Sustainable Robotics Solutions in Smart Cities. The Challenge of the ECHORD++ Project

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***Abstract*— The objective of this paper is to explain novel sustainable robotics solutions for cities. Those new proposals appear under the ECHORD++ project which is a good tool to meet academia and industry with the objective of providing innovative technological solutions. In this paper, authors explain the tool as well as the methodology to promote robotics research in urban environments, and the on-going experience will demonstrate that huge advances are made in this field.**

Keywords—: Smart cities, Sustainability, Robotics, Communication systems, Sewer Systems)

I. INTRODUCTION

Demand is a major potential source of innovation yet the critical role of demand as a key driver of innovation has still to be recognized in government policy. Public demand, when oriented towards innovative solutions and products, has the potential to improve delivery of public policy and services, often generating improved innovative dynamics and benefits from the associated spillovers. In principle, the potential for using public procurement as an instrument for innovation is considerable [1].

In 1972, the Club of Rome declared that an economic concept based on growth was not sustainable in the long term. Forty years later, society recognizes that the main resources will be depleted in the near future. The implementation of the robotics in industry is since 30 years ago. This is due to the fact that the use of robots 1) increases the competitiveness of our companies, 2) influences socioeconomically over the productive sector as a mechanism to increase productivity and the quality of the product, 3) increases energy efficiency and, 4) decreases the energy consumption (preserving the natural resources in a more optimal way). Because of all this, robotic products should be cheaper generating lower gas emissions.

Industrial sector has been for many years the main user of robots. Nowadays, due to the significant research advances in robotics, a clear trend of growing use of robots in the service sector is observed. The present indicators indicate that the largest expenditure of natural resources (for example, energy) comes from the service sector. Therefore, to encourage and promote the future possibilities of the robotics in this type of activities is needed. Due to these needs and challenges the European project ECHORD++ (European Coordination Hub for Open Robotics Development ++) is born. The idea is to provide modern cities with robotic solutions to solve the challenges of these cities to achieve greater comfort and well-being.

Half of the world's population lives in cities, and that proportion is expected to climb stressing infrastructures, power grids, roadways as well as government services. To become more efficient, 'green' and make citizen lives easier, municipalities are turning to technology, specifically robotics technology. Many cities from the first world are in constant evolution. These cities provide core infrastructure and give a good quality of life to their citizens, a clean and a sustainable environment applying 'Smart' solutions. In fact a smart city has to be able to meet citizens' requirements (environment, mobility, energy, etc.) improving the daily live. ECHORD++ project seeks the most suitable, optimal and innovative robotic solutions to the new needs and challenges in developed cities. The solutions are not in the market yet so academy and industry should be working together to achieve innovative and sustainable marketable robotics products. Then, we will able to acquire these products on the market in the future. The new robotics solutions implement by this project are based in the sustainability item (specifically, in 'energy') where the gas emissions and the energy waste are vital aspects to obtain a marketable robotics product. This work is centered in these sustainable robotics solutions implemented so far in ECHORD++.

The concept of Smart City is neither unique nor universal. But there is a common concept: the use of Information and Communication Technology ICT seeking at the same time and holistically the more featured developments in the digital transformation of cities towards the sustainability, efficiency and citizens and visitors' wellness, [2].

Europe has a long tradition of outstanding research and manufacturing in robotics. However, finding common ground between manufacturers and the research community has proven difficult in the past. Defining the future direction of robotics research has revealed to be the real challenge. ECHORD++ was installed as an incubator to promote innovation by facilitating the cooperation between academia and industry [3]. The project wants to further stimulate this interaction between robot manufacturers, researchers and users. This goal will be achieved by implementing three different instruments: i) the experiments, ii) Public and users Driven Technological Innovation (PDTIs) and iii) Robotic and Innovation Facilities (RIFs). Specifically, project managers will focus in PDTI, that it is the methodology followed to develop a final technological product that is innovative and ready for commercialization (throughout the pairing academia-industry). Another key feature is that the product is not yet in the market and it is expected to be the solution for more than one cities.

This tool is tailor-made to meet the needs of the innovative robotics technologies of the manufacturing industry (mainly Small and Medium Enterprises, SME) with small lot sizes and the need for highly flexible solutions) and public bodies, looking for robotics technology with basic functions at competitive prices for tender processes), [4].

