs	100 €
4 Cameras	2.627 €
Other sensors	100 €
Wi-Fi adapter	35 €
Air monitoring system	80 €
Support equipment costs	**3.200 €**
Remote station (provided by Eurecat)	2.500 €
Router	300 €
RC	400 €
Man power* costs (40 hours x 20€/hour)*	**800€**
Maintenance costs	**1.169€**
ARSI system validation (20 hours x 60€/hour)	**1200**
TOTAL COSTS	**13.656 €**

* It is estimated that assembling a robot manually will take 40 hours. The estimated cost per hour cost is of 30€/hour.

Based on a preliminary product benchmark and the know-how and the market expertise of the consortium, it is considered that a price of 18.500€ for the acquisition of ARSI inspection system by IBAK would make a competitive business opportunity and increase its economic viability for all the actors in the value chain.

In the following table the forecast sales of SimTech Design are offered:

SD	2019	2020	2021	2022	2023
Revenue	555.000	832.500	1.202.500	1.665.000	2.220.000
Cost of goods	-409.680	-614.520	-887.640	-1.229.040	-1.638.720
Gross margin	145.320	217.980	314.860	435.960	581.280
Operating costs	-87.192	-130.788	-188.916	-261.576	-348.768

Net income	58.128	87.192	125.944	174.384	232.512
Accumulated incomes	58.128	145.320	271.264	445.648	678.160

The estimations shows that ARSI could potentially represent a business of an accumulated 678.000€ profit for SimTech Design in 5 years time after the end of the project

5.4.4 For the Large Industry - IBAK

IBAK estimates for the solution to be competitive it could be offered at a 50% margin over cost, which results in a market selling price of 27.750€. The following table shows the sales forecast of ARSI inspection system for IBAK. The operating costs include mainly the commercialization costs, marketing costs and salaries.

IBAK	2019	2020	2021	2022	2023
Revenue	832.500	1.248.750	1.803.750	2.497.500	3.330.000
Cost of goods	-555.000	-832.500	-1.202.500	-1.665.000	-2.220.000
Gross margin	277.500	416.250	601.250	832.500	1.110.000
Operating costs	-99.900	-149.850	-216.450	-299.700	-399.600
Net income	177.600	266.400	384.800	532.800	710.400
Accumulated incomes	177.600	444.000	828.800	1.361.600	2.072.000
ROI	0,2	0,5	1,0	1,7	2,5

According to the estimations, IBACK could its breakeven point on 2021 and have its own Return of Investment (ROI) already in the third of exploitation. The estimations shows that ARSI could potentially represent a business of an accumulated 2M€profit for IBAK in 5 years time after the end of the project

5.4.5 For the Service Company - Fomento de Construcciones y Contratas (FCC)

The economic benefits obtained by FCC will not come directly from the sales of ARSI inspection system (as FCC is the target client), but from the potential cost reduction in their inspection service contracts thanks to the use of ARSI. Then, this section presents a comparison of the service cost reduction that FCC could obtain by using ARSI. The table below shows the inspection cost per inspection brigade comparing the current set up with the use of ARSI.

Considerations: For safety reasons the inspection brigades of the accessible galleries are composed always for a minimum of 4 operators. Operators will always work in pairs, either outside of the sewers placed in each sewer access (entrance and exit) and within the sewer galleries. According to FCC, it is expected that ARSI system will replace the operators inside the sewer and therefore two operators will be enough to perform inspection missions.

Reductions in costs with the proposed ARSI Concept of Operations are highlighted in the table below.

