ROBODILLOS

A Networked Mobile Robotic Platform for Shared Autonomy Sewer Inspection Operations

Phase I Report

ECHORD++

Public end-user Driven Technological Innovation (PDTI)

Urban Robotics Challenge: Utility Infrastructures and Condition Monitoring for Sewer Networks

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Summary

During Phase I, the Robodillos consortium has successfully developed the TRL4 solution design for the Robodillos system, an advanced robotic platform for sewer inspection operations that synergistically integrates state-of-the-art wireless communication technologies with autonomous multi-robot systems technologies in a unique, robust, agile, scalable and reliable solution. During this phase an array of activities including hardware, software and algorithm development were carried out, coupled with appropriate dissemination activities. Expected impact metrics were revised and reaffirmed based on updated estimations on the developed solution design in Phase I. The milestone designated for Phase I has been successfully attained and the involved tasks T1-T3 has been successfully carried out. A detailed solution design has been prepared and a detailed business plan has been developed. Based on the Robodillos solution design and business planning, Robodillos will offer **a cost reduction** of more than **64%** compared with current practice, with an **inspection cost** of less than **0,27 € / lineal meter** and a **performance** up to **1.335.360 lineal meters per year**.

1 Tasks and documentation required during Phase I

1.1 Project Implementation

<table>
<tr><td colspan="3">Task 1: Solution Design and Technology Development [M1-M5]</td></tr>
<tr><td>Participant</td><td>Role</td><td>Person-months</td></tr>
<tr><td>CUT</td><td>Leader</td><td>4</td></tr>
<tr><td>HEL</td><td>Partner</td><td>3</td></tr>
<tr><td colspan="3">Objectives:

The aims of this task are to provide the Robodillos system design and to develop algorithms and technologies required for sewer inspection operations.
This task contains the following activities:
Establishment of the Robodillos GNC³ architecture by creation main modules of the system for the Command Center Level and the Team Member Level;
Development of main capabilities of the User Interface and principal functionalities of the High Level Coordination and Supervision module at the Command Center Level;
Development of technologies and algorithms for SLAM, sensor fusion, and local motion task planning at the Team Member Level.
Providing the solution design for sewer inspection task.</td></tr>
<tr><td colspan="3">Description of work – Degree of Objectives Implementation:

Work in this task has provided the Robodillos system design and developed the</td></tr>
</table>

required algorithms and technologies for basic functionalities (TRL4) required for the sewer inspection operations

During this task the overall Robodillos GNC^3 architecture has been defined and the solution design for the sewer inspection task has been prepared (see section 3: Solution Design).

At the Command Center Level, the User Interface module has been created under the ROS framework. The user interface has the capability of providing real-time system data, sensor information and measurements to a user. The core algorithms for the High Level Coordination and Supervision module were developed (see Annex I). These core algorithms enable the assembly of a feasible global motion task to fulfil the sewage inspection. Local motion tasks are dispatched to each team member (see Annex I). Basic user interface capabilities enable the monitoring of global and local tasks execution.

Work performed at the Mobile Ad-Hoc Networking pillar included achieving a deal with Silvus Technologies Inc. for supplying for limited time period to the consortium 4 MIMO MANET radios to evaluate their performance. CUT has also evaluated alternative radio technologies in order to determine the most cost effective solution. Radio tests were carried out at a sewer-like structure under the Asprokremos water dam in Paphos (Cyprus). Performance parameters of the radios were determined and were implemented in the developed communication system models since the algorithms developed for the High Level Coordination and Supervision module take into account the capabilities of the radio hardware in determining their sewer coverage plan (see Annex I).

At the Sensing and Perception pillar, modifications to the algorithms previously developed by the Robodillos consortium participants [KLK11, PCGL15] in order to be able to handle the Robodillos specifics as well as alternative methodologies [GSB07,MS14] have been considered under ROS. The consortium is in the process of adapting and optimizing the algorithm developed by its members in [GSB07] for utilization with the SLAM and Sensor Fusion & Management modules.

At the Mobility and Autonomy pillar novel local motion planning algorithms were proposed (see Annex I) that can handle the problem of sewer coverage with communication connectivity maintenance. The configuration requirements defined by the Communication module of the Mobile Ad-Hoc Networking pillar are taken into account in generating a local motion and task plan for each of the Robodillos team members. A mock-up environment was set-up by HEL to test the maneuvering capabilities of the Robodillos robot (see Annex II). An array of modifications were introduced to the Helikas Atum Rover by HEL in order to enhance its mobility envelop and in order to accommodate the necessary equipment for the Phase I evaluation.

Task 2: System Modeling and Simulation [M1-M6]

Participant	Role	Person-months
CUT	Leader	4
HEL	Partner	1

Objectives:

The objectives of this Task are as follows:

- create models of the Robodillos system and its sub-systems including the User Interface, the Atum rover, and rover onboard sensor suites;
- Provide simulation framework similar to the sewer topology.

Description of work – Degree of Objectives Implementation:

In this task a dynamic model of the Robodillos rover has been developed in the ROS/Gazebo simulator. The model and preliminary estimations of its dynamic parameters that were based on the Atum Rover were provided by HEL and were ported to SolidWorks and subsequently ported to Gazebo. Through the Gazebo simulator basic imaging and sensor suites (laser scanners, IMU, odometry, camera) were implemented. The four sewer cross-sections that were provided by BCASA, i.e. T436C, T174, T162B and T133 and also T111 and T130 were implemented in the Gazebo simulator in order to create arbitrary sewer topologies. The User Interface is directly coupled with the Gazebo simulator through the ROS/Gazebo framework. Snapshots of the simulation framework are provided in Annex III.

Task 3: Validation and Benchmarking [M5-M6]		
Participant	**Role**	**Person-months**
CUT	Leader	2
HEL	Partner	2

Objectives:

The aim of this task is to validate the Robodillos system design and algorithms developed in tasks 1 and 2 and to benchmark its performance against the current sewer network inspection task performance.

Description of work – Degree of Objectives Implementation:

During this Task a series of simulation as well experiment studies were performed to determine and validate the technologies and algorithms developed in Task 1 and models and simulation software developed in Task 2. In particular simulation studies of the developed algorithms are reported (see Annex I) and system simulation studies have been performed under the ROS/Gazebo system simulation and visualization system developed in Task 2 (see also Annex III). Experimental studies were performed in the mock-up environment (see Annex II) and also at the sewer-like structure under the Asprokremos water dam in Paphos (Cyprus).

Based on these test, the specification of the Robodillos system design were determined (see Section 3: Solution Design). Moreover, these tests enabled the extraction of realistic performance data for the Robodillos solution design. These data were used for benchmarking the Robodillos system performance in sewer inspection operations against the current practice.

1.2 Deliverables and Milestones

During Phase I of Robodillos, the deliverable D3.1 “Robodillos solution design” was scheduled in the Robodillos proposal. This deliverable has been successfully produced and is detailed in Section 3: Solution Design.

For Phase I the Milestone “Phase I” was assigned in the Robodillos proposal. This milestone comprised the following (quoting from the Robodillos proposal):

“Full system design; demonstration of major features critical for the technology development including risk analysis; timeline for the entire project (Phases II and III)”

Involved tasks T1, T2 and T3 with expected milestone date M06 and the following means of verification (quoting from the Robodillos proposal):

“This milestone is related to the successful accomplishment of the Robodillos solution design and providing simulation results of its major functionalities and features. The deliverable D3.1[1] is attained and demonstrated in terms of images/videos/simulations. The timeline and detailed description of the project tasks for Phases II and III is provided.”

Following is a detailed discussion on the means of verification for Milestone “Phase I”

Means of verification: *“This milestone is related to the successful accomplishment of the Robodillos solution design and providing simulation results of its major functionalities and features”*

Robodillos Consortium response: The Robodillos solution design has been successfully carried out (see section 3: Solution Design). Simulation results of its major functionalities and features were provided as detailed in section 1.1 Project Implementation and references therein.

Means of verification: “*The deliverable D3.1 is attained and demonstrated in terms of images/videos/simulations.”*

Robodillos Consortium response: Deliverable D3.1 has be attained and documented in the current document. Images, videos and simulations are provided as detailed in section 1.1 Project Implementation and references therein.

Means of verification: “*The timeline and detailed description of the project tasks for Phases II and III is provided.”*

[1] In the original proposal it was designated as D1 instead of D3.1 due to a typo (there is no deliverable D1).

Robodillos Consortium response: The timeline and detailed description of the project tasks for Phases II and III are provided in Annex IV: Timeline and project Tasks for Phases II & III

1.3 Dissemination Milestones

During Phase I, no dissemination activities were planned in the Robodillos proposal. Nevertheless, the Robodillos consortium during Phase I performed a series of dissemination activities as follows:

- The Coordinator was the organizer of a euRobotics week event in November 2015 at its premises. During this even CUT presented the Robodillos project and HEL presented its Atum rover indicating its connection with the Robodillos project.
- A front-line press release was produced for the Cyprus University of Technology web-page that diffused to the University's social media channels.
- A paper (see Annex I) with acknowledgement *"This work was supported under Grant Agreement 601116 EU/FP7/ECHORD++ Urban Robotics PDTI/ROBODILLOS"* was submitted to the submitted to the 55th IEEE Conference on Decision and Control, 2016

1.4 Technical KPI Milestones

During Phase I, Milestone "Phase I" defines the relevant indicators for the fulfillment of the technical objectives for Phase I. The details of this Milestone are analyzed in section 1.2 and references therein.

1.5 Impact KPI Milestones

Impact KPI Milestones were not assigned for the Phase I of Robodillos. However, a conference paper (see Annex I) has been submitted to the top IEEE CSS conference, the 55th IEEE Conference on Decision and Control, 2016, and a decision is expected towards the end of July 2016.

In addition, a comprehensive business plan has been produced during this Phase I. This is detailed in section 4 Economic Viability of Robodillos.

2 Solution Design

2.1 Detailed explanation of the solution design

To achieve the targets of the project, Robodillos is built through the synergistic integration across four technology pillars:

- Multi-Robot Guidance, Navigation, Coordination, Communication and Control (GNC^3);
- Mobile Ad-Hoc Networking;
- Sensing and Perception;
- Mobility and Autonomy.

Multi-Robot Guidance, Navigation, Coordination, Communication and Control (GNC^3)

The Robodillos GNC^3 technology pillar serves as a technological framework, gluing together and exploiting the synergies of the four technology pillars. The Robodillos GNC^3 architecture is balanced between centralized high-level command aspects and decentralized, individual team-member-level operations as depicted in Fig. 1.

At the Command Center Level, the Robodillos GNC^3 provides the User Interface, where a user located outside the sewer, can interact with the system providing his own instructions (initiatives) to the system that are then filtered through system-wide policies, enabling a mixed initiative control [LK07]. The User Interface provides all the vital system data to the user, including real time images and video of at least VGA quality of any kind of imagery sensors available through the Sensor Fusion & Management module of every Robodillos team member. The User Interface also provides real time graphs of the current system state (GPS information) overlaid over regional maps, network topology and performance information, global and local task status and system status. The User Interface has also the capability to provide 3D real-time visualization of the sewer and the Robodillos team based on information received by the SLAM modules. In addition to the visual cues offered by the user interface, it is augmented with audible cues to attract the attention of the user to important events and also with a haptic interaction device (force-feedback joystick), so that the user can have an effective interaction with the system, while system wide policies are communicated from the system to the user through visual, audible and haptic feedback. The User Interface will also provide the user with basic system simulation capabilities for operator training purposes. Snapshots of the GUI and the Robodillos Simulator that were prepared during Phase I are depicted in Annex III.

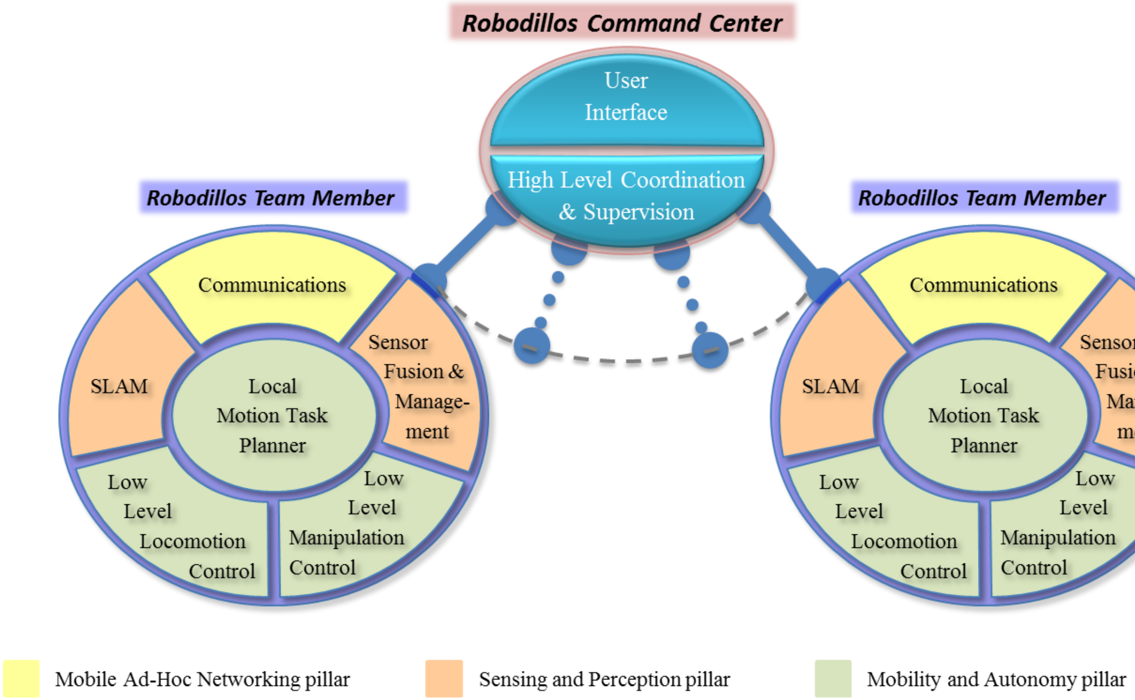

Fig.1 The Robodillos GNC^3 architecture.

Also, at the Command Center Level, the High Level Coordination and Supervision module provides centralized coordination, communication (as discussed in the **Mobile Ad-hoc Networking** subsection) and supervision services to Robodillos [LK05, LOI05, GJD13]. During Phase I a novel planning and supervision algorithm (see Annex I) was produced that has the capability to provide the necessary supervision and planning services. The High Level Coordination and Supervision module monitors the global task execution and global policy enforcement for the system. It is responsible for receiving global and local task specifications along with user initiatives from the human operator, appropriately assembling a feasible deadlock-free global task in such a way that global system policies are fulfilled while dispatching filtered individual motion task specifications to the Local Motion Task Planner of each team member [GD15]. Also this unit is responsible for global task re-planning in the case a Local Motion Task Planner declares an individual Motion Task Plan infeasible [GD13].

At the Team Member Level, the Robodillos GNC^3 architecture provides the necessary modules to enable the effective fulfillment of sewer inspection operations. The Communications module in conjunction with the High Level Coordination & Supervision module and the Local Motion Task Planner module is responsible for the realization of the two layers of the Mobile Ad-Hoc Networking technological pillar as this is discussed in the **Mobile Ad-Hoc Networking** subsection.

The Sensor Fusion & Management along with the Simultaneous Localization and Mapping (SLAM) modules form the first layer of the Sensing and Perception technology pillar and are discussed in the **Sensing and Perception** subsection.

The Local Motion Task Planner along with Low Level Locomotion Control and the Low Level Manipulation Control modules form the first layer of the Mobility and Autonomy technology pillar and are discussed in the **Mobility and Autonomy** subsection.

Mobile Ad-Hoc Networking

Wireless communications in existing sewer networks that lack communications infrastructure is one of the most important bottlenecks in developing effective robotic sewer inspection systems. There are several relatively recent studies for underground communications especially focusing to the case of mines, following increased interest on the topic after several underground mining disasters where communications emerged as a vital aspect. In [YGA09] an array of underground mine communication solutions were surveyed with the most favorable being radio devices, which observe their environment and react upon the changes to it to achieve a designated goal in an intelligent way – the so-called cognitive radio. In [MSA08, YGA08] experiments involving robots being deployed for underground mine search and rescue operations are reported where a communication solution of using a borehole to establish communication between a surface station and a radio controlled robot moving to distances up to 1000ft in the underground mine is demonstrated. An experimental characterization of non-line of sight (NLOS) ultra-wide-band communication in underground mines is presented in [RTG12, NDH10] where an NLOS path loss exponent ranging from n = 3 (for omni-directional antennas) to n = 4.74 is reported. In [FBM13, MTN12] the advantages of orthogonal frequency division multiplexing (OFDM) and multiple-in multiple-out (MIMO) in underground communications are discussed, whereas in [MAD06, GLZ09, WFJ10] the advantages of mobile ad-hoc networking (MANET) or mesh networks for underground mine communications are discussed. The effect of frequency in wireless underground mine communication is discussed in [HWG05].