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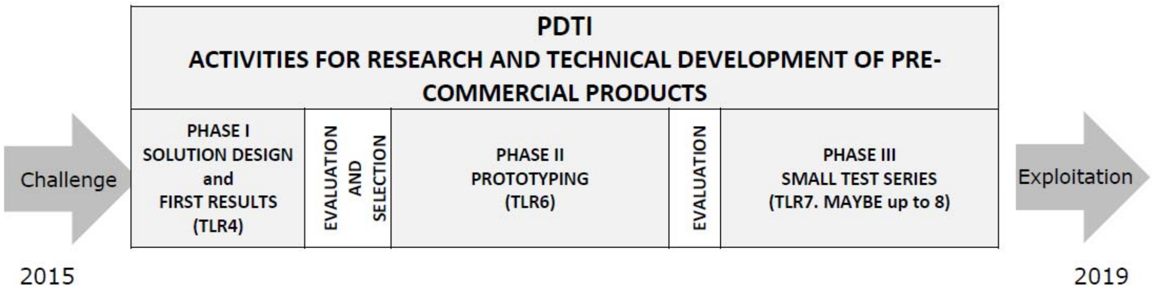

Fig. 1. PDTIs activities for research and technical development of commercial products.

In all cases, academic partners or research institutes in conjunction will do the research with the potential users of the robotics technology. This research project, funded by EU 7th Framework Program, has as main objective to give solutions to the demands proposed by public bodies in European cities.

Regarding the PDTI side, ECHORD++ consists of different stages: initially, local authorities in city councils analyze the existing problems in the city that should be solved in a technological manner (by means of a robotized solution); each city can present a unique proposal in a public call; secondly, when all the presented proposals are collected a panel of experts score and rank them following some specific indicators (citizen's needs, social impact, sustainability impact, economic impact, efficiency…), only the best ranked proposal wins and this proposal will be "the challenge" to be solved; then, the proposal is refined by the winner city and presented, a public call is open to consortia (research centers and private companies) as a European project and only the two best ranked solutions are accepted to be working to solve the challenge. These two consortia are funded by ECHORD++ project to work in parallel for solving the challenge (Phase I, Phase II and Phase III, see Fig. 1), [5]. At the end of this process of 36 months, the suitable prototypes (evaluated by panel of experts- final reviewers) will be considered for industrial production and deployment.

II. THE PHASES OF THE ECHORD++ PROJECT

A. *The Process and the Challenge*

After a selection among 14 European cities that submit an innovative technological challenge, the city of Barcelona won the challenge in Urban Robotics with the project proposal "Robots for the inspection and the clearance of the sewer network in cities". After this selection an open call was performed by ECHORD++ administration and a total of 10 consortiums applied for the project. Finally, two consortiums were selected to develop their research in this challenge, ending up with a real prototype which will be presented at the end of the 36-month project. Some specific European regulations exist regarding this subject (Regulation (EC) No 1013/2006, and Decision No 1386/2013/EU). To develop this research project, proposers have to follow the Barcelona city regulations in this matter, Environmental Municipal Ordinance (1999). The new robotics solutions should include: 1) mobility and autonomy and 2) communication and teleoperation (ICTs). At the end of the project, the innovative technological solutions for the challenge of the Barcelona city proposed by both consortiums will be evaluated by a panel of experts, and it is expected that two robotics commercial products are the outcome of the project.

Sewer inspections require many people to work in risky and unhealthy conditions. Introducing a robotic solution in this process aims at reducing the labour risks, improving the precision of sewer inspections and optimizing sewer cleaning resources of the city. This system should be able to determine the state of the sewer in order to identify sewer segments where its functionality has been reduced either by sediments or by structural defects. Other functionalities required are sewer monitoring and water, air and sediment sampling. To well carry out these tasks, some general functions are required like remote operation, video and images capture, scanning and map building, communication and teleoperation, among others. Those items have to be approached with efficiency and in a sustainable manner.

As we mentioned in the Introduction, two consortiums (SIAR, Sewer Inspection Autonomous Robot and ARSI, Aerial Robot for Sewer Inspection) have currently developing two possible technological solutions.

B. *New Technology and objectives*

The requirements for the new technology are given by the inherent sewer characteristics, that is, different ranges of pipe sizes, possible high concentration of, not explosive, but toxic gases as hydrogen sulphide, slippery areas, obstacles, atmosphere with 100% humidity, water temperature 16 °C, and no telecommunication coverage in the sewer. The devices that could be considered as robots are able to move themselves in one direction by sewer. They can record video in 360º to register the state of the sewer being able to analysing it by zooming and navigating in 360º by the video images. They need to access into the sewer system at one point and being recuperated in any other point in an autonomous way; they are equipped with cameras, laser, Lidar and inertial navigation systems, sonar sensor (for underwater detection if there is any stream of water) and hydrogen sulphide sensor, using a powerful communication system. With all this collected data by the sensors, it is possible to generate a model of the interior of the sewer and identify the possible impairments. The improvements in the existing technology that this project seeks are to facilitate real-time decision making, innovation that makes inspection devices more autonomous, to have more degrees of freedom to move around the network, and the possibility to intensify the checking of a zone where impairment has been detected.