Current inspection brigade costs (€)			
Description	**Units**	**Unit cost**	**Total Cost**
Staff	4	36.312,64	145.250,58
IVECO Daily Van*	1	19.840,77	19.840,77

Brigade inspection costs using ARSI (€)			
Description	**Units**	**Unit cost**	**Total Cost**
Staff	**2**	36.312,64	**72.625,29**
IVECO Daily Van*	1	19.840,77	19.840,77

Auxiliary Material	1	3.047,60	3.047,60
Necessary Material	1	9.362,24	9.362,24
Fuel	1	500,00	500,00
TOTAL			**178.001,19**

Auxiliary Material	1	3.047,60	3.047,60
Necessary Material	1	9.362,24	9.362,24
Fuel	1	500,00	500,00
ARSI solution	**1**	11.800	**13.656,00**
TOTAL			**119.031,90**

This represents cost reduction per brigade of 43,2%

**According to FCC: The vehicle and the materials costs are amortized along the service. An amortization of 9 years was considered for the vehicle.*

Additionally to this cost reduction, that will increase the profit margin of FCC in their inspection service contracts, market advantages will be discussed and negotiated with FCC so that the company is acknowledged as the end user leading to the introduction of this product to the market.

5.4.6 For the Public Entity – BCASA

According to the Challenge Brief *Urban Robotics document version 29.12.2014* released by the Public Entity, Barcelona Cicle de l'Aigua SA (BCASA), describing the challenges to address in the PDTI, there are currently 4 brigades operating for the inspection of the sewer network. Then, taking into account the cost analysis performed from FCC information (previous section) the cost of 4 brigades using current inspection methods compared to the use of ARSI is as follows:

	Total cost per 1 brigade	Total cost per 4 brigades
Current Inspection methods	178.001,19 €	712.004,76 €
Inspection using ARSI	119.031,90 €	476.127,60 €

Taking into account the labour days (214 working days) and journey duration (8 hours), which gives a total of 1,712 hours/year the cost per hour of an inspection brigade is:

	Cost/ per hour
Current Inspection methods	103,97€/h
Inspection using ARSI	69,53 €/h

NOTE: *The information used to obtain this calculations is the real data provided by the Service Company and it may slightly differ from the information presented by BCASA in its documentation, namely, Challenge Brief Urban Robotics document version 29.12.2014. More specifically the differences are highlighted in here:*

	BCASA document	*Obtained thanks to the service company*
Cost per hour per brigade	110€/h	753.280 €/year
Total cost per 4 brigades	103€/h	712.004,76 €/year

Taking into account that the sewer inspection cost in Barcelona, as reported by BCASA, is about 1 million € (12,5% of total cost of sewer management), **the public entity will be able to reduce almost 440.000€ cost per year in sewer inspection by using ARSI system**.

5.4.6.1 Analysis of the productivity (meter a day)

Taking into account the battery life limitation of current aerial platforms and, hence, of ARSI system, the consortium offers here an analysis of the productivity expected by the ARSI system compared to current methods.

Considerations: One inspection mission will last an hour on average. Also it is considered an effective inspection time of 6 hours per day. Therefore, the brigades are able to carry out 6 missions/day on average.

The aerial robot have an autonomy of 10 minutes as reported in section 3 – Solution design. As described in section 4.3.2, in this 10 minutes of mission brigades are expected to inspect a minimum of 300 meters (at a minimum flight speed of 0,5m/s) and a current maximum of 600 meters (at 1m/s flight speed). Therefore:

USING ARSI SYSTEM			
Pessimistic scenario		**Optimistic scenario**	
Aerial robot speed 0,5m/s -> **300 meters inspected per hour**	6 missions/day	Aerial robot speed 1m/s -> **600 meters inspected per hour**	6 missions/day
Total meters inspected/day	6 missions/day * 300 meters = **1800 meters/day**	Total meters inspected/day	6 missions/day * 600 meters = **3600 meters/day**

Based on the experience of the FCC, current brigades inspect a total of 2000 meters/day (333 m/hour), therefore the use of ARSI system would increase and in any case, maintain, the current productivity but a lower cost.

5.4.7 Cost per meter comparison

Taking into account the total cost presented (4 brigades), the following table provides a comparison of the cost per meter of sewer serviceability inspection considering 1.000.000 meters.