Robodillos circumvents the communications bottleneck implementing a **two-layered** approach:

- Utilizing a COFDM, MN-MIMO, MANET/mesh based wireless networking solution;
- Enforcing a network connectivity and performance maintenance predicate within its GNC^3 architecture.

On the **first layer**, a cutting-edge digital wireless communication solution, provided by Silvus Technologies Inc., [STI15] is implemented. This solution utilizes Coded Orthogonal Frequency Division Multiplexing (COFDM), Mobile Networked Multiple Input Multiple Output (MN-MIMO) Antenna Techniques and Mobile Ad-Hoc Networking (MANET/mesh). The combination of these technologies yields an appropriate solution for NLOS communication, that is completely decentralized and infrastructure-less, appropriate for mobile communication nodes with dynamically changing network topology. Silvus Technologies Inc., has participated in many US funded research projects to develop NLOS radio technologies including projects for NLOS robotic tele-operation, and has successfully demonstrated the operation of their systems for both data and video transmissions in underground mines – an environment closely related to the sewer networks - for static and moving nodes in NLOS setups. Cyprus University of Technology as the Coordinating Organization for Robodillos has signed a non-disclosure agreement with Silvus Technologies Inc., for the supply of their radio technology for the needs of Robodillos project. During Phase I of the project, Silvus Technologies Inc. supplied 4 radios to the Robodillos consortium for 4 weeks to study their performance characteristics. Based on a series of test performed by the Robodillos consortium during Phase I of the project at the sewer-like network under the Asprokremos dam in Paphos (Cyprus) the performance envelop of the Silvus solution was determined and based on this the synthesis of the basic Robodillos team was determined (see section 2.1: Logistics required and operational issues by using the solution) and this decision is also reflected in the business plan (see section 4: Economic Viability of Robodillos). Currently Silvus technologies offers the most advanced MIMO MANET solution in the market based on the market research performed by the consortium. However as competing technologies in the MIMO MANET market emerge over time, the Robodillos consortium is continuously monitoring alternative communication solutions that might reduce the overall cost of the system while maintaining or improving its performance. The Robodillos coordinator is in contact and has already obtained and is evaluating competing technologies from ACKSYS Communications & Systems – a European MIMO Mesh radio manufacturer.

On the **second layer,** a dedicated Communications module is allocated in Robodillos GNC^3 architecture. This module, in conjunction with the High Level Coordination & Supervision module, enables a high-level system specification defining network connectivity and performance to be enforced, ensuring specification fulfillment throughout Robodillos operations [LK04]. A recent algorithm developed by the consortium during Phase I, is capable of providing some components of this service regarding connectivity (see Annex I). That way Robodillos fully exploits the advantage offered by the cutting-edge technology implemented in the first layer, while ensuring that the MANET system is always operating within an optimal envelop. This is achieved through continuously monitoring and reacting to vital global (i.e. network-wide) and local (individual nodes) communication aspects, like quality-of-service, return signal strength intensity, signal-to-noise ratio, network delays and node routing load. This information is augmented with network performance models [LBR14, QYG13] and also the ones proposed in a recent paper by the consortium (see Annex I) that dynamically adapt to the environment to relate the spatial network arrangement, environmental characteristics and network performance so that the GNC^3 system can produce and implement on-the-fly appropriate motions and topological arrangements of the Robodillos team members [AK10, FLP06, LK05] (see also Annex I).

This two-layer approach enables reliable real time omni-directional networking with data rates up to 70Mbps (with TCP) with worst case scenario real time video streaming capabilities meeting or exceeding the VGA standard (depending on the network quality predicate enforced in the second layer).

Sensing and Perception

The Robodillos Sensing and Perception technology pillar consists of **two layers**:

- Sensing and perception algorithms provided through the GNC^3 architecture;
- The Robodillos sensor suite.

The **first layer** consists of the Sensing and Perception algorithms, comprising the SLAM module and the Sensor Fusion & Management module in the GNC^3 architecture.

The Sensor Fusion & Management module in conjunction with the SLAM module and the Local Motion Task Planner module is responsible for the realization of the Sensing and Perception technological pillar. This module manages and enhances the Robodillos sensor suite by automatically reconfiguring sensor parameters for optimal operations and by producing auxiliary motion task specifications to the Local Motion Task Planner module, in order to increase the information acquisition capability (quality and quantity) for specific sewer inspection functionalities. It processes and fuses sensor measurements with a-priori and accumulated knowledge to:

(a.) Quantify the sewer serviceability by deducing the monitoring parameters specified in the criteria for serviceability reduction, that include the thickness of the waste accumulated in the tunnel gutter, the section of the tubular sewer free from waste, the waste height deposited on the sill, in the bucket and at the curb. Based on this result the User Interface will be able to appropriately notify the user of the current sewer serviceability state, while producing a “pop-up” alarm in case of serviceability reduction.

(b.) Locate and identify critical structural defects including cracks, fractures, breaks (with or without loss), and collapse.

(c.) Enable high level sewer monitoring and decision support by sewer management authorities by implementing the air and water sensing systems discussed in the second layer, to enable identification of human safety and risk situations, to locate and follow spills and leaks, to determine tendencies and to produce data for environmental research

(d.) Perform location and date-time-tagged sampling of water, air and sediments by appropriately dispatching manipulation specifications to the Local Motion Task Planner module. Sampling operations can either be triggered based on perceived sewer conditions or by following the user’s command.

The Sensor Fusion & Management module is also responsible for the acquisition of digital images, real time continuous video feed (of at least VGA quality -depending on the network quality predicate – see subsection **Mobile Ad-Hoc Networking**), local HD video and snapshots recording and storage (on demand), WVGA-30fps video recording and 3D point cloud scan storage and real-time streaming (on demand) from the laser depth imaging system.

The Simultaneous Localization and Mapping (SLAM) module is responsible for fusing a-priori information about sewer topology and sewer element location (a-priori information could be partial or outdated or not available) with 3D geometric information provided by the laser depth imaging system, with information provided by the navigation sensor suite and with system dynamics information [NR11, HMR13, TM06]. The SLAM module in addition to localizing the Robodillos team, it creates or updates the sewer maps, it localizes the sewer elements including manholes, home drain inlets, street drain inlets, points where two or more sewer lines cross at the same level and connect, points where a noticeable reduction or broadening occurs and points with sudden slope changes. The SLAM module provides cartography based, geo-referenced localization with GPS coordinates (including angular position of each element from True North), with sewer elements presented through the User Interface as overlays to regional 2D maps (this service is partially provided by the Silvus communication solution presented in the **Mobile Ad-Hoc Networking subsection,** when provided with synthetic GPS data that can be assembled by the SLAM module) whereas the user will have the option for real-time 3D visualization of the sewer through the developed GUI (see Annex III), its elements and the location of Robodillos team members. The paths connecting sewer elements are categorized in the User Interface as straight or curved. The maps produced during inspection can be stored, processed off-line and re-used in subsequent inspections.

The **second layer** in the Robodillos Sensing and Perception technology pillar consists of four sensor suites: (a.) the imaging sensor suite, (b.) the sewer monitoring sensor suite, (c.) the sampling elements and (d.) the navigation sensor suite.

The imaging sensor suite (a.) is designed to enable symmetrical 3D scanning for the purposes of mapping, localization and navigation, and to also provide information for determining the sewer serviceability and identifying critical structural defects. This is achieved by two symmetrically arranged laser-scanning range finders, implemented at the front and rear end of the Robodillos robot. Such sensors (see e.g. [HOK15]) enable (with the use of first layer algorithms) reliable detection of features with characteristic dimension of at least 20mm. The laser scanners are arranged on mechanized oscillating turrets enabling them to perform panoramic 3D sweeps of the space whereas the sweep precision and characteristics is controlled through the first layer algorithms, enabling “scan focusing” to detect and identify small features. The imaging sensor suite also includes three low-light high-resolution digital cameras (see e.g. [BAS15, AVE15, ARE15]). The cameras will be equipped with the H.264/MPEG-4 AVC video compressing capability to significantly reduce communication bandwidth requirements (or with the recently introduced highly efficient H.265/HEVC codec if appropriate implementations become commercially available). One camera (minimum 5MP@30fps) is equipped with 360-degree panoramic optics installed on the top of the ROV to cover front, back and side viewing. Another (minimum 3MP@30fps) camera is equipped with fish-eye optics, again on the top of the ROV to cover top viewing. The third (minimum 3MP@30fps) camera is equipped with wide-angle optics located on the manipulator to enable viewing of the end-effector during manipulation operations. Robodillos optics are treated with special anti-fog coating to ensure system performance throughout Robodillos operations.

The sewer monitoring sensor suite (b.) consists of an array of air and water sensors and waste height measurement system. More specifically, a temperature (T) sensor (e.g. the DS18B20 sensor) is implemented for measuring the water temperature that is mounted on the robotic arm's end effector. The sensor is in a waterproof housing with operating range -55^{0}C to +125^{0}C and accuracy +/- 0.5^{0}C. A combined relative humidity (RH) and temperature (T) sensor (e.g. the DHT22 sensor) provides temperature measurements in the range of -40^{0}C to +80^{0}C with accuracy +/- 0.5^{0}C and relative humidity measurements in the range 0-100%RH with typical accuracy +/-2%RH (max +/-5%RH). A carbon monoxide (CO) sensor (e.g. the MQ-7 sensor) provides CO measurements in the range of 20ppm to 2000ppm. A hydrogen sulfide (H_2S) sensor (e.g. the MQ-136 sensor) provides measurements for concentrations from 1-200 ppm. A methane (CH_4) sensor (e.g. the MQ-4 sensor) provides measurements for concentrations from 200-10000 ppm. An oxygen (O_2) sensor (e.g. the GS Yuasa Oxygen Sensor SK-25 sensor) provides measurements for air oxygen concentrations from 0-30%. Lower Explosive Limit (LEL) percentage estimation is achieved through a combustible gas sensor (e.g. the MQ-6 sensor) combined with measurements from the methane and oxygen sensors to determine through first layer algorithms the Lower Explosive Limit percentage. A volatile organic compound (VOC) sensor (e.g. the TGS-2602 sensor) provides VOC measurements in the range of 1ppm to 30ppm of EtOH. All air sensors are mounted on the upper deck of the Robodillos platform, placed in a Stevenson screen-like miniature protective enclosure. Operations of Robodillos in up to 100% RH is achieved by appropriately treating – where necessary – sensitive equipment with special anti-corrosive and sealant coatings. All sensors are temperature and humidity calibrated. A dedicated waste measurement system is developed for Robodillos. First layer algorithms determine the existence and level of bulky waste (stones, construction debris, wood, sticks, etc.) from the surface variations in 3D laser scan data. In the case of non-bulky waste, local waste height measurement is achieved by a specially-designed actuated tip, mounted on the manipulator that is guided into the waste. Tip guidance is performed through algorithms in the Mobility and Autonomy pillar and the waste measurement is extracted through first layer algorithms of the Sensing and Perception pillar.

The sampling elements (c.) consist of sediments, water and air sampling systems. The sediments sampling is achieved by an actuated clamshell, which is installed on the manipulator, with capability of capturing 300ml of sediments. To avoid sample contamination, the clamshell is sealed when closed. For the air and water sampling a vacuum pump is installed and the vacuum is directed towards the air or water sampling system through an electromechanical valve. For water sampling a 400ml cylinder is installed that is connected to the vacuum pump. A no-return valve ensures that after sampling the sample remains sealed and no contamination occurs. A moisture/water trap ensures that no water flows to the vacuum pump network. Water sampling is achieved through a flexible tube connected on one end to the cylinder and to the other end (the tip) to the manipulator's end-effector. Sampling is achieved by submerging the tube tip in the water. Air sampling is achieved by forcing air through a filter placed in a separate cylinder containing 530mg of active carbon by directing the vacuum pump flow to the air sampling system. The air sampling cylinder also uses no-return valves to ensure that the sample remains sealed and no contamination occurs.

The navigation sensor suite (d.) is designed to provide the necessary Robodillos motion related information to the first layer algorithms. An Inertial Measurement Unit and Attitude Heading Reference System (AHRS) (see e.g. [VEC15]) provides 3-axis accelerations, 3-axis rotation rates (gyroscope), 3-axis magnetic field, and barometric pressure measurements. All wheels are equipped with differential encoders and the manipulator is equipped with absolute encoders for all degrees of freedom.

Mobility and Autonomy

The Robodillos Mobility and Autonomy technology pillar consists of **two layers**:

- Motion task planning and control algorithms utilized through the GNC^3 architecture;
- Robodillos mechanical, electrical/electronic and computing systems.

The **first layer** consists of the Mobility and Autonomy algorithms, comprising the Local Motion Task Planner, the Low Level Locomotion Control and the Low Level Manipulation Control modules in the GNC^3 architecture.

The Local Motion Task Planner module [LOI05, LK05] (see also Annex I), is responsible for fulfilling the local motion task specification provided by the High Level Coordination & Supervision Module in conjunction with the Sensing and Perception pillar. This module provides collision avoidance, tip-over avoidance and navigation capabilities with the last ranging from mixed initiative tele-operation to fully autonomous operation. In the event that a motion task specification cannot be fulfilled, even under local plan reconfiguration [GD13, GD15], this module reports the task specification as infeasible to the High Level Coordination & Supervision Module.

The **second layer** in the Robodillos Mobility and Autonomy technology pillar consists of the Robodillos mechanical, electrical and electronic (including computational) systems.

Robodillos mechanical construction is based on the Atum rover depicted in Fig. 2, developed by the Robodillos industrial partner, Helikas Robotics Ltd.

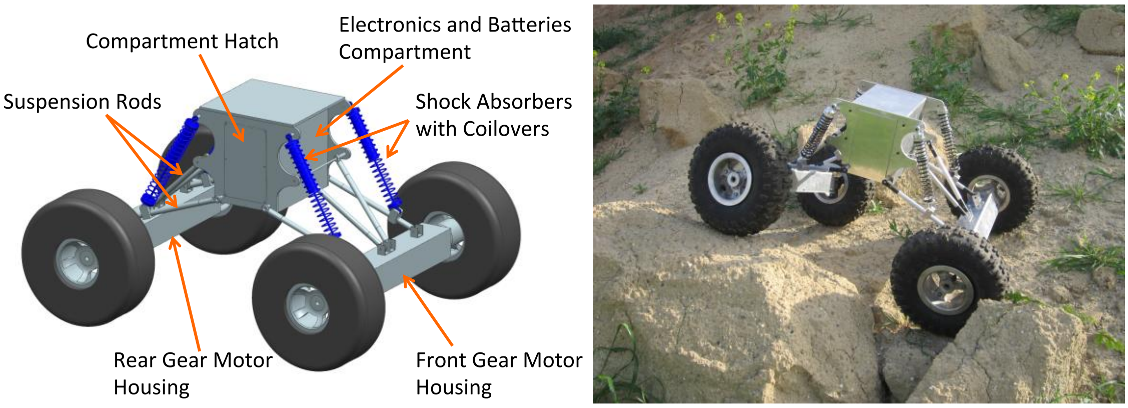

Fig. 2 The Helikas Robotics Ltd. Atum rover. Left: 3D design of Atum and system components. Right: Atum operation in rough terrain.