The objective of developing this new technology is to mechanize sewer inspections in order to reduce the labour risks, objectify sewer inspections and optimize sewer cleaning expenses of the city. Regarding the sewer monitoring, the objective of sewer monitoring is to approximate the robot to the maximum level of sensitivity which will allow the sewer manager to make decisions without exposing to risky locations. The task of sample collecting is greatly important in order to obtain valid and traceable information which could be used afterwards to determine environmental legislation and policies.

C. *Description of the pilot case: Barcelona sewer system*

The current need of the City of Barcelona is to mechanize sewer inspections in order to reduce the labour risks, objectify sewer inspections and optimize sewer cleaning expenses of the city. The sewer network of Barcelona is 1,532km long, from which approximately 50% is accessible, which means that the pipe is at least 1.5m high and workers are allowed to go inside it. In order to determine the state of the network, visual inspections are done with different frequencies depending on the slope and other characteristics of the sewer. Workers walk all along the pipe, in some sections even four times a year, and decide where it is necessary to clean. Moreover, sewers are classified as confined spaces, which require special health and safety measures, in addition to other risks like slippery sections, obstacles or biological risks from the eventual contact with wastewater.

These features made the process of sewer inspection a risky and expensive process that requires improvements urgently. Sewer inspection is a service included in the public management of the sewers of Barcelona. Nowadays, sewer inspections are done by people performing visual inspections and collecting information about the state of the sewage like sediment level and type, pipe obstructions, etc. Because of the sewer risks, the performance of the inspections is about 1.5km of sewer every 6 hours. This methodology requires approximately 1 million Euros per year in staffing expenses only, excluding equipment, machinery, health and safety measures, or other expenses. There is no regulation that applies to this public service except for the prevention of occupational hazards and, in particular, the regulation of access to confined spaces. The city is willing to amend the legislation of its jurisdiction for introducing this new technology. Barcelona sewage system network has a wide variety of sewers. This enables us to test the technology in various sewer sizes and facilitates the transfer of the technology to other cities.

Fig. 2. SIAR prototype of Phase 1

There are two technological solutions proposed (SIAR and ARSI projects) that are currently working and making progresses. Phase I of both projects has successfully showed the proposed solution of each one as proof of concept in the tests conducted in mobility, autonomy and communications. Currently these projects are in Phase II, during which all the aspects of the solution will be developed and validated to ensure a complete solution for robot-assisted sewer inspection. It is expected to obtain a prototype inspecting the Barcelona sewer network at the end this phase.

III. SIAR PROPOSAL

A. *Robotic solution in a nutshell*

The SIAR solution seeks to solve the problem by the creation of an autonomous robot (see Fig. 2), with the possibility of control from a human operator in case of need of emergency. By using the proposed wireless system, augmented by the deployment of self-powered wireless repeaters, it will be possible to transmit bidirectional data between robot and an external operator, allowing the operator to change the mission in real time, instead of having to wait for the end of the sewer exploration to identify problems on the sewer system.

The SIAR system will go beyond existing solutions through the inclusion of some innovative features, while maintaining affordable costs. Those features include configurable locomotion system with interchangeable wheels and tracks modules and variable length/width of the traction system; reliable navigation system based on data fusion from low-cost commercial RGB-D cameras, inertial measurement unit (IMU) and encoders. Those sensors perform accurate localization and navigation on the sewer system, instead of using more complex and expensive sensors for the same task. The main task is the inspection system with easy exchangeable sensor payload, allowing the use of the robot in different applications instead of the usually set of sensors used only for sewer inspection, and the introduction of devices for air/waste sampling that is not possible to find in the commercial inspection robots.

The SIAR project will develop a fully autonomous ground robot able to navigate through the sewage system with a minimal human intervention and with the possibility of manually controlling the vehicle or the sensor payload when required.

B. *The robotic solution for deploying/collect the repeaters and communications*

The main goal of the robotic arm is the deployment and collection of the wireless repeaters in the sewer. The wireless repeaters intend to increase the signal range. The nVIP2400 Wifi devices were disassembled and suitable batteries were selected in order to reduce the overall size and weight. The electrical components and the battery were then assembled together in a plastic box. The box has a handle on the top to allow the coupling with the claw of the robotic arm. Table 1 shows the items that compose the repeater, their consumption or battery capacity and their weight.

