siar **s**ewer **i**nspection **a**utonomous **r**obot

D28.4 – Operation Procedure and Sewer Inspection Service. Improvements in Cost/Benefit.

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ECHORD

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1. Introduction

Phase I SIAR prototype, developed by the Consortium, has being used to test the different solutions in the real sewer environment. These field tests allowed to define preliminary operational procedures for the deployment of the system and robotic inspection of the environment.

This report presents these preliminary operational procedures and how to run a sewer inspection service with the SIAR robot. They are based on the experiments performed with Phase I robot prototype during Phases I and II, and they should be updated in the light of the experiments with the new prototype.

This report presents also some preliminary figures regarding the improvement in cost/benefits of using the SIAR solution.

2. Operational Procedure

This section describes the procedure to operate the robot in the sewers. Starts with the description of the procedures for charging the batteries and ends with the description of the required equipment for a mission.

2.1. Battery Management

2.1.1. Robot Batteries

The SIAR robot uses two 12V 20Ah LiFePO4 batteries to power all the systems of the robot. Before the mission the operator needs to fully charge the robot batteries. The system uses an external charger able to charge both batteries in parallel while powering the robot electronics (Figure 2.1). This feature is particularly useful to preserve the batteries while the operator is uploading the mission setup and retrieving the mission log files. A full charge of the robot will take 8 hours using a 5A LifePO4 charger. When full charged the robot will have a minimum power autonomy of 4 hours of continuous operation.

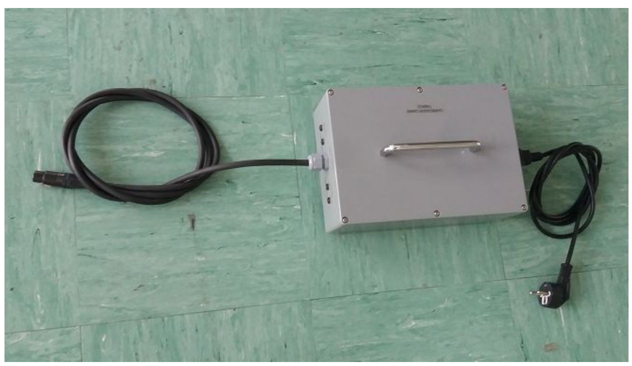

Figure 2.1. Robot charger.

<u>Battery Swapping</u>

A spare set of battery will be available. These batteries will provide, in case of need, minimum of 4 extra working hours. The operator should use the charger to charge these batteries and in case of need swap these batteries with the ones on the robot. This procedure should be made out of the sewer galleries, to prevent dirt contamination of the connectors and components.

2.1.2. Wireless Repeaters Batteries

The system includes deployable wireless repeaters to increase the communications range between the robot and the external control console. The wireless repeaters are insulated elements with their own battery (11.1V 1450mA LiPo battery). The wireless repeater has a minimum power autonomy of 2.5 hours of continuous operation. The battery can be charged with a LiPo charger in less than 2 hours (see Figure 2.2).

Figure 2.2. Repeaters battery charger.

In the current version the operator will need to open the repeaters boxes and plug the batteries to the charger. In the future the boxes will have a power connector where the charger will connect and charge the batteries without the need to unmount the wireless repeaters boxes.

2.2. Required Equipment

When preparing a mission the following equipment should be included:

SIAR Robot - inspection robot with all its components, i.e. charged batteries, cameras, robotic arm, etc;

Remote Control Station - fully charged with spare batteries and external power supply;

Transportation Van - to transport the robot and control station;

Electric winch - to lower the robot into the sewer;

Spare batteries - expected power autonomy is of 4h (minimum) which should be enough for a working day. Nevertheless a spare power pack should be included to increase the operation time in case of need;

Batteries charger - To charge the batteries and/or externally power the robot (while setting up operation).

Wifi repeaters - To increase the communication range (they will be transported by the robot);

F710 controller from Logitech - To drive the robot in teleoperated or assisted teleoperated modes;

Personal protection garment - adequate garment to enter inside the sewer and to manipulate the robot: gloves to manipulate the robot while is being deployed/retrieved to/from the sewer; helmet to be used by the operator in the sewer; long insulated rubber boots to use inside the sewer; and finally mouth and eyes protection masks and glasses.

Water and cleaning material - To remove the accumulated dirt from the robot.

2.3. Sewer Inspection Procedure

The sewer inspection procedure describes the steps required to perform an inspection mission. The system starts with the mission preparation as described in Section 2.3.1, where an area is selected for inspection. This is an offline work to be performed before performing the inspection in the sewer.