Atum design utilizes driving symmetry to enable easy and effective exploration of narrow corridors leading to dead-ends. This is a particularly useful aspect for Robodillos since symmetric locomotion enables exploration of narrow sewer location where the only way out is by backing up. Atum employs a three-part chassis, with all locomotion components contained in two identical front and rear frames. This core configuration design provides improved manufacturability through significantly decreased unique part count while minimizing the time required for development by employing standard components from multiple manufacturers. Atum construction is almost entirely out of aluminum to minimize weight and to facilitate machining. The center section can house an array of components including computers, primary electronics bay, and the power source. Moreover, the center section supports an array of extensions including a top bay, robotic arm and additional extension compartments to increase storage capacity. Each frame drives a pair of wheels and each wheel has a single gear motor providing drive torque. The single gear motor at each wheel guarantees that always there is traction, even if one wheel is not in contact with the ground. Atum utilizes skid-steering for direction control, an aspect particularly suitable for Robodillos due to the increased robustness in rough terrain driving similar to tracked vehicles. The improved traction offered by this arrangement is essential for Robodillos robots that operate in the harsh environment of sewers. An additional advantage of Atum, particularly suitable for Robodillos is the capability for in-place rotations. This provides Robodillos with high maneuverability especially in tight turns where a traditional Ackerman configuration would have failed. To further exploit the benefits of the skid-steering mechanism and minimize the side friction effects in the Robodillos project, Atum is fitted with knobby, mud-terrain tires. Atum suspension system provides improved traction and mobility through increased compliance with the terrain. Atum suspension is entirely passive. Passive suspensions have shown their effectiveness in applications such as planetary exploration robots and in Robodillos, the first layer algorithms of the Mobility and Autonomy pillar will exploit this advantage. Atum employs a body averaging suspension, which keeps the center section at half the pitch angle between the front and rear frames. This allows for large excursions of a single wheel while traversing an obstacle while maintaining overall system ground clearance. In addition, the highly flexible suspension, allows the maximum amount of tire area to contact the ground, while keeping the robot as low as possible. The Robodillos robot characteristics can be summed up as follows: height: 0.51m, length: 0.75m, width: 0.58m, ground clearance: 0.22m, top speed: 3.2Km/h, mass: 18Kg (only the Atum Rover) , energy: 650 Wh. The Robodillos conceptual design is depicted in fig. 3. A detailed description of the dimensions and weight of individual components of the Robodillos robot is provided in Annex VI: Robodillos dimensions and weight analysis.

For the needs of Robodillos a specialized manipulator is developed to enable sediment and water sampling and waste height measurement (see Fig. 3). The manipulator has two plus one (for the actuated tip) prismatic degrees of freedom and a rotational degree of freedom to increase its dexterity and also to enable storing the manipulator away from the robot’s field of view when not in use (i.e. when navigating). Although not its main purpose, the manipulator can in special cases enhance the Robodillos mobility envelope by acting as an actuated ground contact.

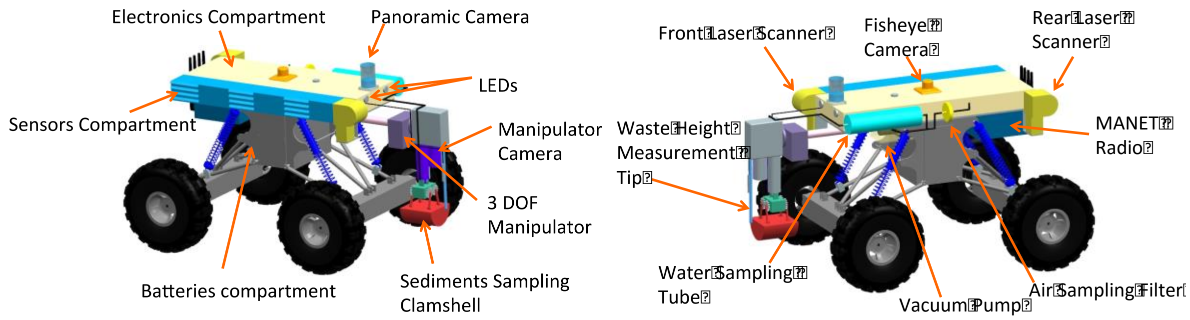

Fig. 3 The Robodillos conceptual design.

Regarding the electrical systems, the locomotion subsystem of Atum is powered by a 6-cell Lithium Polymer battery 22.2 VDC 20Ah, providing autonomy of approximately 4 hours. Robodillos computing, communications, sensing and manipulation systems, utilize three 3-cell Lithium Polymer batteries 11.1 VDC 6.2Ah each, providing an average autonomy of in excess of 4 hours based tests performed during Phase I.

For the electronic (including computational) systems of Robodillos, a dedicated microcontroller unit is utilized to independently control each wheel and the manipulator (including the sediment sampling clamshell), based on the algorithms developed in the first layer. A second microcontroller unit is dedicated to the acquisition and processing of sensor measurements and to control the air and water sampling systems. A redundant computational system is implemented in Robodillos to increase system reliability. The system consists of a redundant array of two PC/104-Plus single board computers and two FPGA modules. With all systems installed, additional storage space will still be available for possible upgrades e.g. additional batteries. The base station consists of a laptop computer, a haptic feedback joystick, and the battery pack that will power the base radio. The laptop computer communicates through cable with the base radio that is submerged in the manhole at the inspection initiation location.

Alternative or competing technologies/approaches

In non-maintained or natural environments, Sandia's cave robot, RATLER [RATL06], RedZone's sewer robots [RZR06] and ROTEKSAN's sewer robots [ROT15] navigate within cluttered caves and sewage-filled pipes for the purpose of inspection. These systems are tele-operated via communication links such as tethers (ROTEKSAN, RedZone) or line-of-sight radio signals (RATLER). These robots do not utilize autonomy as part of their operational capabilities.

Mechanical configurations of subterranean robots, ranging from simple two-wheel differential drive robots to general purpose six wheel mobile platforms, have been used in subterranean operations [ZMO07]. These robots were instrumental in developing and demonstrating the potential of subterranean operations.

The first robot to capture map data from mine environment was "Terregator", a six wheeled multi-purpose research vehicle [CCD91]. Terregator utilized semi-autonomous navigation using a combination of sonar and laser scanners for position estimation and obstacle avoidance. These sensors also enabled Terregator to acquire high resolutions scans of coal mine interiors. However, limited computing power, lack of miniaturization and the requirement of a gasoline generator made the system difficult to deploy in narrow and confined subterranean operations.

The first robot to perform subterranean modeling using Simultaneous Localization and Mapping (SLAM) was a two wheeled differentially driven robot based on the Pioneer platform. Utilizing scanning laser range finders and software designed to map the corridors inside a building, this robot acquired data within the NIOSH research mine and demonstrated the feasibility of relying on SLAM without any GPS or inertial information in order to produce accurate and detailed subterranean maps. However, the data obtained from this Pioneer was acquired in a special, paved portion of a research mine. Pioneer's small, underpowered wheels, designed for indoor operations, were unable to provide locomotion in muddy or even moderately difficult terrain.

Tethers offer one means to provide power to a robot as well as continuous communications. However, tethers must be effectively and actively managed in order to avoid either the robot or the environment destroying the tether or even becoming tangled. A base station tether reel requires the robot to maintain tension on the tether. While this is simple to accomplish over short straight-line distances, in the extensive and convoluted environment found in sewers it becomes impractical or impossible. The more corners the robot goes around, the higher the friction on the tether, until eventually the tether friction becomes greater than either the tractive force of the robot or the strength of the tether. Robot mounted tethers largely eliminate the problem of cumulative frictional forces on the tether by deploying tether as needed based on robot motion. However, robot mounted tethers are limited in size and weight (and hence length) by available robot payload capacity. As with base station mounted tether, a system to prevent the robot from running over its own tether is also necessary. Ultimately, the configuration trade off is between the added complexity and motion restrictions a tether brings versus the ability to provide off-board power, processing and control to a robot [ZMO07]. Therefore Robodillos was designed to be self-sufficient with respect to on-board power, communications and computation capacity.

Beyond determining its physical dimensions, the nature of the sewers influenced the design philosophy of Robodillos. Since the environment is risky and unhealthy for humans, the robot configuration needs to be highly reliable. Reliability usually dictates simplicity, so configurations such as walking robots with multiple moving parts, or flying robots that introduce additional issues, led the consortium to the Robodillos design, avoiding those implications. Fewer actuators, high redundancy, fewer degrees of freedom and simplified operations and controls were favored.

2.2 Logistics required and operational issues by using the solution

Based on the Robodillos solution design and the business plan analysis performed during Phase I, the **Robodillos Inspection Team** is described in the Table below:

Robodillos Inspection Team

• Inspection brigade consisting of
  ○ 1 skilled officer (with sewer inspection training)
  ○ 1 skilled officer (with sewer inspection training) and with training on the operation of the Robodillos system
  ○ 1 van (leasing)
• 1 Robodillos Master robot. This is the robot as described in the Solution Design
• 2 Robodillos Slave robots. These are like the robot described in the Solution Design but with reduced sensor suites and without the manipulator. More specifically Robodillos Slave robots **will not** have the following:
  ○ Manipulator system
  ○ Air/water temperature sensor
  ○ RH, HS, CO, O_2, pH,
  ○ Air and water sampling systems
• 1 Robodillos Base station

Based on our Phase I analysis and design (see section 4: Economic Viability of Robodillos), two (2) Robodillos Inspection Teams will be required to fulfil the benchmark scenario of the Barcelona sewer system.

To detail all the logistics operations for the Robodillos we will describe a typical business day of the Robodillos Inspection Team:

At the beginning of the business day the officer picks up two sets of batteries that were charged during the previous night. The base station computers synchronize their data between themselves. Based on the sewer coverage plan that is produced by the Robodillos Command Center, the two teams are assigned each a specific portion of the sewer map that will be inspected the specific day.

For each Robodillos Inspection Team, the officers load the van with the Robodillos system and one of the officer drives the van to the designated location. The first set of batteries is installed. The manipulator’s clamshell is installed on the Robodillos Master by the skilled officer with Robodillos training. Both officers deploy the Robodillos system through the nearby manhole, and they both return to the van where they connect the base station computer with the cable that runs down to the radio that is in the sewer deployment location.

Case 1: Typical business day without any inspection findings:

The Robodillos trained officer initiates the inspection from the command center in the van. Since no findings are reported by the Robodillos system, the trained officer commands the system back to base after 4 hours of inspection. The system is stopped and the Robodillos trained officer goes in deployment location and switches the batteries with the second set and returns to the van. Then the second inspection round begins. The Robodillos system is automatically redeployed to resume from where it left. The inspection continues until the end of the business day. The trained operator commands the system back to the base and both officers recover the system, perform a sanitation/cleaning procedure and check the system for any visible indications of damage or wear. The manipulator clamshell is removed.

- **Subcase 1.1:** If a sediment sampling procedure was performed: The contents of the clamshell are emptied in a sample container to be send for analysis. The clamshell goes through the sanitization/cleaning procedure and is placed in a neutralizing solution.
- **Subcase 1.2:** If an air sampling operation was performed: The air filter is removed and placed in a sample container to be send for analysis. A new air filter is installed.
- **Subcase 1.3**: If a water sampling operation was performed: The air-tight water sampling syringe is removed and placed in a sample bag to be send for analysis.

The batteries are removed and the system is loaded in the van. One of the officers drives the van back to the office, where the system is unloaded and the batteries are put to charge overnight.

Case 2: Typical business day with inspection findings that require action from the officers:

The Robodillos trained officer initiates the inspection from the command center in the van. A finding is reported by the Robodillos Command Center at a remote location (not within walking distance). The trained operator command the system to pause at it current location. Both officers recover the base radio and cable, sanitize it and load it in the van. The manhole is then closed and sealed. One of the officer drives the van to the closest manhole of the finding that was reported by the system. This point now becomes the new base point for the running inspection. The skilled officer descents to the location of the finding to resolve the issue. When the issue is resolved the base radio is deployed at the new location and the Robodillos trained officer orders the system to resume. The system automatically reconfigures itself to resumes and complete the inspection from the new location. If a new finding is reported, the procedure described in Case 2 is repeated until no new finding is reported and the procedure continues as in Case 1.

3 Test Series

In order to assess the actual performance of the system the Robodillos consortium performed a series of test at the sewer-like structure under the Asprokremos water dam in Paphos (Cyprus) (see Annex V) and also at a mock-up environment setup at the premises of HEL (see Annex II).

3.1 Viability of the robotic solution mobility in the sewer network conditions

The conditions of the sewer like structure at Asprokremos were as follows: High humidy, running water, water dripping, straight tunnels with turns at 90^{o} and at 110^{0}. The Robodillos system had no problem moving and maneuvering in the channel, performing in-place rotations, steering and moving in straight line.

During the test at the mock-up environment (see Annex II), the Robodillos robot successfully execute various maneuvers.

3.2 Communications suitability in underground sewage system network

During the communication tests we performed with the Silvus radios solution at Asprokremos our system could successfully stream in real-time high definition video (6Mbit bandwidth consumption) at straight lines (the maximum straight line stretch was 228m where no performance drop was observed) and on 90 degree curves we could stream real-time high definition video in up to 20m after the curve and at 60m the rate dropped to about 1 frame per second. We were able to communicate between one 90 degree and one 110 degree turn with a setup of 20m->90deg->130m->110deg->20m with three radios. We needed 4 radios for increasing the last part from 20m to 60m without reducing the framerate. Due to the size of the sewer network we could not test the radios at bigger distances. By extrapolating our calculations, we expect that the communications solution will have no problem communicating in straight lines at least 500m. Based on the Barcelona sewer topology that was provided by BCASA (see sewer map in section 4: Economic Viability of Robodillos), the radio solution with four radios will be able to cover an area of more than 152,100.00 square meters containing 3120 lineal meters of sewers (see Annex VII: BCASA Sewer Network Blueprints).

3.3 Autonomy versus mobility of the robotic solution

During our mobility and communications tests at Asprokremos we observed for an hour of continuous operation a battery drain of less than 15%. This implies that the estimated four (4) hour autonomy that we use for our calculations is a conservative estimation and fully capable of supporting our business plan and solution design.

4 Economic Viability of Robodillos

4.1 Robodillos system cost analysis

A detailed business plan is drafted in this section and will be updated during the project development and a final version will be drawn towards the end of the project. The Robodillos system consists of a Robodillos Master robot, 2 (two) Robodillos Slave robots and the Base station. The tables below show the Robodillos pricing analysis:

Robodillos Master Robot Cost Analysis			
Item	**Qty**	**Price**	**Total**
Rover	1	2.000,00 €	2.000,00 €
Manipulator	1	500,00 €	500,00 €
Camera 180 degrees	1	120,00 €	120,00 €
Panoramic optics with camera	1	445,00 €	445,00 €
Laser scanner with mechanism	2	1.200,00 €	2.400,00 €
MANET MIMO COFDM	1	10.000,00 €	10.000,00 €
LiPo 22.2V 20Ah battery	1	300,00 €	300,00 €
Lipo 11.1V 6.2Ah battery	3	65,00 €	195,00 €
LEDs	6	20,00 €	120,00 €
Air/Water temperature sensor	2	10,00 €	20,00 €
Relative Humidity sensor	1	20,00 €	20,00 €
Gastight syringe	1	50,00 €	50,00 €
Hydrogen sulphide sensor	1	85,00 €	85,00 €
Carbon monoxide	1	10,00 €	10,00 €

sensor			
Oxygen sensor	1	150,00 €	150,00 €
pH sensor	1	100,00 €	100,00 €
Sediments samling mechanism	1	500,00 €	500,00 €
Computers pc-104	2	350,00 €	700,00 €
FPGAs	2	1.000,00 €	2.000,00 €
Auxiliary equipment (electronics, etc)	1	2.000,00 €	2.000,00 €
Vacuum Pump	1	100,00 €	100,00 €
Air Sampling Filter	1	50,00 €	50,00 €
Manipulator Camera	1	120,00 €	120,00 €
Labor	1	5.000,00 €	5.000,00 €
Software/algorithms/ IPR	1	8.000,00 €	8.000,00 €
		TOTAL COST	34.985,00 €

Robodillos Slave Robot Cost Analysis			
Item	**Qty**	**Price**	**Slave robot**
Rover	1	2.000,00 €	2.000,00 €
Camera 180 degrees	1	120,00 €	120,00 €
Panoramic optics with camera	1	445,00 €	445,00 €
Laser scanner with mechanism	2	1.200,00 €	2.400,00 €
MANET MIMO COFDM	1	10.000,00 €	10.000,00 €
LiPo 22.2V 20Ah battery	1	300,00 €	300,00 €
Lipo 11.1V 6.2Ah battery	2	65,00 €	130,00 €

LEDs	6	20,00 €	120,00 €
Computers pc-104	2	350,00 €	700,00 €
FPGAs	2	1.000,00 €	2.000,00 €
Auxiliary equipment (electronics, etc)	1	2.000,00 €	1.000,00 €
Labor	1	5.000,00 €	2.500,00 €
Software/algorithms/ IPR	1	8.000,00 €	8.000,00 €
		TOTAL COST	29.715,00 €

Base Station Cost Analysis			
Item	**Qty**	**Price**	**Total**
MANET MIMO COFDM	1	10.000,00 €	10.000,00 €
Laptop Computer	1	2.000,00 €	2.000,00 €
Lipo 11.1V 6.2Ah battery	1	65,00 €	65,00 €
Base for radio	1	100,00 €	100,00 €
Joystick	1	100,00 €	100,00 €
Auxiliary equipment(cables,etc)	1	500,00 €	500,00 €
Labor	1	1.000,00 €	1.000,00 €
Hardware	1	50,00 €	50,00 €
Software/algorithms/ IPR	1	8.000,00 €	8.000,00 €
		TOTAL COST	21.815,00 €

Robodillos cost analysis outline	
Item	Price (€)
Robodillos robot	35.035,00

Robodillos Slave robots (2)	59.443,00
Robodillos Base Station	21.815,00
Robodillos system total	**116.243,00**

Based on the anticipated cost reduction for the customer operations, a 35% profit margin is considered justified, setting the final selling price is **160.000 €**. The table below illustrates the impact of the Robodillos solution to the visitable sewer inspection service of Barcelona.