With the LiPo battery (3S) the repeater power autonomy will be close to 2.5 hours. Please note that this consumption is calculated in the worst case scenario with the repeater working at its maximum power and letting the batteries to be discharged at 80% of their capacity, following the manufacturer's guidelines. To increase this autonomy, the repeater will be equipped with a small magnetic reed sensor that will connect/disconnect the battery power from the wireless nVIP2400 WiFi device. The top of the wireless repeaters box installed on the robot will contain magnets that will deactivate the power from the repeaters. When the repeater is taken from the robot, by the robotic arm, the reed sensors stops sensing the magnet and the battery is connected to the wireless Wifi device inside the box. In this way, it is expected that each repeater will have power enough for performing a full mission of operation. The robotic arm has five degrees of freedom and it is actuated with the use of five Herkulex servos of different forces. The arm is composed of three segments. The claw is attached to the end of the third segment and it has the freedom to rotate. When completely extended the robotic arm is able to reach a distance of 495mm.

TABLE I. WIRELESS REPEATER COMPONENTS

Item	Power (W)/Capacity(Wh)	Weight (g)
LiPo Battery (3S)	1450mAh@11.1V (16.1Wh)	97.3
nVIP2400	6W (max)	100.1
Enclosure+Handle		90
Antenna		30
Total	<2.5 hours of operation	317.4

Communications rely on line of sight. As long as this line of sight is maintained the range and performance is satisfactory. The consortium intends to use repeaters to maintain communication beyond line of sight. It is recommended that the consortium evaluates the practicalities of deployment and retrieval of the repeaters in more detail as they may become a major impediment to practical application. Following the comments of the review, the consortium has been working on the following aspects to analyze and improve the practicalities of the communication repeaters deployment/retrieval tasks:

1. Final design of the repeater package, including weight, batteries, autonomy and functionalities.

2. Design of the arm, including DoF (degrees of freedom), sizes, gripper and maximum payload

3. Sensing approaches for estimating the relative position between robot and repeater for picking up the repeaters back to the robot (passive and active markers).

C. *Automatic Deployment/Collection of Repeaters*

The deployment of repeaters whenever the Line-of-Sight (LoS) is expected to be lost, and therefore the quality of the links could begin to degrade, is proposed. This will extend the operational range of the robot in more than 300 m. for each repeater.

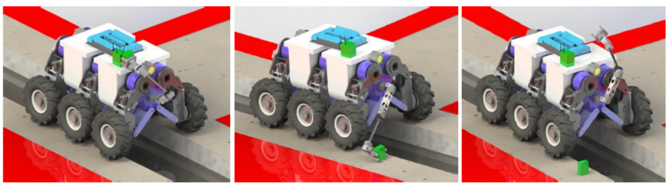

Fig. 3. SIAR Robot deploying one wifi communication repeater.

To this end, the robotic platform will be equipped with a 4DoF manipulator on its back, which will automatically pick-up one of the available communication repeaters and deploy it on the ground (see Fig. 3). This manipulator will also be used to retrieve the already deployed repeaters in its way back. The robotic arm will be based on standard servo motors from Dynamixel (or similar). Currently, IDM is specifying the arm components based on the required payload and workspace. When completely extended the robotic arm will be able to reach a distance of 500mm. Its gripper will be based on an electromagnet which will be actuated during the deployment and collection of the repeaters (their enclosure will contain a metal part).

A robust estimation of the pose of the repeaters is very important for their recovery using the manipulator. The design of the box will include passive AR tags for this. This would allow us to estimate the 6DoF relative position from the robot to the repeater. Some preliminary experimental results have been obtained by adding AR tags to the current repeaters made for Phase I. Artificial illumination is provided by the SIAR robot.

While the illumination devices of the robot can be used to detect the tags, in order to enhance the detection robustness under more severe conditions, some alternatives are being studied. These alternatives include the installation of an array of LEDs on the repeater (active markers). The added power consumption is very low and these can be a simple way to localize the repeaters. Moreover, plain colored markers can be used, as the distance to the repeater and its relative orientation to the camera can be estimated by the depth information. The actual research is still immature, and those the next phase is expected to have a more consolidated robotics architecture that will be able to cover more sewer length, with a reliable communication system and able to located inside the sewer.