Once the mission is analyzed, the system is ready to use in the sewer. The Control Center must be deployed near a manhole and the wireless repeaters might be deployed depending on the needs. Section 2.3.2 describes the manual *vs* robot deployment of the wireless repeaters. Once the system is ready, the operators need to insert the SIAR robot inside the sewer. The robot deployment is described in Section 2.3.3.

Already in the sewer, the robot should be turned ON and wirelessly connected to the Control Center to start the mission (see Section 2.3.4). The mission will run in autonomous mode, but the operator will always have the option to take control of the robot for driving and performing inspections of the sewer area. The robot will continuously send telemetry information to the Control Center during the mission: the robot location, robot autonomy, velocity, inclination and also detected anomalies on the sewer structure (see Section 2.3.5).

After the conclusion of the inspection mission the robot should be retrieved from the sewer in the same insertion point, so that the operator does not need to move from one position to another. The operator can then easily extract the collected mission information to an external HDD. This information can be accessed by the operator and used to identify further issues on the sewer galleries.

2.3.1. Mission Preparation

One or more areas to be inspected are given to the operator. The operator must create an inspection plan for the operation day. This inspection plan must take in account the inspection capabilities of the robot, the distance to travel, the Points of Interest (POIs) to inspect, the terrain, the communications and required logistics.

The plan is then divided in missions, one mission for each defined inspection area. The operator creates a mission inspection plan for each mission using the Plan Editor of the Control Center. In this window, the operator can select the area to be inspected, select the manhole where the robot will be deployed and define the POIs that the robot should visit. Figure 2.3 shows a proof of concept of the Plan Editor window that will be present in the Control Center.

PoI ID	Type	Latitude	Longitude	Observations
0	Manhole	41.38515	2.184226	Deployment point
1	Manhole	41.385339	2.184484	
17	Fork (S)	41.38551107	2.184730101	Maintain direction
21	Fork	41.385864	2.185167557	
2	Manhole	41.385739	2.185026	

Plan Editor / Repeater Disposition

Figure 2.3. Plan Editor of the Control Center. The inspection plan is represented in a blue line. The repeaters to be deployed are represented in a black box with a gray gripper.

The operator will also be able to define the location of the repeaters that should be placed in the sewers to ensure a communication link between the robot and the base station at any moment. When a repeater is placed, an approximate map of RSSI levels (Received Signal Strength Indicator levels) in the neighboring areas is calculated and represented. In this way the operator is able to determine the number of repeaters that should be used in the mission and its approximate location.

2.3.2. Manual *vs.* Robot deployment of the wireless repeaters

In the experiments carried out up to date, the deployment of the repeaters at the experimental areas for communication between the robot and the base station has always been made manually. For example, in the experiments made in May 23th, 2017, the base station was placed at the van, outside the sewers, and it was able to communicate with the robot inside the sewer at a distance of more than 200 m, with the aid of two repeaters (see Figure 2.4) placed in the commercial street intersections with Fusina and Ribera streets. The operator was able to tele-operate the robot in the assisted teleoperation mode while receiving real-time images of the cameras onboard the robot.

Figure 2.4. Disposal of the robot, base station (laptop) and repeaters (black boxes with grippers) in the furthest location reached in the experiment of the 23th of May, 2017.

In Phase III the deployment of such repeaters should be made automatically by the robot with the help of an onboard manipulator. However, we are also considering the manual deployment of the repeaters to establish a temporary communication infrastructure. The procedure will go through the fixation of the repeater to a manhole with a rope of such length that allows the robot to pass below it. In this case, before the start of the mission, an operator should go to the selected manholes and drop a repeater inside while the other operator configures the platform in the manhole where the base station is placed. Note that the operator is not required to get inside the sewers for deploying the communication systems and therefore only one operator can handle such task.

Table 1 summarizes the advantages and drawbacks of each deployment. This is a preliminary list to be updated with experimental data from the experiments scheduled for July 11th, 2017.

	Automatic repeater deploy	Manual repeater deploy
Potential Benefits	• The deployment of the repeaters can be made without prior planification • The operator workload decreases	• The manipulator is no longer needed • The repeaters can be equipped with batteries with more capacity • The deployment is safer
Potential Costs	• A manipulator is necessary to perform a mission • The repeater battery has to be sized according to the arm • Less repeater autonomy • Potential risks of bad positioning of the repeater and/or repeater fall to the main gutter • After completing the mission, the robot must go back and collect all repeaters	• The deployment of the repeaters must be planned prior to the execution of the mission • The repeaters cannot be located exactly in the junction of two crossing gutters • More repeaters are likely to be needed • Need to open more manholes before and after the mission. In some cases in streets with road traffic

Table 1. Comparison between automatic and manual deployment of the sensors.