Impact of the Robodillos solution to the visitable sewer inspection service of Barcelona.		
Current situation	Required Ex-	Robodillos response
Inspection performance is about 1500 meters every 8 hours	At least 1000 meters every 8 hours	The maximum speed of Robodillos robots is 3.2Km/h. How- ever this maximum speed will never be achieved in average. This is due to the need for robots to stop to perform inspection, sampling and waste height measurements. Also according to the experiments that we have performed to similar environment in Cyprus, to observe the connectivity of the radios and also from the blueprints of the sewer network that we have obtained from BCASA we have concluded that the Robodillos robot and slave robots can cover a distance of 3120 meters every 8 hours. This distance is approximately equal to the perimeter of 9 building blocks of the BCASA sewer network blueprints (see Annex VII)
An inspection brigade is composed by 2 skilled officers, 1 pawn and a driver equipped with a van (leasing) and costs	At least 30% cost reductions	Only two skilled officers are required during operation: The system operator and a second officer to aid in the system deployment and recollection. A transportation means is required to transfer and recollect the system at the deployment location. Estimated cost **75 €/h**.

There are 4 brigades available that inspect at least 1.000.000 meters of sewers per year. That means: 4 brigades * 110€/h * 8 h * 214 la- bour days = **753.280**	At least 60% cost reductions	Based on the results of our experiments, only 2 brigades with 2 Robodillos systems, will be capable to inspect more than 1.000.000 meters per year (1.335.360 meters per year). That means 2 brigades * 75€/h * 8 hours * 214 labour days = 256.800**€/year**
Unitary cost is 753.280€ /1.000.000m = **0,75 €/ lineal meter**	At least 60% cost reductions	Unitary cost for 2 Robodillos systems and 2 brigades is 256.800 € / 1.000.000 m ≈ **0,27 € / lineal meter**. (For the anticipated system performance of 1.335.360 meters per year the estimated cost drops to 0.19 € / lineal meter**).**
Sewer inspection costs in Barcelona are about 1 million euros per year, representing the 12.5% of the total sewer management costs.	At least 30% cost reductions	Conservative estimations indicate that 2 Robodillos systems with 2 brigades robot will enable a cost reduction of (0,27 [€ / lm] – 0,75 [€ / lm])/ 0,75 [€ / lm] = **64 % cost reduction**. (For the anticipated system performance of 1.335.360 meters per year the estimated figure is 74.7 % cost reduction).

4.2 Cost Analysis of the Barcelona Sewer Operator

Based on the above calculations, the city of Barcelona sewer operator, by purchasing two Robodillos systems with total cost of 320.000€ and 262.790€ running cost will fully compensate its investment cost from the first year of operation and additionally save in the first year 417.210 € and 737.750 € in every subsequent year.

The Table below demonstrates a detailed analysis of the sewer operator cost for the first year:

First year costs of sewer operator	
Robodillos Systems	320.000€

Brigades Running Cost	256.800€
Additional Batteries	990€
Sample Containers (50 samples/year)	5000€
Total Cost	**582790€**

The Table below demonstrates a detailed analysis of the sewer operator cost for the subsequent years:

Subsequent yearly costs of sewer operator	
Brigades Running Cost	256.800€
Sample Containers (50 samples/year)	5000€
Additional Tires	450€
Total Cost	**262250€**

4.3 Market Analysis

Based on our market analysis, there are **540 major cities with sewer networks** in Europe [VIS14] where the Robodillos system can be potentially implemented. We base our hypothesis on a conservative **8% market share** for Robodillos, that is a total of **32 customers** up to 2023.

The Table below demonstrates the production cost assessment for Robodillos. By this business plan, it is forecasted that by the project completion (2019) one sale of the Robodillos basic package will be performed to the Barcelona municipality. In the next year (2020) 4 sales of the Robodillos system will be performed to interested parties and the following year (2021) 8 sales of the Robodillos basic package are forecasted. Based on this scenario, the industrial partner will become profitable in 2020.

Production cost assessment for Robodillos System									
	2015	2016	2017	2018	2019	2020	2021	2022	2023
Robodillos Robot Production Volume	0	0	0	0	2	4	8	12	16
Unit price	160000	160000	160000	160000	160000	160000	160000	160000	160000
Sales revenues	0	0	0	0	320000	640000	1280000	1920000	2560000
R&D	0	30000	30000	16000	6000	6000	3000	3000	3000

Management	0	0	0	7000	7000	7000	7000	7000	7000
Blue Collar	0	0	0	0	3000	6000	12000	18000	24000
Labor Cost	0	30000	30000	23000	16000	19000	22000	28000	34000
Overhead	0	10000	10000	10000	10000	20000	20000	30000	30000
Material costs	0	15180	3000	0	43830	87660	65745	87660	87660

SW/IPR costs	0	0	0	0	64000	128000	256000	384000	512000
Total Direct Costs	0	25180	13000	10000	117830	235660	341745	501660	629660
Marketing and Distribution costs	0	0	0	10000	25000	30000	30000	35000	35000
Cash flow in	0	0	0	0	320000	640000	1280000	1920000	2560000
Cash flow out	0	23315	55080	43000	158830	284660	393745	564660	698660
Cash flow delta	0	-23315	-55080	-43000	161170	355340	886255	1355340	1861340
Cumulated cash flow 1	0	-23315	-78395	-121395	39775	395115	1281370	2636710	4498050
Funding									
ECHORD++ direct cost	0	6072	600	0	0	0	0	0	0
ECHORD++ overhead	0	10000	10000	0	0	0	0	0	0
Cash flow in	0	16072	10600	0	320000	640000	1280000	1920000	2560000
Cash flow out	0	0	0	43000	158830	284660	393745	564660	698660
Cash flow delta	0	16072	10600	-43000	161170	355340	886255	1355340	1861340
Cumulated cash flow 2	0	-7243	-67795	-232190	-31245	719210	2886835	6878885	13238275

5 **Annex I:** Algorithmic Developments for Robodillos

Paper submitted to the 55th IEEE Conference on Decision and Control, 2016

Multi-Robot Coverage on Dendritic Topologies Under Communication Constraints

Savvas G. Loizou and Christos C. Constantinou

***Abstract*— This paper proposes a novel algorithm for performing multi-robot coverage on networks with dendritic topology where the communication topology is location dependent and where the motion of each robot is constrained by the presence of the other robots in the network. The algorithm provides complete network coverage by the minimum number of robots, maintenance of communication constraints and robot collision avoidance. The minimum number of robots required for coverage is a by-product of the proposed algorithm.**

The efficiency of the algorithm is demonstrated through simulation studies.

I. INTRODUCTION

Multi-robot coverage is a topic that has received a lot of attention during the last decades. Several methodologies are surveyed in [2]. Distributed algorithms using Voronoi partitions and Lloyd's algorithm have been utilized in [3], [4] to tackle the problem. Solutions to the constrained coverage problem based on virtual potential fields were proposed in [10],[9]. In [6] the Spanning Tree Covering (STC) algorithm was proposed. In [1] the Least Recently Visited (LRV) algorithm has been presented to solve the problem of coverage, exploration and sensor deployment. In [8] an algorithm for unknown environment coverage utilizing information gathered by previously deployed nodes while simultaneously attaining line-of-sight communication was presented. Sensor-based coverage algorithms for unknown environment were used in [11].

The main motivation for this work comes from the field of autonomous robotic coverage of large-scale under-ground sewer networks. An array of issues particular to the motivating problem differentiate this work from the existing literature and the proposed solution is the first to the authors' knowledge that tackles this problem. Sewer network systems (see fig. 1) are typically dendritic networks converging in the downstream direction without closed loops. In network systems theory such networks are characterized as tree or more precisely directed tree networks where the directionality is inherited from the sewage flow direction. Sewer network flow channels are typically or restricted dimensions allowing only a single inspection robot at a given position. Robots operating in such networks can only interchange positions at channel junctions. Wireless communications in underground sewer networks are much more challenging than in above-ground settings. The main transmission path is through the underground network's channels, usually non-line-of-sight and with severe attenuation over corridor bends and turns and of course issues related to multi-path reflections. Hence, the communication coverage pattern for each robot differs fundamentally from the typical disk coverage pattern encountered in the multi-robot coverage literature and is strongly dependent on the local topology of the network at each robot's location.

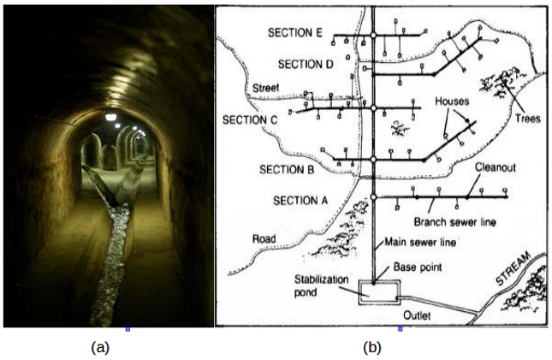

Fig. 1. (a) Sewer flow channels at an Y-junction (b) Master sewer system map. Source: USAID (1982)

Utilizing the planar embedding of the underlying tree topology of the network, a new structure, the *topological buffer* is proposed that enables collision free multi-robot coordination. A wireless communication model that takes into account the local network topology enables the calculation of the communication range at each robot location. Finally, an appropriate abstraction of the multi-robot team as entities commuting through topological buffers embedded across the nodes of the network graph, enables the fulfillment of the coverage algorithm. The resulting algorithm guarantees complete network coverage with the minimum number of robots while maintaining communication between the robots and a base station and avoiding collisions between the robots. A side result of the algorithm is the minimum number of robots required for coverage.

The rest of the paper is organized as follows: Section II presents preliminary notions and definitions while section III introduces the System Modeling. Section IV presents the Coverage Algorithm and section V introduces the Simulation Results. Conclusions are provided in section VI.

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II. PRELIMINARIES

If K is a set then $|K|$ is the cardinality of the set. Let V denote a set of vertices and let $E \subseteq \{(v_1, v_2)\,|v_1, v_2 \in V\}$ denote a set of edges. Then a graph is the tuple:

$$G = \{V, E\}.$$

The degree of a vertex is the number of incident edges to the vertex. If $v \in V$ is a vertex then $N_G(v)$ is the set of adjacent vertices to v. A tree is a connected acyclic graph. A star graph of order n, S_n is a tree with n nodes, with one node having vertex degree $n-1$ and the rest having degree 1. Let $A = \{a_1, \ldots a_i, \ldots a_n\}$, where $n = |A|$, be an ordered set and denote with $A(k)$, $k \in \{1, \ldots, |A|\}$ the k'th element of A. If A and B are ordered sets, then define their disjoint union as

$$C = A \biguplus B$$

where C is an ordered set where:

$$C(k) = \begin{cases} A(k), & k \in \{1, \ldots, |A|\} \\ B(k), & k \in \{|A|+1, \ldots, |A|+|B|\} \end{cases}$$

Define the prefix operator of a non-empty ordered set A as

$$Pre(A) \triangleq A(1)$$

and the postfix operator as

$$Post(A) \triangleq A(|A|).$$

Define the head operator of a non-empty ordered set A to be the ordered set

$$Head(A) \triangleq \{A(i)|\ i \in \{1, \ldots |A|-1\}\}$$

and the tail operator to be the ordered set

$$Tail(A) \triangleq \{A(i)|\ i \in \{2, \ldots |A|\}\}.$$

Definition 1 (Omni-directional buffer): Assume a is an element. An omni-directional buffer is an ordered set B endowed with the following operations.

- ${}^{\rightarrow}B[a]$: push left operation transacted as $B := \{a\} \uplus B$
- $B^{\leftarrow}[a]$: push right operation transacted as $B := B \uplus \{a\}$
- ${}^{\leftarrow}B$: pop left operation transacted as $B := Tail(B)$
- $B^{\rightarrow}$: pop right operation transacted as $B := Head(B)$

By restricting the operation of the omni-directional buffer we get the following:

Definition 2 (Directional buffer): An omnidirectional buffer restricted to operations ${}^{\rightarrow}B[a]$ and $B^{\rightarrow}$ is a left-to-right $(\rightarrow)$ buffer denoted as $\overrightarrow{B}$, whereas when restricted to operations $B^{\leftarrow}[a]$ and ${}^{\leftarrow}B$ is a right-to-left $(\leftarrow)$ buffer denoted as $\overleftarrow{B}$.

We can now define the *topological buffer*:

Definition 3 (Topological Buffer): A topological buffer T is an arrangement of a collection of omni-directional buffers $B_1, \ldots B_n$, each restricted to a direction $d_i \in \{\leftarrow, \rightarrow\}$, $i \in \{1, \ldots, n\}$, arranged on a star S_n topology. Left-to-right buffer operations are directed towards the central hub of the star topology whereas right-to-left operations are directed away from the hub. Assume a is an entity[1]. The topological buffer is endowed with the following operations:

- ${}^{\rightarrow}T_i[a]$: push left operation on $(\rightarrow)$ buffer $\overrightarrow{B}_i$ transacted as: $\overset{\rightarrow\rightarrow}{B_i}\ [a]$
- ${}^{\leftarrow}T_j$: pop left operation on $(\leftarrow)$ buffer $\overleftarrow{B}_j$ transacted as: ${}^{\leftarrow}\overleftarrow{B}_j$
- $T^{i \rightarrow j}$: switch element from $\overrightarrow{B}_i$ to $\overleftarrow{B}_j$ buffer, transacted as the sequence: $\overset{\leftarrow\leftarrow}{B_j}\ [Post(\overrightarrow{B}_i)]$, $\overset{\rightarrow\rightarrow}{B_i}$.
- $T[D]$: reset buffer directionality, where D is a set of directions and transacted as $d_i := D(i),\ i \in \{1, \ldots, n\}$

Contents of buffer B_i of the topological buffer are addressed with $T(B_i)$.

Remark 1: Operations on the buffers are considered to be blocking, in sense that concurrent operations are not allowed on the same buffer.

Fig. 2 depicts a topological buffer on an S_3 topology.