Inspection cost per meter of sewer serviceability inspection (considering 1.000.000 of meters)		
Method	***Total cost***	***Cost per meter***
Current inspection methods	712.005,76 €	**0.712 €/meter**
Inspection using ARSI	476.127.60	**0.471 €/meter**

Total cost per meter using ARSI system will be around 0.471 €/m, below of the targeted threshold of 0,50 €/m

6 Project management report

The Phase I of ECHORD++ Urban PDTI refers to the *System Design*. In this first 6 months of the project three R&D consortia, including ARSI, were working on their solutions towards the design concept (TRL4). Based on the evaluation criteria for this phase, only two consortia will be selected to continue to the next phases: phase II *Prototyping* (12 months, TRL6) and phase III *Small scale test series* (12 months, TRL7-8).

Phase I of ARSI consisted on two tasks, both contributing to this deliverable:

- Task 1 *Infrastructure description and operation conditions* was led and executed by FCC. FCC holds and extensive experience in sewer inspection and, in particular, they currently operate in the sewer of Barcelona city. This task focused on the analysis of their current inspection procedures for the definition of the set of minimum technical and operational requirements for drone-based inspections. This was later complemented by the definition of the concept of operation and logistic aspects described in section 4.
- Task 2 *Conceptual design of the inspection robotics equipment* involved all partners and was led by SimTech Design. The activities within this task led to the elaboration of the system design and the implementation of the first system prototype, including a highly capable multirotor platform (see section 3.1) that has been equipped with all the sensors described in section 3.2, and some software development to demonstrate the feasibility of the concept.

Likewise, two deliverables were due during this period:

- D2.1 ARSI operations requirements and system design (this document)
- D2.2 Towards automatic sewer inspection: first results, submitted separately.

There was one single milestone within this phase which is reviewed in the next section.

6.1 Review of Milestone I – Month 06

This milestone was foreseen for month 6 in the ARSI work plan, at the end of phase I, connected to the major objectives of this phase:

- analysis of feasibility of ARSI concept of operation and system design,
- demonstration of critical technological features and review of risk analysis
- study of the economic viability of the solution
- review of the work plan for the upcoming phases

Acceptance of the deliverables D2.1 and D2.2 shall be interpreted as an achievement of milestone I, together with a satisfactory performance during the upcoming PDTI official tests. The next subsections will provide further details on each of the objectives for this milestone.

6.1.1 Concept of operations and full design

The elaboration of the system design and concept of operation described in this document has followed an iterative approach, involving all four ARSI partners. Each single step and technical assumption was validated with the representatives of the ECHORD++ PDTI Urban challenge and BCASA. Thanks to their feedback and directions, some of the original ideas were adapted or reoriented to better fit the current needs of sewer network inspections. The soundness of the current solution design was, therefore, verified during the analysis thanks to this cooperation, and secondly validated in the field with the set of tests described in D2.2.

6.1.2 Demonstration of key features and updated risk analysis

The core functionality of ARSI has been well covered in D2.1, and initial results are described in D2.2. This preliminary experiments helped the consortium in their risk management. The risk analysis submitted at the proposal time has been reviewed accordingly (see Table 10 below). At this stage, there is not a critical risk that could prevent from a correct development of the final solution.