2.3.3. Deploying the robot in the sewer

The requirements of the solution, in terms of mobility, power and inspection capabilities have taken the SIAR robot design to a total weight that surpasses 25 Kg. Regarding operational concerns, a tripod and an electric winch is considered as part of the system. This solution allows the deployment of the robot through the manholes. The actual system uses a electric winch installed on the operator's van.

Phase I robot prototype was too high to enter the manhole so it had to be divided in two, to be able to enter inside a standard manhole (Figure 2.5). The payload box was removed from the main frame. This was accomplished by disconnecting the motor and battery cables and removing the four screws that fixes the payload box to the main frame robotic platform. The payload box was then descended into the sewer gallery by hand or using the electric winch. Then the winch was connected to a heavy weight rope that was installed on the robotic platform. The robot was then descended into the sewer and a second operator had to mount the payload box and connect the cables and batteries. This operation requires two or more operators.

Figure 2.5. Deployment of the Phase I SIAR prototype.

The mechanical design of the phase II system takes into consideration the standard dimensions of the manholes, as well the isolation to the environmental conditions (IP67). This will allow to pass the manhole without the need to split the robot. This operation will need to be coordinated by two workers, one that will operate the winch and align the robot wheels with the manhole stairs and a second worker placed inside the sewer that will help the robot to be deployed inside the sewer gallery. This worker will also be the responsible to install the deployable repeaters on the robot. With the new design the deployment will be simpler and faster.

Additionally, the operator has to deploy the communication device of the base station, which can be placed on the floor or can easily be fixed to one step of the manhole. Note that a long RJ-45 cable can also be deployed for connecting the base station with the aforementioned communication device. Even though this cable is convenient to maximize the throughput of the communication link, it is not mandatory. A wireless configuration is possible at the expense of reducing the bandwidth.

2.3.4. Running the mission

Once the robot is deployed inside the sewer, at the base station, the software can be started from a Linux-based system via the launch menu or by double-clicking its icon in the desktop. The base station will try automatically to connect with the robotic platform and will display information about the platform, including the remaining battery level and the status of the radio links.

While the robot is connected to the base station, the platform can be controlled in different operation modes: autonomous, assisted teleoperation and pure teleoperation. These operation modes are described as follows.

Autonomous mode

The operator will be able to command an entire work plan for the whole operating day given as a sequence of POIs to be visited by the robot platform. This plan will be designed with the aid of a graphical editor. Therefore, this operating mode will further reduce the operator's workload required for navigation, allowing him to focus in his inspection duties. Moreover, it would be crucial in the case where the communication is lost. In this way, the platform can safely perform an automatic return home procedure.

Once the robot is deployed and the plan is loaded at the control station, the robot will begin to automatically move through the sewers as soon as the start button is pressed. The operator can pause the mission at his will, any time during the mission. Thus, he can tele-operate the robot to gather more information in the desired areas.

Assisted teleoperation mode

In this mode, the robot can be operated with the aid of a remote controller. Whenever this method is active, the robot automatically navigate through the center of the sewer, avoiding falling into the gutter, while the operator is able to adjust the velocity of the inspection. This mode has already been tested in the sewers operating the robot from the outside at speeds of up to 0.5 m/s in straight zones and 0.2 m/s in curves. These speeds are far beyond the expected exploration speed defined in D28.1 (0.2 m/s). These tests only included assisted teleoperation in sections without forks, as the automatic mode in these areas is still under development. Please refer to D28.5 for details on the methods used in the assisted teleoperation mode.

Whenever a fork has to be crossed the robot should traverse the gutter and thus the automatic centering mode fails to negotiate it (see Figure 2.6). In these cases, the operator should select the desired direction by using the fork direction button. When the desired direction is pressed, then the robot will plan its trajectory accordingly and will start the fork negotiation. The robot will go back to the automatic centering mode as soon as possible.