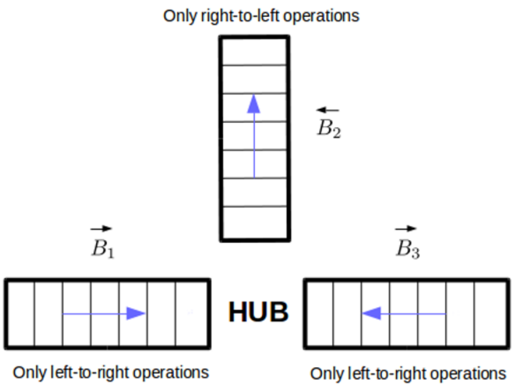

Fig. 2. Topological buffer on an S_3 topology

III. SYSTEM MODELING

A. Network Modeling

Since we are considering dendritic networks, a planar embedding of a rooted tree graph G is used (see e.g. fig. 3). The vertices of the graph represent crossings and bends whereas graph edges represent the corridors of the underground network. At each vertex we install a topological buffer with S_k topology where k in the degree of the vertex. We denote by $v\{T\}$ the topological buffer at vertex v. Left-to-right buffer directionality is assigned to the incoming edge and right-to-left directionality is assigned to outgoing edges. The vertex set of the graph is augmented with coordinate information for every vertex. For a vertex v, $p_x(v)$ is it's x-coordinate and $p_y(v)$ it's y-coordinate. Define the set:

$$V^* \triangleq \left\{(v, v_x, v_y)|v \in V,\ v_x = p_x(v),\ v_y = p_y(v)\right\}$$

Then the planar embedding of the graph is provided by:

$$G^* = \{V^*, E\}.$$

[1] i.e. a robot abstraction

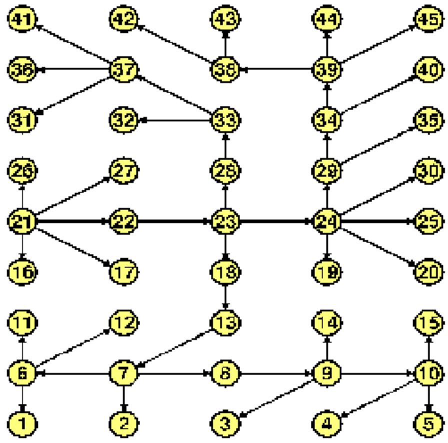

Fig. 3. Network Model

B. Robot Modeling

To capture robot motion in the sewer network an abstraction of the robot kinematics is assumed. Robot motion along sewer network channels represented by graph edges is abstracted as transitions of robot entities between neighboring topological buffers. A robot transition is a locking operation for the topological buffers. This enforces collision avoidance since no two robots can transverse the same edge in opposite directions at the same time. To this extend, due to the ordering enforced by the topological buffers, two robots cannot exchange positions in the same buffer. This abstract behavior is assumed to be executed by appropriate low level motion planners on each robot.

The following algorithm abstracts the robot model:

Algorithm 1 Robot Model

Require: Robot id R_{id}
Require: Robot position at v_{init}
Require: Robot destination at $v_{final} \in N_G(v)$
Ensure: New Robot location

```
if R_id ∈ Pre(v_init{T}(←B_{v_final})) then
    →v_final{T}[Pre(v_init{T}(←B_{v_final}))]
    ←v_init{T}_{v_final}
    return Success
else
    if R_id ∈ Post(v_init{T}(→B_{v*})), v* ≠ v_final then
        T^{v*→v_final}
        return Success
    end if
end if
return Failed
```

where the listing reads, in mathematical notation:

if $R_{id} \in Pre(v_{init}\{T\}(\overleftarrow{B}_{v_{final}}))$ **then**
  $^{\rightarrow}v_{final}\{T\}\left[Pre(v_{init}\{T\}(\overleftarrow{B}_{v_{final}}))\right]$
  $^{\leftarrow}v_{init}\{T\}_{v_{final}}$
  return Success
else
  if $R_{id} \in Post(v_{init}\{T\}(\overrightarrow{B}_{v^*}))$, $v^* \neq v_{final}$ **then**
    $T^{v^* \rightarrow v_{final}}$
    return Success
  end if
end if
return Failed

C. Communications Modeling

Assume that a transmitting agent a is placed at vertex v. Then the communication graph $G^*_{a,v}$ induced by the agent is a subgraph of G^*. In the proposed communications model, signal attenuation related to the geometrical arrangement of the network is being considered. Let $(v_i, v_j) \in E$ be the vertices of an incident edge $e_{i,j}$ of $G^*_{a,v}$. We consider a decay rate that depends on the angle between edges and is constant along the edge. The path loss (dB) along $e_{i,j}$ that depends on a and v, can be modeled as:

$$PL_{i,j,a,v} = -\lambda_{i,j,a,v} \|e_{i,j}\|$$

where $\|e_{i,j}\| = \left\| \begin{bmatrix} v_{x,i} \\ v_{y,i} \end{bmatrix} - \begin{bmatrix} v_{x,j} \\ v_{y,j} \end{bmatrix} \right\|$ and $\lambda_{i,j,a,v}$ the decay rate along $e_{i,j}$ for a source a placed at v. Now assume transmission along edge $e_{i,j}$ continuing along edge $e_{j,k}$. We assign a path loss on the $i \rightarrow j \rightarrow k$ connection, incurred at vertex v_j that is a function of the angle between the two edges:

$$PL_{i,j,k} = f_{\lambda}(arg(e_{i,j}, e_{j,k}))$$

where $arg(e_{i,j}, e_{j,k})$ is the angle between $e_{i,j}$ and $e_{j,k}$. Accurate calculation of λ and of function $f_{\lambda}(\cdot)$ is beyond the scope of this paper.

Fig. 4 depicts the communication pattern for robots placed at nodes 38 and 14 calculated according to the communication model.

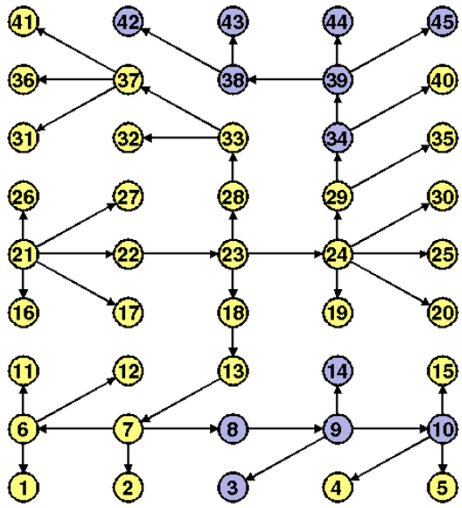

Fig. 4. Communication patterns for $G^*_{a,38}$ and $G^*_{a,14}$

IV. Coverage Algorithm

A. Algorithms

The coverage algorithm assumes that robots are identified and prioritized by their R_{id}. Since topological buffer operations by the robots are blocking operations the algorithm iteratively loops around R_{id}'s effectively permitting only a single robot operation at any time instance. During the initialization phase $G^*_{a,v_{root}}$ is calculated with cutoff signal loss at $-\infty$. This enables the determination of the *hardest* vertex to communicate to as the vertex with the minimum signal strength. A shortest path from the root to this vertex is calculated using Dijkstra's algorithm [5] and this path is used as the initial plan. During algorithm iterations, vertices identified as denoting the communication backbone for the current plan restrict their topological buffer operations to always have at least one robot in them. The communication backbone consists of robots whose communication subgraph union forms a connected component to the base station located at the root and whose per-pair intersections are at most a single vertex. The communication backbone is initialized by inserting the root vertex into it. The algorithm starts iterations after the first robot is inserted into the root buffer facing the second vertex in the current plan. The coverage algorithm is provided by 2 combined with 1 and 3. The following abbreviations are used in the presented algorithms: NPP: next plan position, PPP: previous plan position CBB: communication with backbone, cbb: communication backbone, Move Robot: Use Algorithm in 3, TB: Topological buffer, CL: current location, DSD: Determine shortest directed path from CL to non-covered leaf, NRP:Next Robot Position, RM: Robod Model: Use Algorithm in 1.

B. Analysis

Since the algorithm is an on-line algorithm, each *loop* R_{id} can be executed onboard the corresponding R_{id} robot. Thus, the complexity of the proposed algorithm is dictated by the DSD step that entails the determination of an uncovered reachable leaf from the current location and then the shortest directed path to it using Dijkstras algorithm hence having a worst case complexity of n^2 per iteration.

The algorithm provides by construction the collision avoidance property where in the context of this paper a collision is interpreted as traversal of the same edge by two robots at the same time in opposite directions or position swapping on the same edge between two robots.

Assuming operation of a rooted tree network the algorithm is guaranteed to be deadlock free since each R_{id} loop is performed by locking all other robot's R_{id} loops. Moreover livelock situations at leaf nodes where plan reversal is taking place are guaranteed to never occur since only a singe robot is allowed to be at a leaf topological buffer (line 4 of Algorithm 2).

Communication of every robot with the base station is guaranteed by the communication backbone structure, where a robot can move to a new position only if backbone communication is available and backbone nodes are canceled only when becoming leaves.

Coverage is guaranteed since vertex nodes are abandoned only after becoming a leaf nodes (plan reversal only possible at a leaf node).

The resulting solution uses only the minimum number of robots since at each time all robots are involved in the same plan. This implies that no robots are being utilized for auxiliary plans that would reduce the robot availability for the main plan. Since robots are introduced to the system only when the limits of communication have been reached this

Algorithm 2 Coverage Algorithm

Require: Initial plan *Plan*
Ensure: Network Coverage

1: **while** G^* not covered **do**
2: **loop** R_{id}
3: **if** Not at *Plan* Leaf Node **then**
4: **if** NPP is *Plan* Leaf and populated **then**
5: **return** noProgress
6: **end if**
7: **if** CBB avaiable at NPP **then**
8: Progress? $\leftarrow$ Move Robot to NPP
9: **return** Progress?
10: **else**
11: Add CL to cbb
12: **return** Progress
13: **end if**
14: **else**
15: **if** At backbone and Last in TB **then**
16: Remove CL from cbb
17: **end if**
18: Reset CL TB direction to point out to PPP
19: Reset PPP TB direction to point in from CL
20: Progress? $\leftarrow$ Move Robot to PPP
21: **if** TB is empty **then**
22: *Plan* $\leftarrow$ Head(Plan) $\uplus$ DSD
23: **end if**
24: **return** Progress?
25: **end if**
26: **end loop**
27: **if** noProgress for all R_{id} **then**
28: Insert new robot in root buffer
29: **end if**
30: **end while**

Algorithm 3 Move Robot Algorithm

Require: R_{id}, NRP
Ensure: Motion Succesful

if R_{id} is in TB pointing towards NRP and at Prefix **then**
if (CL NOT in cbb) OR (CL in cbb AND size(TB) > 1) **then**
Progress? $\leftarrow$ RM(R_{id}, CL, NRP)
return Progress?
else
return noProgress
end if
else
if R_{id} is in TB at Postfix **then**
Progress? $\leftarrow$ RM(R_{id}, CL, NRP)
return Progress?
else
return noProgress
end if
end if

implies that only the minimum required number of robots will be used.

V. Simulations

In order to test and verify our algorithms, a set of simulations were performed using Matlab and the Octave - networks - toolbox [7]. A 5×9 square grid with a rooted tree was used as a network model (see fig. 3).

The algorithm was initialized and executed as described in section IV. The root was fixed at node 21. Fig. 5 illustrates the simulation results for our algorithms. The yellow vertices show the places that were not visited and the white vertices show the places that the robots have covered. The pink vertex represents that there are more than one robot in this buffer. Finally, orange vertices indicate the presence of a single robot in that buffer. As mentioned earlier, the starting point for operations is the root vertex node 21 (see fig. 5(a)). Robots initially deploy up to the vertex with the lowest communication signal (fig. 5(b)). Graphs (c) and (d) depict snapshots of the robots covering the network while commuting through topological buffers and maintaining communication. In graph (d) vertex 33 is pink to denote more than one robots in the buffer. Finally, graph (e) demonstrates that the robots have managed to perform the coverage task successfully.

VI. CONCLUSIONS

In this paper we have proposed the development of a novel algorithm for multi-robot coverage on dendritic topologies under communication constraints. This is the first to the authors' knowledge solution to the specific problem. The resulting algorithm guarantees complete network coverage with the minimum number of robots while maintaining communication between the robots and a base station and avoiding collisions between the robots. The minimum number of required robots for coverage is a by-product of the algorithm, and a very useful information for planning ahead inspection operations. Non-trivial simulation results support the provided claims for the presented algorithm.

One of the major advantage of our algorithms is that they can tackle a coverage problem in urban restricted environments such as sewers and pipe networks with restricted dimensionality allowing only a single inspection robot at a given position.

Further research is directed towards optimizing the algorithm for time-optimal coverage and for energy optimal coverage. Moreover adaptation of the methodology for implementation on actual systems is something that we are looking into.

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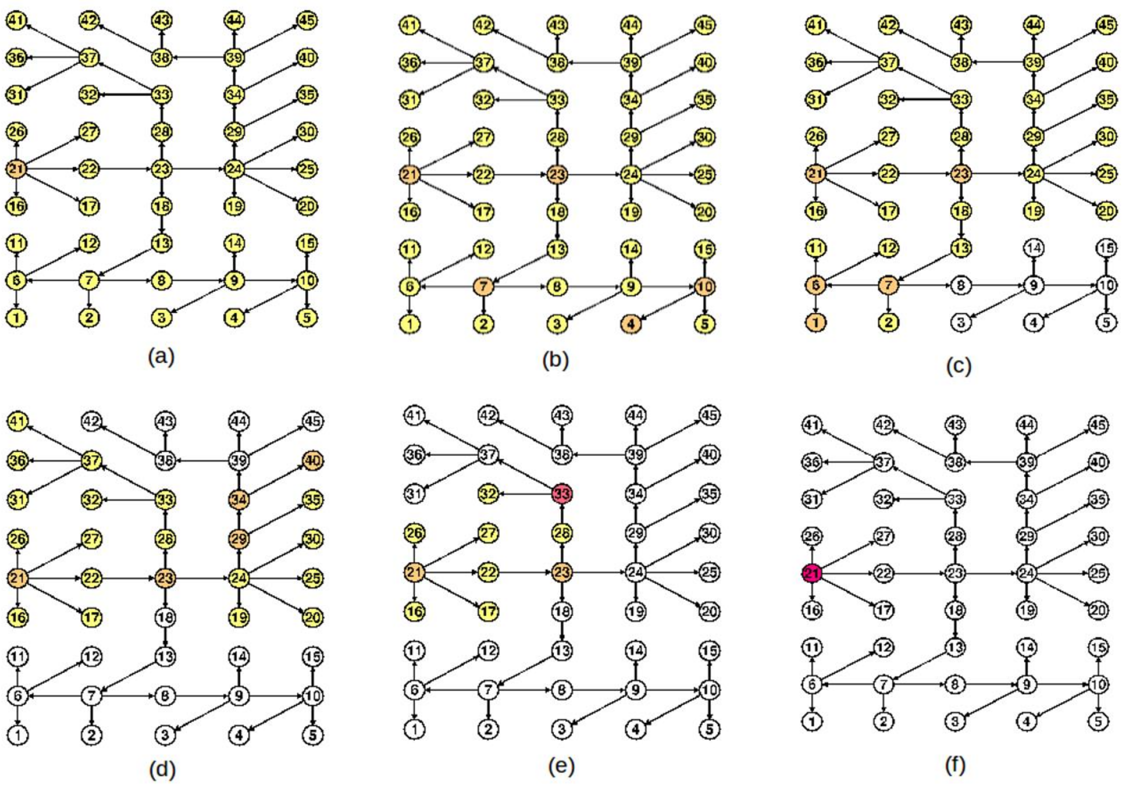
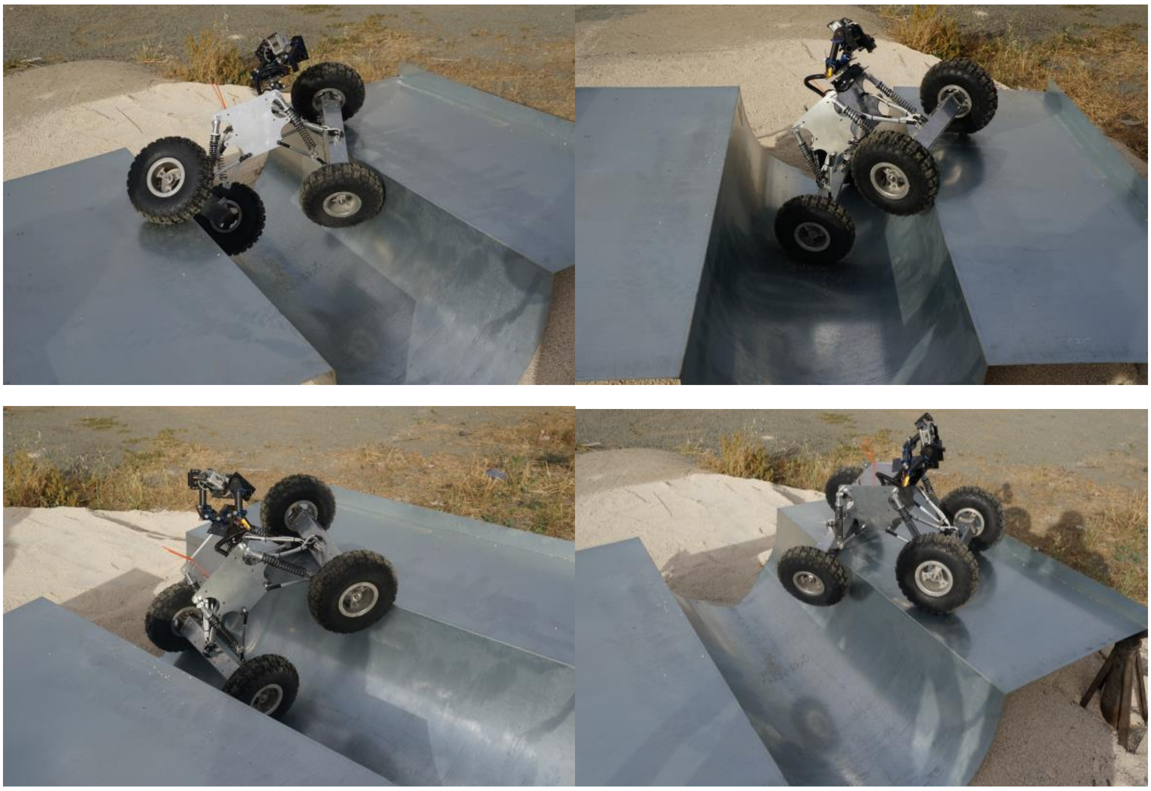