IV. ARSI PROPOSAL

A. *Robotic solution in a nutshell*

The proposal is the use of a Micro Aerial Vehicle (MAV) (see Fig. 4) for inspection tasks in the sewer avoids the mobility constraints from which a ground robot would suffer, such as paths with steps, steep drops and even objects in the way. Additionally, a flying platform is able to move faster through the sewer network than the terrestrial alternative and needs simpler logistics in deployment and operation (see Fig. 5). On the other hand, a MAV solution has to overcome strong constraints of size, weight and energy, as its flying space is bounded by sections less than 100 cm wide. Therefore, its size and consequently payload are limited to minimal dimensions.

Fig. 4. ARSI platform setup.

Fig. 5. Quadrator flight in a real sewer in the city of Barcelona.

The ARSI consortium has addressed the problem of sewer inspection with the integral design of an aerial platform, multi-rotor type, endowed with sensors for semi-autonomous navigation and data collection within network, and capable of communicating with an on-surface operator. The different drones that will operating inside the sewer will be monitored and controlled from a van parked outside, in the street, and the workers will assist the robots to replace the batteries. Initially, it is expected that drones can work in tunnels with a minimum width and height of 80cm. Nowadays, a human worker can operate inside a sewer of a minimum width of 60cm and 1m high, under these dimensions only robots can operate. That means that human workers can only work in 843km of sewer, a 55% of the sewer network in Barcelona; the remainder of the sewer is covered with teleoperated cable robots, and the inspection of 1.5km takes 6 hours in average [6].

The main features of the design consist in:

- Optimal layout of the payload on the platform (embedded PC, 2D laser scan, multiple image sensors, LED lights, gas sensor and antenna) which minimizes the weight and energy requirements.
- Localization and motion planning methods in GPS-denied environments.
- Careful design of the image sensors and their configuration in order to ensure a detailed view of the whole section for structure assessment and defect detection purposes.
- Use morphology of the sewer network to enable out-of-sight communication.
- Integration of mission planner within operational software of sewer maintenance companies.

B. 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, the solution is described. The procedure aims at optimizing the range provided by our communications system and the autonomy of the batteries.

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 [7][8]. 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.

1) Behaviour of the waves in the sewer

Despite this very challenging environment, an analysis of the behavior of electromagnetic waves in confined spaces helped us build our solution for wireless communication between the ARSI vehicle and the Remote Station. The experiments carried out so far have shown that the combination of high-frequency signal and reduced dimensions of the sewer tunnels causes waves to keep “ricocheting” on the walls. 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.

2) First solution and methods

ARSI consortium experimental results have confirmed that sewer tunnels act as a waveguide for Wi-Fi signal. In straight stretches of tunnels, Wi-Fi signal travels for hundreds of meters with very little attenuation. In these 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 Fig. 6 left, which depicts a section of the Barcelona sewer network (in green) in the Eixample area where the ARSI evaluation will take place.

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 Fig. 6 left, 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 streets 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 Fig. 6 right, 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.

Using careful placement of the Wi-Fi emitter, we estimate that this behavior of the signal allows us to cover more than 500m in total, which is more than the range current batteries can provide for our aerial platform for our nominal inspection speed of 0.5m/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 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. In terms of communications, the objective in Phase II is primarily to reproduce the previously explained results obtained in Phase I in the area around Mercado del Born, and to make robust the sensors and general Wi-Fi setup.

More specifically, the project pretends to achieve:

- Reliable Wi-Fi propagation with Line of Sight (LoS) in sewer tunnels of lengths between 100-150m, typical in Barcelona, including in the Phase II evaluation area around Mercat del Born;

Fig. 6. left, Wi-Fi propagation (in red) in Barcelona serwer tunnels (in green); right, improved Wi-Fi coverage (in red) after taking sewer network topology (in green) into account.

- Build a model of the Wi-Fi propagation around curves and bends in the tunnels. This characteristic of sewer networks, which we observed during Phase I, gives users more flexibility when planning inspections using the ARSI platform.

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Since the kick-off meeting in mid-November 2016, one visit to the sewers around Mercat del Born have been carried out, primarily to get to know their specificities and potential difficulties for the aerial platform. The next milestone is to carry out extensive communications tests in Mercat del Born in 2017.

5. CONCLUSIONS

In this paper, the challenge of sewage cleaning monitoring using robotics and communications is shown. This challenge is carried out by two selected consortiums in the ECHORD++.The communication solution proposed in Phase I for both consortiums is explained obtaining satisfactory results. Next, in Phase II, a prototype (from the communication solution proposed en Phase I) will be presented. Then, both consortiums once again will be reviewed to pass Phase III.

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