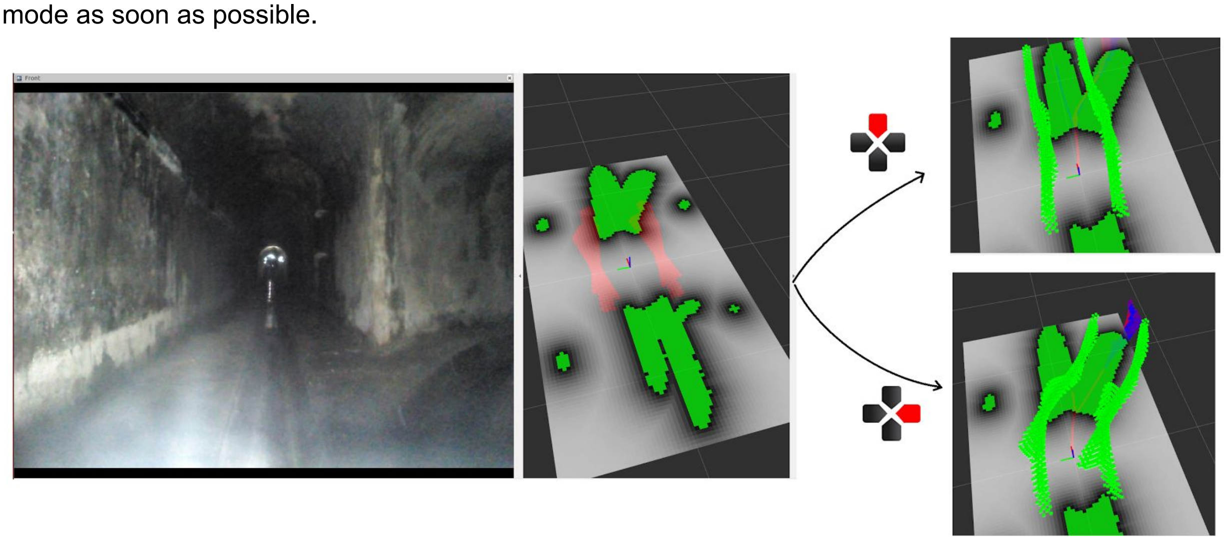

Figure 2.6. (Left) The robot finds a fork and has to enter the gutter to continue its trajectory, so the automatic centering mode fails. (Right) Operator decides the direction in the fork and a trajectory is then planned.

Teleoperation mode

In this mode, the robot can be purely teleoperated from the base station, where the operator controls the degrees of freedom of the robot. A F710 controller from Logitech is used for this purpose.

Figure 2.7 shows the controller that is used to control the robot from the base station as well as the different functionalities associated to buttons and joysticks. These buttons can be used in both teleoperation and assisted teleoperation mode. The following control functionalities are associated with each button.

- **Start button** → It is necessary to press the Start button to start operation. It also exits panic mode, if the red button had already been pressed. In autonomous mode, If the Start button is pressed the robot switches to assisted teleoperation mode.
- **Panic mode** → It will instantaneously stop the robot. In autonomous mode the robot pauses the execution of the mission.
- **Command stick** → The robot will move according to the position of this stick. Note that if the robot is in assisted teleoperation mode, the operator can only command the robot to go forwards or backwards and the robot will ignore the turning commands.
- **Reverse operation** → This convenient button reverses the commands given through the command joystick. Also, the images from the rear camera are displayed to the operator in reverse mode.
- **Automatic mode** → It will switch between pure teleoperated and assisted teleoperated modes.
- **Choose fork direction** → In assisted teleoperation mode, whenever the robot finds a fork it will stop and wait for the operator to choose the direction the robot should follow. Then, the robot will perform a maneuver to follow the desired direction.
- **Width adjustment** → This joystick will be used to adapt the width of the platform.
- **Slow mode** → The operator can switch between normal and slow modes of operation. The maximum velocity is set to 0.5 m/s and 0.2 m/s in each mode, respectively. It can be useful when traversing narrow areas.
- **Turbo button** → When this button is pressed, the maximum velocity is set to 1 m/s (instead of 0.5 m/s).

Figure 2.7. Controller used in the experiments and available commands.

2.3.5. Control center information

In this section the design of the information that will be available at the control station is detailed.

Figure 2.8 shows the main window of the control center. This window shows real-time images from the onboard cameras that are specifically placed for operator awareness purposes. The application will switch between the front and rear cameras according to the operation mode, i.e., it will show the rear camera when the reverse mode is on, or the front camera otherwise. Additionally, the system shows the approximate location of the robot over a map of the environment as well as the location of deployed repeaters and alarms regarding to structural defects or serviceability losses in the sewer system.

FIgure 2.8. Main control window. On the left, real-time images gathered from the front camera. On the right, the location of the robot (blue) and the manholes (green) and forks (red).