Fig. 5. (a) Initial condition, (b) Deployment to the hardest to communicate to vertex, (c) and (d): Coverage in progress,(e) Multiple robots at vertex 33, (f) Coverage task completed successfully

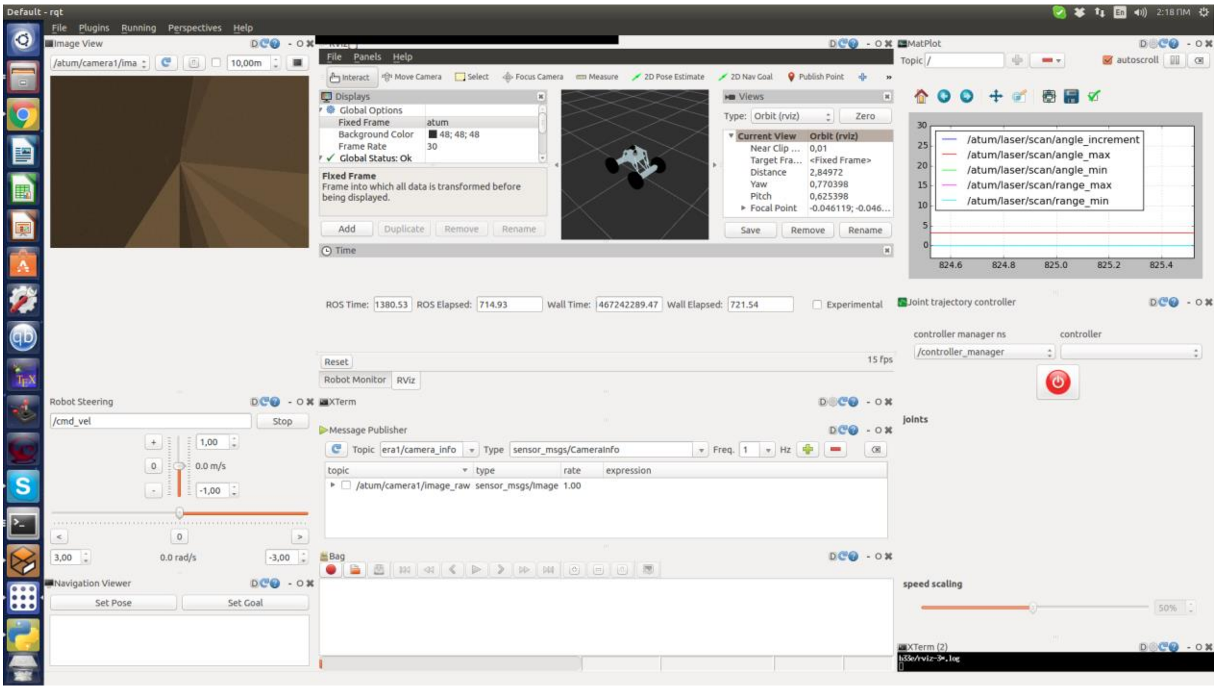
6 Annex II: T436C cross-section mock-up environment

Mock-up environment with the set-up of a T436C cross-section at the HEL premises to evaluate the mobility envelop of the ATUM rover in order to introduce the necessary modifications for the Robodillos rover.

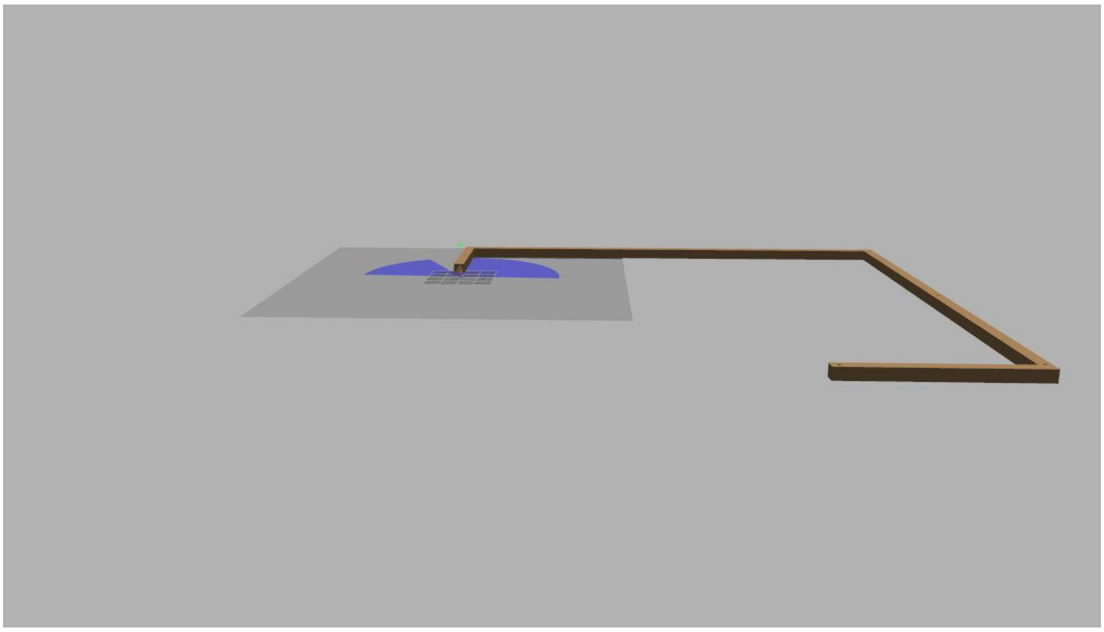


7 **Annex III:** The Robodillos Dynamic Simulation Framework.

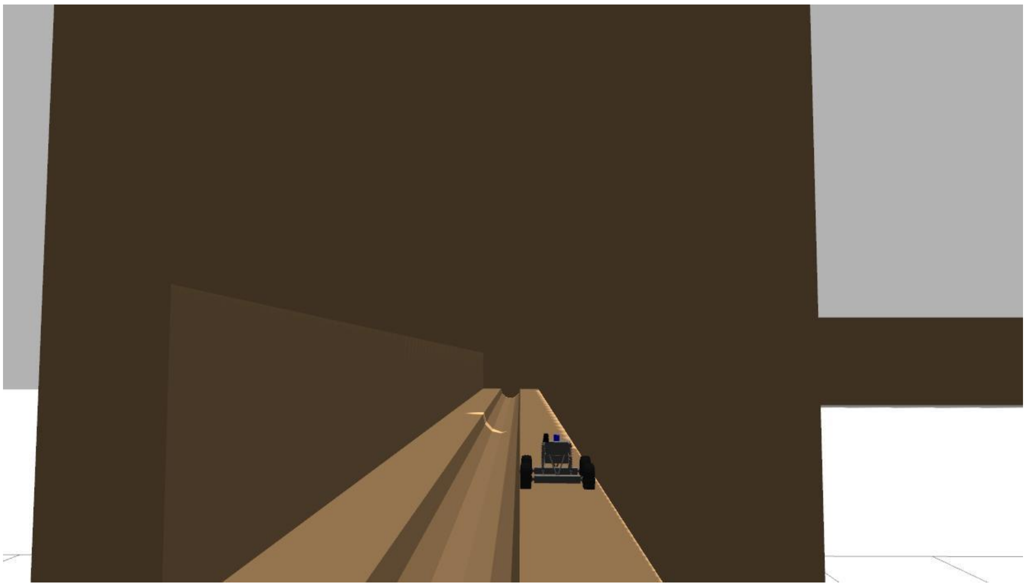
Note: A video of a system simulation is provided along with this document.



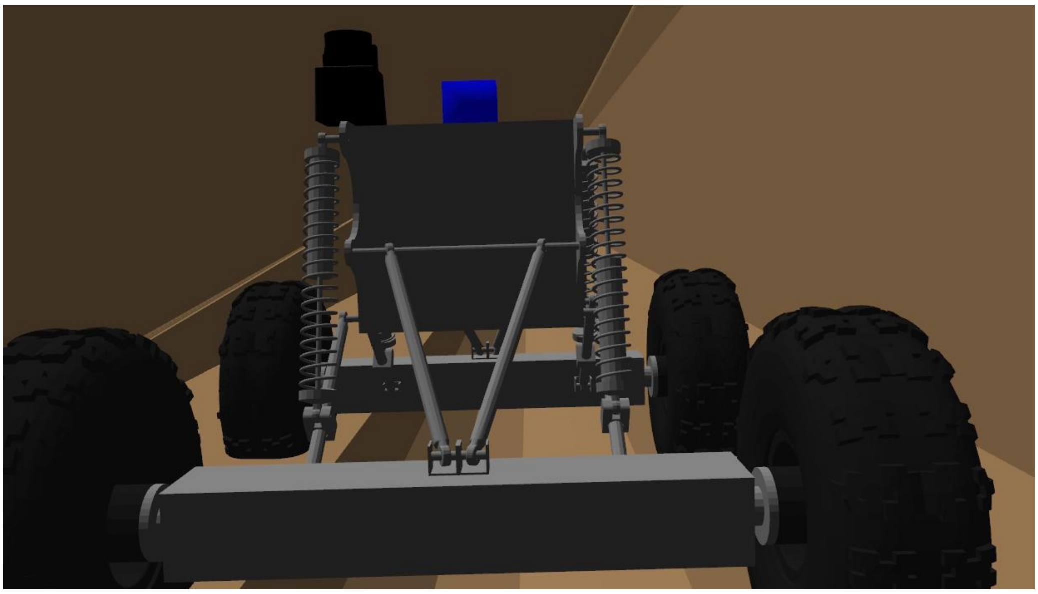
The Robodillos GUI



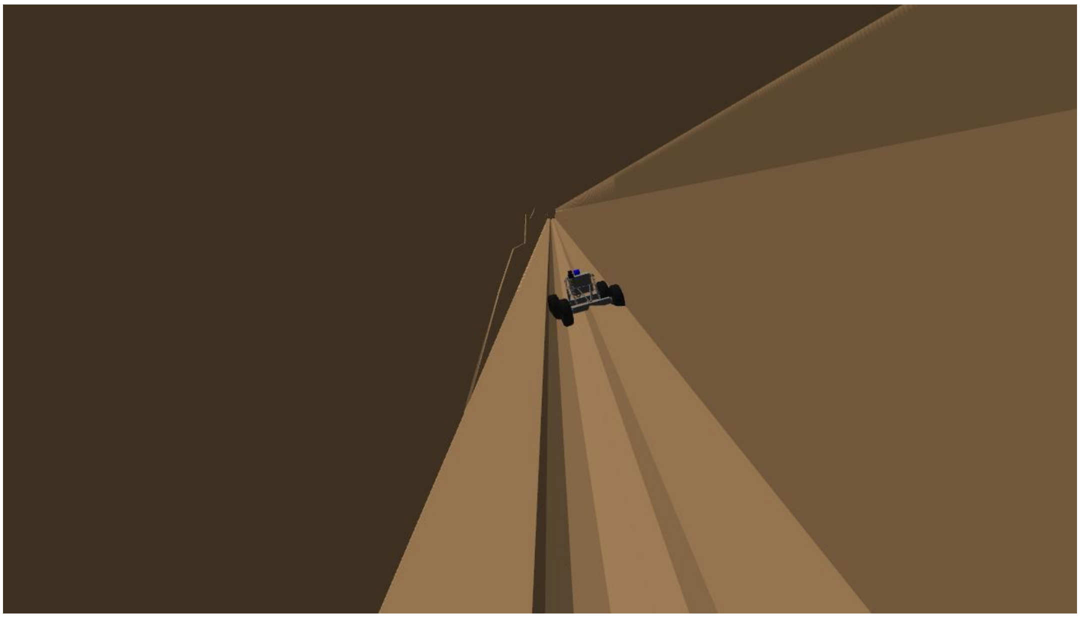
The Robodillos Simulator 3D visualization system: A sewer setup like the one of Phase I test. The blue colour is the laser scanner sensing range just before entering in the sewer.



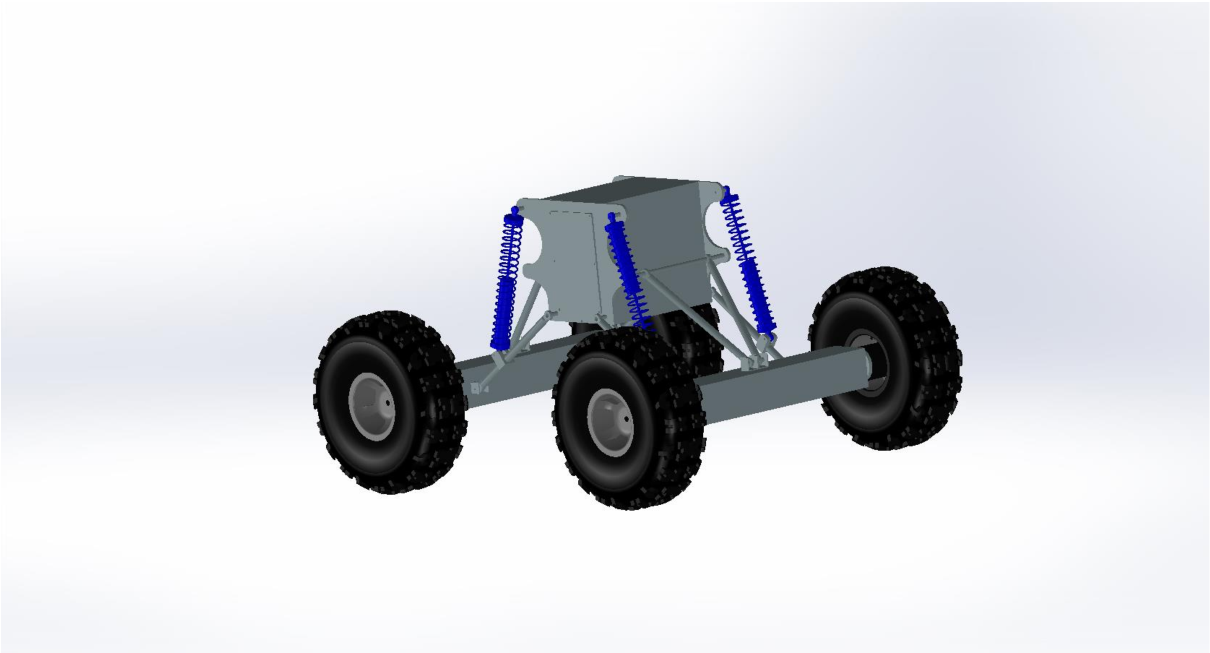
The Robodillos Simulator 3D visualization system: The Robodillos rover during inspection in the sewer