Table 10: Updated risk analysis corresponding to Milestone 1

Risk	Task	Probability	Recommended mitigation action
Reduced MAV endurance	T3	~~Medium~~ Low	A significant part of the efforts spent in this phase has been devoted to optimize the platform endurance. According to our design and the initial tests, the inherent reduced flight time of a MAV does not impose a significant risk for the success of the project and its impact. Therefore, this risk is reduced to low.
Low quality visual data due to light conditions	T3, T4, T6	~~High~~ Medium	Likewise, a significant part of the efforts spent in this phase has been devoted to integrated and validate artificial illumination, without impacting the endurance. The initial datasets are promising, however, automatic detection is still a challenge for the project and therefore, the risk level is only reduced to medium.
Environment Hazards	T3, T4	Medium	The consortium has already address the problem of humidity by implementing a water protection to all electronic components of the system. However, the risk remains an important challenge to be considered.
Insufficient onboard computer resources		Medium	A Single board computer (SBC) provides reasonable computing resources. All algorithms proposed in the design have been carefully evaluated taking computational needs in mind, however, this risk will remain active until the final implementation of the algorithms is validated.
Underground wind gusts		Low	As described in D2.2, the team has carried out intensive series of tests on different sewers in the city of Barcelona. Underground wind gusts have not been an issue if we compare to the inherent turbulences created by wall and ground effects. Therefore, this risk remains low.
Debris vs. crack discrimination	T6	High	This risk remains active until further advances of the project.
Availability of training reference image	T6	~~Medium~~ Low	Thanks to the easy access to the sewer, the consortium has already gathered an immense amount of data for training of the algorithms. Therefore, this risk is reduced to low.
Poor market interest	T7	Low	According to the preliminary reactions to our dissemination activities, there will be a considerable market interest. The consortium has already received expression of interest of other cities and institutions.

6.1.3 Study of the economic viability of the solution

The thoroughly economic feasibility analysis and business plan developed in this deliverable proves the economic viability of the proposed solution. In particular, the interest and potential shown by the industrial partners ensure the future exploitability of the ARSI solution.

6.1.4 Detailed timeline for Phase II and Phase III

Given the progress described in this document, a thoroughly review of the work plan for the next two phases has been done, concluding that the original work plan is still valid and does not require modifications.

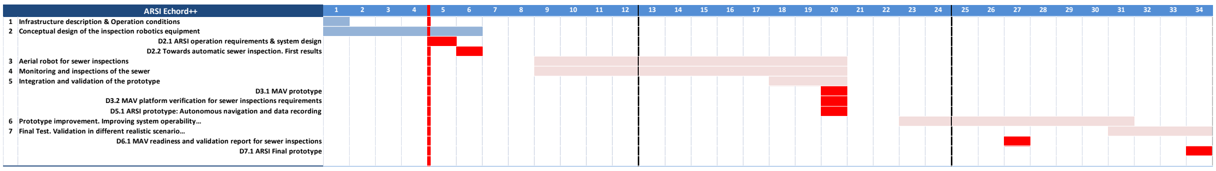


Figure 52: Timeline for Phase II and Phase III

7 Dissemination activities

The ARSI consortium has been active disseminating the potential applications of drones for the inspection and monitoring of sewer systems.

The following table summarizes the dissemination activities performed in Phase I:

Date	Event/Action	Notes
18th Nov 2015	Brokerage	ARSI Echord++ project presented as part of the capacities and project portfolio of Eurecat in the Brokerage Day organized by the SPARC PPP in Brussels
19 Nov 2015	Conference	Dedicated presentation of ARSI ECHORD++ project at FCC stand in Smart Cities Expo 2015
19 Nov 2015	Conference	Presented ARSI ECHORD++ as an innovative application of robotics technologies in urban applications at Catalonia Smart Drones Conference
7 Dec 2015	Newspaper article	Dedicated article about ARSI in Spanish national newspaper El País (the first general information newspaper in Spain with around 1,5M daily readers), including a video of one of our tests in Barcelona sewers.
7 Dec 2015	Newspaper article	Article in international newspaper TheLocal.com about ARSI
23-24 Sept 2015	Seminar and Workshop	The ARSI Echord++ project was presented in a poster and a presentation as part of the technical capacities and portfolio of Eurecat. There were 104 attendees, including 22 different nationalities and 59 companies and knowledge centres representing 16 different countries. SPRINT Robotics seminar and Inspection Robotics euRobotics Topic Group meeting (The Netherlands)
26 May 2016	Workshop	Presented ARSI ECHORD++ at the workshop about the Current situation and future perspectives for drones application in enterprises, organized by the Catalan Foment del Treball
16 June 2016	Conference	Presented ARSI ECHORD++ at the Vibot Day 2016