The current software, which includes the main operator window has been successfully tested during the experiments carried out in the “Mercat del Born” area in May 22-23, 2017. In particular, during the first day of the experiments an operator from BCASA was capable of guiding the SIAR platform in a straight section of the sewer from the outside of the sewers in assisted teleoperation mode for more than 50 m. Figure 2.9 displays a picture taken in the experiment.

Figure 2.9. An operator from BCASA safely guides the robot in assisted teleoperation mode from the outside of the sewers.

In the second screen, this map is presented larger, and each system will be selectable. When selected, additional information about each element is displayed (e.g., battery status, pictures and characteristics of the detected defects, etc.). The operator will be allowed to change and update the information, as well as to create new alerts whenever required. This part of the system is still under development.

2.3.6. Collecting information from the system

Once the mission has ended the operator must hold the Power Off button on the controller to save the robot logs obtained during the mission. This information can be collected at the base station by plugin an external HDD to the robot. Note that this can be done while the robot is charging.

Then, the logs must be loaded by the control station software. In particular, this software allows the operator to reproduce the experiment from any starting point and to alter the place at which the experiment is played. It will also extract the alerts into a report document. Finally, the software will be able to process the information obtaining a detailed 3D model of the visited sewers that can be used to detect anomalies. The details of this procedure can be found in D28.5, Section 4.2.2.

3. Improvements in Cost/Benefit

The focus of the Consortium is to develop a reliable solution, that can be easily used by current work forces of sewer inspection services and, last but not the least, will contribute for an effective reduction of costs related with the sewer network inspection and maintenance.

An analysis of the principal cost data for the visitable sewer inspection service in Barcelona (in the challenge call document), mentions that currently:

- An inspection brigade is composed by 2 skilled officers, 1 pawn and a driver equipped with a van(leasing) and costs 110 €/h;
- Nowadays there are 4 brigades available that cost a total of 753.280 €/year;
- These 4 brigades inspect the 1.000.000 m of visitable sewers at least once a year;
- A brigade can approximately inspect 1168 lineal meters per day;
- The unitary cost is 0,75 €/m.

Based on the performed tests with the Phase I prototype it is expected that the system is able to execute its mission at a medium velocity between 40 to 50 cm per second. The Consortium is also considering a minimum power autonomy of 4 hours (without charging). This means that the SIAR solution, at a 40 cm/s, should be able to cover a distance of more than 5.5 Km (during the 4 hours). This means that in normal operating conditions the robot will substantially improve the inspected range per day. Presently the inspection teams work 8 hours per day, and in case of need it will be possible to increase the time of operation of the robot by swapping the batteries.

Battery swapp is not being considered because in the 8 hour period we still have to consider the time spent for the logistics: transportation of the inspection brigade (including the robot) to the place; setting up the robot; placing the robot for the inspection mission; collecting the robot after the mission; and cleaning the robot.

On the other hand, with an autonomous robot, the composition of a brigade can be redefined. Only one skilled operator and a pawn should be enough for a mission. This will reduce significantly the hourly cost of the brigade. A reduction of at least one third should be expected.

The exact market price for this type of robot is still difficult to define, it should only be possible after an industrialization and advanced market planning, IDM estimates a target price of about 50,000.00€ for the complete SIAR solution at the beginning of its commercialization. Assuming a lifespan of 5 years for the equipment, and an annual maintenance cost of 15% of the initial value, the total value for the 5 year lifespan raises to 87.500€.

- In a year period, a brigade with an hourly rate of 65€ and a robot will cost: 65*8*214 + 87.500/5 = 128.780€.
- 4 brigades should cost 515.120€

- Neglecting the expected increase on the covered distance and that each team is inspecting the same distance as before, this leads to a unitary cost of 0,51 €/m .
- Nevertheless, as mentioned before, the SIAR partners expect a big increase in the inspected distance per mission, the robotic solution should be able to inspect 5.5 Km per day (currently 1168 m per day). A conservative comparison of these values allows us to define a reachable goal of a unitary cost of 0,20 €/m for the SIAR inspection.

Based on preliminary experiments with the perception system, the Consortium believes in the possibility of having a realtime system for the sewer serviceability and structural defect inspection, and therefore the previous value of 0,20€/m is still valid for these services. Please notice that the 3D information that will be used for both, sewer serviceability and structural defect inspection, can be gathered online and with enough resolution in the current envisaged solution, and we expect to be able to provide the information without requiring the robot to reduce its velocity, so both services can be offered at the same cost. Moreover, the sampling system is already being considered in the platform payload and therefore, the sampling collection should not have impact on the calculated value.