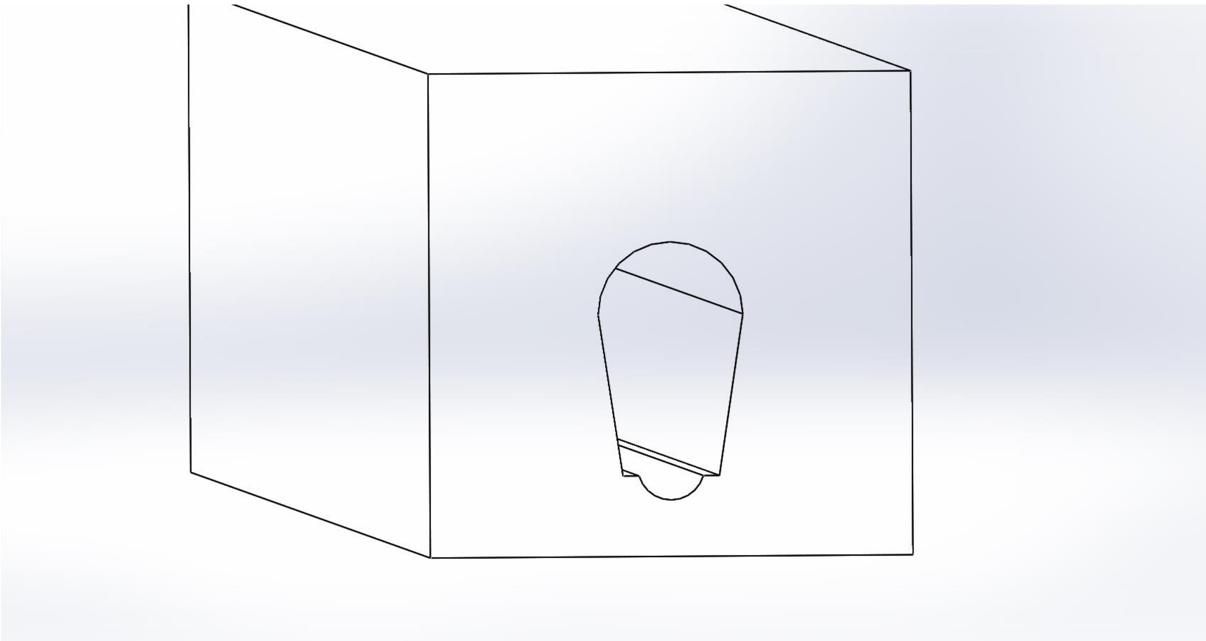
The Robodillos Simulator 3D visualization system: Close-up of the Robodillos rover during the inspection task



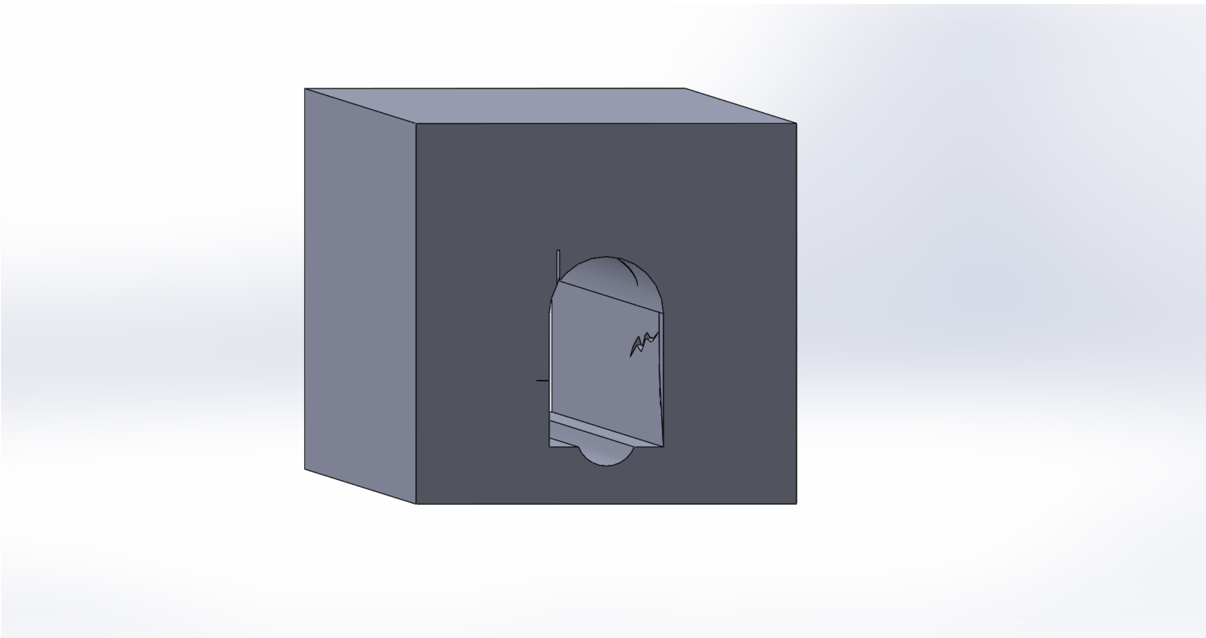
The Robodillos Simulator 3D visualization system: Robodillos rover with two wheels in the pit during an inspection task



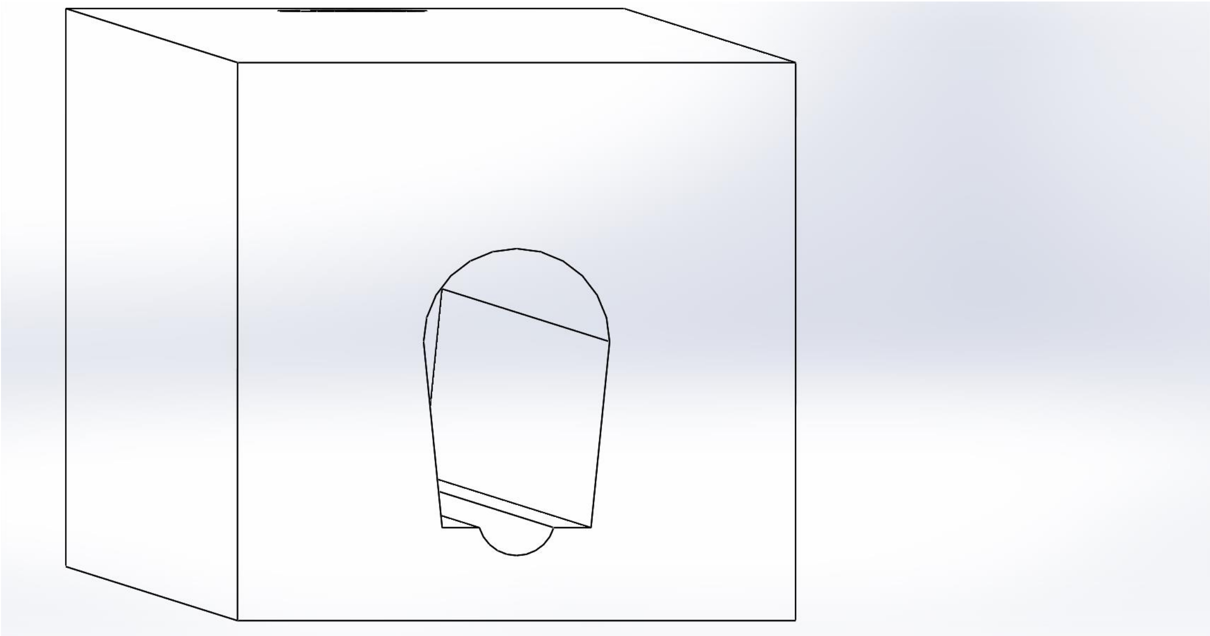
Robodillos Simulator Building Blocks: The Robodillos rover (bare)



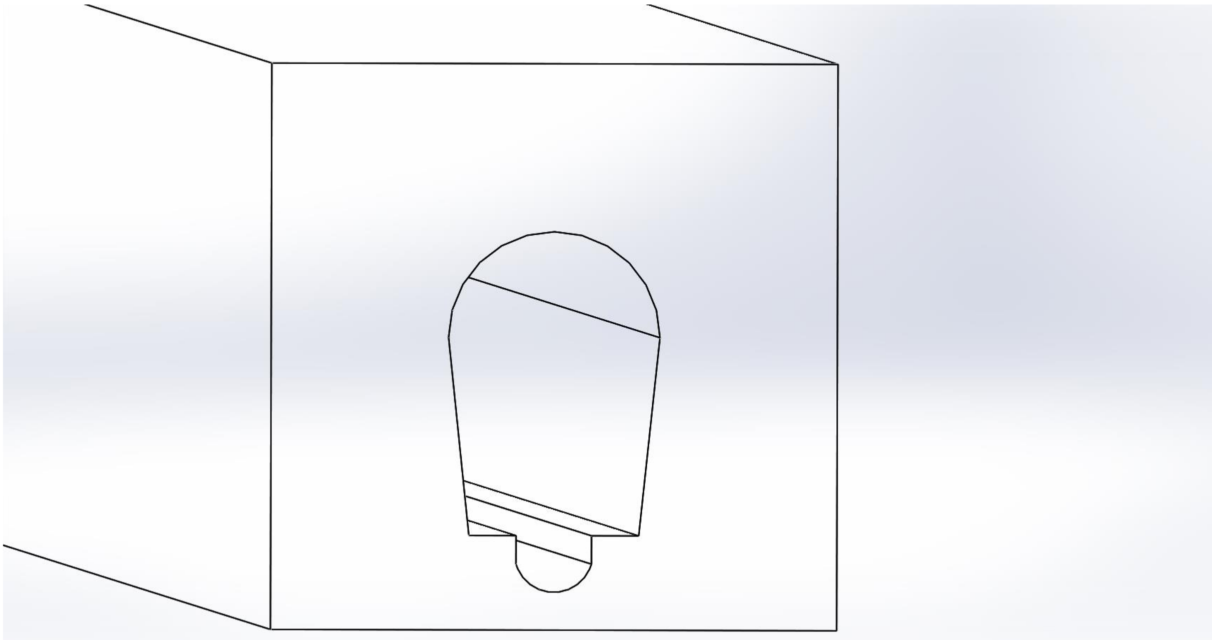
Robodillos Simulator Building Blocks: The T111 cross section



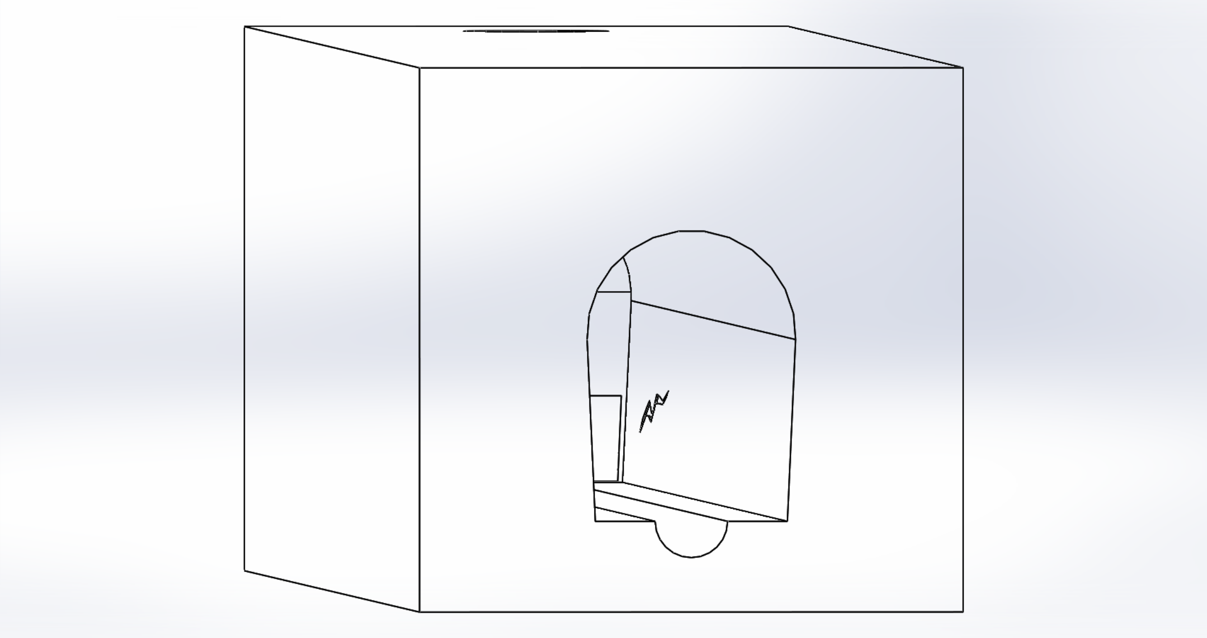
Robodillos Simulator Building Blocks: The T130 cross section with simulated cracks



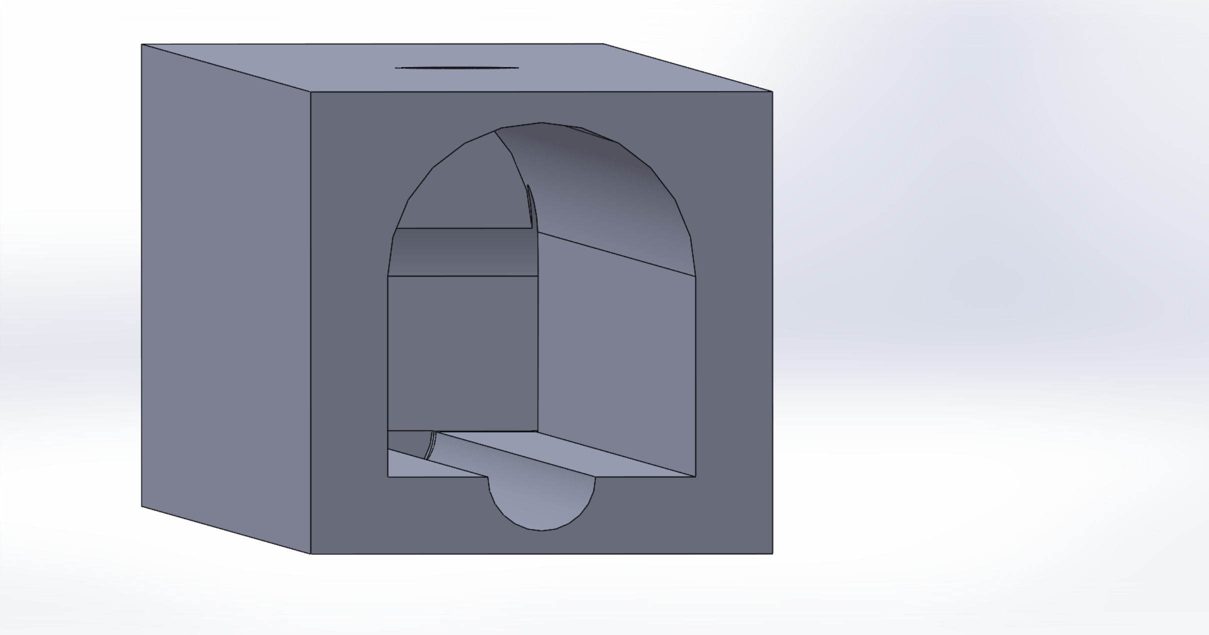
Robodillos Simulator Building Blocks: The T133 cross section



Robodillos Simulator Building Blocks: The T162B cross section



Robodillos Simulator Building Blocks: The T174 cross section with cracks



Robodillos Simulator Building Blocks: The T436C cross section

8 **Annex IV:** Timeline and project Tasks for Phases II & III

8.1 Project Tasks for Phases II & III

Project Tasks for Phases II & III are based on the Robodillos proposal with appropriate enhancements based on the experience gained during Phase I. Tasks 4-9 of Phase II will complete the Robodillos algorithms and technologies and demonstrate working prototype of Robodillos at TRL6. Tasks 10-12 of Phase III will finalize the system development and optimization to ensure the delivery of the Robodillos engineering prototype. Successful completion of the work plan will result in a system of technological readiness level TRL7.