The following table describes two upcoming activities:

Date	Event/Action	Notes
7 July 2016	Workshop	Dedicated presentation of ARSI ECHORD++ project at the Workshop Robotics for Inspection and Maintenance (ROBIM) organized by Robotics and Mechatronics Spanish Robotics Network (REDROM) and Spanish Society for Research and Development on Robotics (SEIDROB)
8 September 2016	Conference	The ARSI consortium is in contact with the European project ROBO-SPECT. ROBO-SPECT focuses on tunnel inspection and both projects are targeting autonomous detection of structural defects. There is an initial agreement between Eurecat and Institute of Communication & Computer Systems (ICCS) to co-organize a workshop on Robotics and Transportation tunnels' structural inspection and assessment on the 8th September 2016.

At this stage, the remaining actions on the original ARSI dissemination plan remain valid for phases II and III when, with more results and time, we will be targeting scientific journals, high-impact conferences and other type of events and exhibitions. The ARSI consortium as a whole agreed that these type of actions were more suited for the upcoming phases.

Among the potential activities to participate during phases II and III is the next European Robotics Forum. In the last ERFs (Vienna 2014, Ljubljana 2015) the programme included an Inspection and Maintenance session promoted by ALSTOM and FADA-CATEC. The consortium will propose this institutions the inclusion of an ARSI project presentation in a potential I&M session for the next ERF in Edinburgh on 22-24 March.

ARSI consortium has been approached by the responsible of the sewer network inspection in the city of Montréal (Québec), through Eng. George del Rio, from the Water Management Services of the Sewage Water Purification department of the city. Eng. Del Rio expressed interest on the aerial solution developed in ARSI, both on the technical aspects and future possibilities for the integration on their daily procedures. Given the current stage of the project, and under the current context of the PDTI phase I, we could not formalized a written expression of interest and support, but it definitely shows the potentials for the exploitation of the solution worldwide.

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9 Annex B: Safety equipment for inspection personnel

Tooling	ARSI Team
Shovel/hoe	3
Pliers	1
Basket 18 l	1
Toolbox	1
Measuring tape 50 meters	1
Plastic basket	1
Wrench	1
Hydrant key	1
Allen wrench (keyset)	1
Stepped ratchet radiator (keyset)	1
Chisel	1
Flexometer 5 meters	1
Fluorescein	100 gr
Rubber bucket	1
Hook	1
Hook to open small manholes	1
Mallet	1
Sledge	1
Hammer	1
Palette	1
Paper hand towel (roll)	1
Wrecking bar	1
Pickaxe	1
Mining pickaxe	1
Water hydrant tap	1
Hacksaw	1
Screwdriver (set)	1
(Fluorescent) worksite marker	1Me
Handsaw	1

Protection equipment	ARSI Team
Anorak	1
High-visibility vest	1
Safety harness	1
Chemical oxygen generator	3
Security high boots	1
Single-use bus ticket	1
Summer protective footwear	1
Winter protective footwear	1

Protective helmet	1
Cap	1
Safety gloves	1
PVC gloves	1
Raincoat	1
Helmet light	1
Socks	2
Carabiner	1
Summer trousers	2
Winter trousers	2
Puffy jacket	2
Polo	2
Soap	1
T-shirt	2
Summer towel	1
Winter towel	1

Collective Protection Equipment	ARSI Team
Gas detector	1
Aluminum ladder 3-6 meters	1
Fire extinguisher 3 kg	1
First aid kit	1
Water well cover	1
Retractable tape measure 6 meters	1
Retractable tape measure 12 meters	1
Winch for tripod	1
Tripod	1

Signaling equipment	ARSI Team
Flashing beacon	3
Cones 500 mm	10
Disc with directional arrow	1
Parking prohibition sign	1
Rotating Warning Light	1
Foldable fence for fall prevention	2
’Road narrowing’ triangle sign	1
’Men at work’ triangle sign	1
Tripod sign stands	4