8.1.1 Task List

Phase II (Working Prototype – duration: 12 months)

Task No.	Task title	Lead Participant (short name)	Start month	End month
T4	Robodillos GNC^3 framework	CUT	9	20
T5	Mobile Ad-Hoc Networking	CUT	9	14
T6	Sensing and Perception	CUT	9	18
T7	Mobility and Autonomy	CUT	9	18
T8	System Prototype and Field Testing	HEL	13	20
T9	Dissemination	CUT	9	20

Phase III (Small-scale test series – duration: 12 months)

Task No.	Task title	Lead Participant (short name)	Start month	End month
T10	System Testing and Optimization	CUT	23	34
T11	Independent Tests, Verification and Certification	HEL	29	34
T12	Dissemination and Exploitation	CUT	23	34

8.1.1 Description of individual tasks

Task 4: Robodillos GNC^3 framework [M9-M20]		
Participant	**Role**	**Person-months**
CUT	Leader	12
HEL	Partner	2
Objectives: The main objective of this task is to provide the Robodillos GNC^3 framework as a common architecture for the Robodillos, from the high command center level down to the individual team member level. The task will provide the further development of the Robodillos GNC^3 technologies and algorithms.		
Description of work and contribution of individual participants:		

This task will involve all four technology pillars by elaborating the Robodillos system modules and algorithms. In particular, for each pillar of the system, the following aspects will be addressed, based on the technologies and algorithms developed in Task 1: 1. User Interface: • Enabling mixed-initiative control by fusing user instructions with system wide policies; • Providing all system data and real time graphs and 3D maps of a sewer to a user; • Providing visual/audible/haptic cues about important events of the system to a user; • Supporting simulation capabilities for offline training. 2. High Level Coordination & Supervision module: • Extending a global path planning algorithm by taking into account the user initiatives; • Providing replanning global path capabilities in the case when local motion paths of the Robodillos team member are determined infeasible. 3. Communication module: • Creation of a Robodillos interaction protocol that will allow the system modules to communicate and share data between team members and the Command Center, transfer information between the member's modules, and monitor and react to vital global and local communication problems. 4. SLAM module: • Elaboration of algorithms used in the module to provide 3D geometric information about the sewer network, localize sewer elements of interest and provide their geo-referenced coordinates. 5. Sensor Fusion & Management module: • Monitoring and assessing the sewer serviceability and performing sampling; • Identification and localization of sewer structural defects; • Producing auxiliary specifications to the Local Task Planner module. 6. Local Motion Task Planner module: • Elaboration of the module's algorithms by enabling local path replanning based on specifications from the Sensor Fusion & Management module and reporting about the local path infeasibility to the High Level Coordination & Supervision module. This task will be led by CUT that is responsible for the development of the modules' algorithms and technologies listed in this task while HEL is responsible for field tests.

Task 5: Mobile Ad-Hoc Networking [M9-M14]		
Participant	**Role**	**Person-months**
CUT	Leader	7
HEL	Partner	1
Objectives:		

This task is aimed at implementing the two-layered approach of the Mobile Ad-Hoc Networking pillar as was described in section 1.1.2 of the Robodillos proposal, by comprising the digital wireless communication solution developed in Task 1 and the dedicated Communication module developed in Task 1 and 5.
Description of work and contribution of individual participants: In order to accomplish the two-layered approach of the Mobile Ad-Hoc Networking a wireless communication solution that was tested and configured in Task 1 (Phase I) will be combined with the Communication module. The radio communication technology will be tuned during this task to enable real-time omni-directional networking and data/image/video streaming capabilities. The Communication module will provide continuously monitoring of the communication network and reacting to vital communication aspects and problems. This task will be mainly conducted by CUT while the Helikas Robotics Ltd. will be responsible for the hardware installation of the radios.

Task 6: Sensing and Perception [M9-M18]		
Participant	**Role**	**Person-months**
CUT	Leader	7
HEL	Partner	1
Objectives: The objective of this task is to implement the two-layered Sensing and Perception pillar as was described in section 1.1.3 of the Robodillos proposal, by combining the SLAM and Sensor Fusion & Management modules developed in Task 1 and 5.		
Description of work and contribution of individual participants: During this task, the two layers of the Sensing and Perception pillar will be fused. The imaging sensor suite will be tuned to provide the Sensor Fusion & Management module with high quality image and video streaming. The sewer monitoring and sampling sensor suites will be finalized in order to provide measurements from onboard sensors and to enable the Sensor Fusion & Management module to reason about the sewer serviceability. The navigation sensor suite will be finalized along with the SLAM module algorithms. In this task, CUT will be responsible for the accomplishment of the pillar's modules and finalizing sensor suites, while HEL is responsible for field tests.		

Task 7: Mobility and Autonomy [M9-M18]		
Participant	**Role**	**Person-months**
CUT	Leader	7
HEL	Partner	2

Objectives: This task is aimed at implementing the two-layered approach of the Mobility and Autonomy pillar as was described in section 1.1.2 of the Robodillos proposal, by combining three modules of the Robodillos GNC[3] architecture (Local Motion Task Planner, Low Level Locomotion Control, and Low Level Manipulation Control modules) developed in Task 1 and 5 and the mechanical, electrical and electronic systems of the Robodillos rover.
Description of work and contribution of individual participants: During this task, the algorithms and technologies of the Mobility and Autonomy pillar will be fused. The Low Level Locomotion Control module will control the movements of the Robodillos rover based on the motion specifications from the Local Motion Task Planner module and the location data provided by the SLAM module. The Low Level Manipulation Control module in conjunction with the Sensor Fusion & Management module of the Robodillos rover will generate the necessary commands to the manipulator for the sediments and water sampling operations. This task will be led by CUT that will be responsible for the accomplishment of the modules. The Helikas Robotics Ltd. will be responsible for the comprising mechanical, electrical and electronic systems of the Robodillos rover and their final tuning.

Task 8: System Prototype and Field Testing [M13-M20]		
Participant	**Role**	**Person-months**
CUT	Partner	3
HEL	Leader	5
Objectives: The objective of this task is to provide a Robodillos system prototype and conduct a series of laboratory and field experiments to validate and verify the capabilities and functionalities of the system. The Robodillos system technology will be demonstrated to customers that will be able to carry out tests while accompanied and supported by the Robodillos consortium members. Certification authorities of member states will be involved to provide feedback on Robodillos developments.		
Description of work and contribution of individual participants: The four technology pillars of the Robodillos system will be put together in this task in order to produce a fully functional (TRL6) robotics system for the sewer inspection and clearance operations. The system prototype will be finally tuned and tested through a series of laboratory and field experiments in local sites in Cyprus that simulate real sewer networks in cities. The field demonstrations and tests will be conducted in the sewer network of Barcelona as well in order to exhibit the Robodillos system prototype to customers. The final users will be able to conduct their own tests of the Robodillos system with maintenance and support of the consortium. The customer feedback and the results of the demonstration tests will be used to improve the system performance and system training capabilities throughout this		

task and the Phase III of the project.

To ensure a smooth and expedient certification and standardization process and to receive their feedback regarding the developments in Robodillos, the consortium will involve certification authorities in member states. Strategies developed in Robodillos will be used to influence new safety standards and rules issued by those authorities regarding sewer inspection issues.

The task will be performed by both Robodillos consortium participants while the Helikas Robotics Ltd. will be a leader in this task. The CUT will be responsible for the final tuning and integration of the Robodillos algorithms and modules in order to provide the fully-operational system prototype. The Helikas Robotics Ltd. will be responsible for the field testing and demonstration of the Robodillos system.

Task 9: Dissemination [M9-M20]

Participant	**Role**	**Person-months**
CUT	Leader	2
HEL	Partner	1

Objectives:

The objectives of this task are to disseminate the results of Robodillos, to setup and maintain the project's web site, to publish project results in the scientific journal and conferences.

Description of work and contribution of individual participants:

This task will provide dissemination activities including presentation of the project results in refereed scientific conferences (like IEEE ICRA, IROS, CDC, etc) and journals (Autonomous Robots, IEEE TRO, etc), development of the Robodillos website to make the aims and results of the project available to public, to publish press releases to major newspapers.
The task will be carried out by CUT.

Task 10: System Testing & Optimization [M23-34]

Participant	**Role**	**Person-months**
CUT	Leader	40
HEL	Partner	11

Objectives:

The objective of this task is to conduct lab experiments and field tests in order to improve and optimize the Robodillos system algorithms and technologies.

Description of work and contribution of individual participants:
During this task, the Robodillos system and its components will be intensively tested in different environments including simulations, lab experiments, field tests in sites similar to sewer topology, and field tests in Barcelona's sewer network. The results of the experiments will be used in the system optimization process that aimed at improvement of the Robodillos performance in terms of computational time, costs, and the quality of the sewer inspection and clearance tasks. In this task, different alternatives may be considered such as optimizing Robodillos software, utilizing faster computers or more FPGAs and introducing redundancy to the system. The task will be led by CUT that will be responsible for the Robodillos software optimization while Helikas Robotics Ltd. will conduct tests and improve the Robodillos hardware performance.

Task 11: Independent Tests, Verification and Certification [M29-34]		
Participant	**Role**	**Person-months**
CUT	Partner	4
HEL	Leader	12
Objectives: The purpose of this task is to conduct the tests of the Robodillos system that are carried out by customers independently of the consortium in order to verify the full functionality of the Robodillos system. Moreover, this task will aim at obtaining the necessary certification and standardization of Robodillos.		
Description of work and contribution of individual participants: The Robodillos will be exposed to a series of field tests carried out by the customers without interaction with the consortium participants. These tests will be used to verify the effectiveness, performance and full functionality of Robodillos in the sewer inspection and clearance tasks. An engineering prototype of Robodillos will be provided as a result of this task. Certification and standardization processes for Robodillos will be carried out in this task to obtain the necessary certificates. The task will be led by Helikas Robotics Ltd. with support of CUT that will help with conducting the experiments and processing of their results.		

Task 12: Dissemination and Exploitation [M23-M34]		
Participant	**Role**	**Person-months**
CUT	Leader	3

HEL	Partner	1
Objectives: The objectives of this task are to actively and broadly disseminate and exploit the results of Robodillos by development of an exploitation plan for results of Robodillos including activities to be implemented during the project and after its completion, and publication of results and their dissemination to the public through academic, technology transfer and industrial channels.		
Description of work and contribution of individual participants: This task will provide dissemination activities including presentation of the project results in refereed scientific conferences and journals, maintenance of the developed Robodillos website, publishing press releases, organizing of a workshop or information events, elaboration of an exploitation plan containing target market assessment, business model definition, risk identification and contingency plan definition. The task will be carried out by CUT with collaboration of Helikas Robotics Ltd.		

8.1.2 List of Deliverables

Del. No.[2]	Deliverable name	Task No.	Nature[3]	Dissemination level[4]	Delivery date[5]
SB	Story Board		O	RE	M34
MMR	Multi-Media Report		O	PU	M34
D9.1	Press release	9	R	PU	M9
D4.1	Robodillos GNC[3] architecture	4-7	O	RE	M14
D8.1	Robodillos system demonstrator	4,6-8	D	PU	M20
D9.2	Project website	9	O	PU	M20
D9.3	Papers in relevant conferences	9	O	PU	M20
D9.4	Press release	9	R	PU	M20
D10.1	Robodillos functionalities and performance	10	O	PU	M28
D11.1	Robodillos engineering prototype	11	P	PU	M34
D12.1	Paper submissions to conferences and journals	12	O	PU	M34
D12.2	Press release	12	R	PU	M34

[2] Deliverable numbers in order of delivery dates. Please use the numbering convention D<T number>.<number of deliverable within that <T>. For example, Deliverable 4.2 would be the second deliverable from Task 4.
[3] Please indicate the nature of the deliverable using one of the following codes: R = Report, P = Prototype, D = Demonstrator, O = Other
[4] Please indicate the dissemination level using one of the following codes: PU = Public, PP = Restricted to other programme participants (including the Commission Services), RE = Restricted to a group specified by the consortium (including the Commission Services, CO = Confidential, only for members of the consortium (including the Commission Services).
[5] Measured in months from the PDTI R&D project start date (month 1).

8.1.3 Summary of technology development effort (in person months, PM)

Phase II (Prototyping – duration: 12 months)

Participant short name	Task 4	Task 5	Task 6	Task 7	Task 8	Task 9	Total PM
CUT	12	7	7	7	3	2	38
HEL	2	1	1	2	5	1	12

Phase III (Small-scale test series – duration: 12 months)

Participant short name	Task 10	Task 11	Task 12	Total PM
CUT	40	4	3	47
HEL	11	12	1	24

8.1.4 List of milestones

MS number	Milestone name	Task(s) involved	Expected date[6]	Means of verification[7]
Milestone Phase II	First Field Trials: Technology demonstration at the site of the public bodies involved. Main functionality is realized at a degree that experts at the public bodies can carry out pre-defined tests, when accompanied by developers.	T4-8	M20	This milestone is related to the successful accomplishment of the Robodillos functional model, its testing and verification by a series of field tests. The developed technology is demonstrated and tested by customers with accompaniment of the consortium participants. The deliverables D2, D3 are successfully completed and presented. The critical decisions for Phase III are provided.
Milestones Phase III	Engineering Prototype Development of prototypes with final technology sub-systems or close analogues in a close to complete form factor. All identified functionality is capable of being demonstrated. Verification trials (independent of developer support) by public bodies possible	T10-11	M34	This milestone is related to the successful accomplishment of the Robodillos engineering prototype. The validation of the prototype is demonstrated through a series of field tests carried out independently of the consortium participants. The deliverables D4, D5 are successfully completed and provided.

[6] Measured in months from the PDTI R&D project start date (month 1).
[7] Show how it can be checked that the milestone has been attained. Refer to indicators if appropriate.

The Gantt chart below shows the timeline of the tasks for Phase II & III and the deliverables and milestones of the project (see Fig. 4).

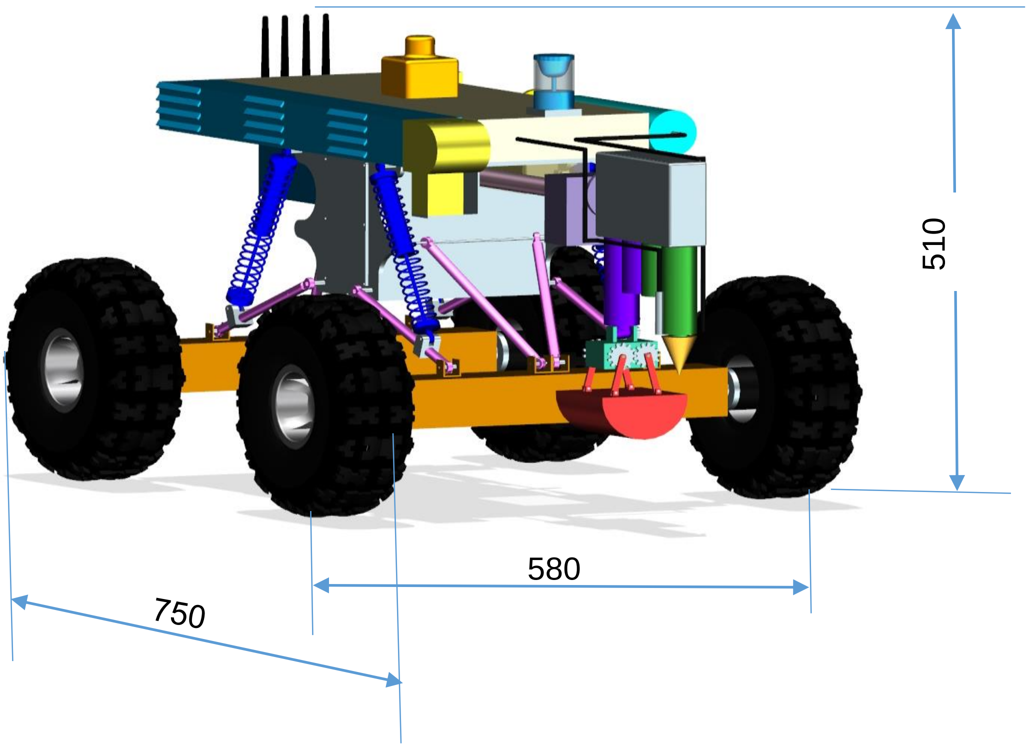
	Phase	Phase 2														Phase 3											
	Milestones												M2														M3
	Month	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
1	Solution Design and Technology Development																										
2	System Modeling and Simulation																										
3	Validation and Benchmarking																										
4	Robodillos GNC^3 framework						D4.1																				
5	Mobile Ad-Hoc Networking																										
6	Sensing and Perception																										
7	Mobility and Autonomy																										
8	System Prototype and Field Testing												D8.1														
9	Dissemination	D9.1											D9.2, D9.3, D9.4														
10	System Testing and Optimization																				D10.1						
11	Independent Tests and Verification																										D11.1
12	Dissemination and Exploitation																										SB, MMR, D12.1, D12.2

Fig. 4. Gantt chart.

9 **Annex V:** Experiments under the Asprokremos water dam

10 Annex VI: Robodillos dimensions and weight analysis

Robodillos dimensions:



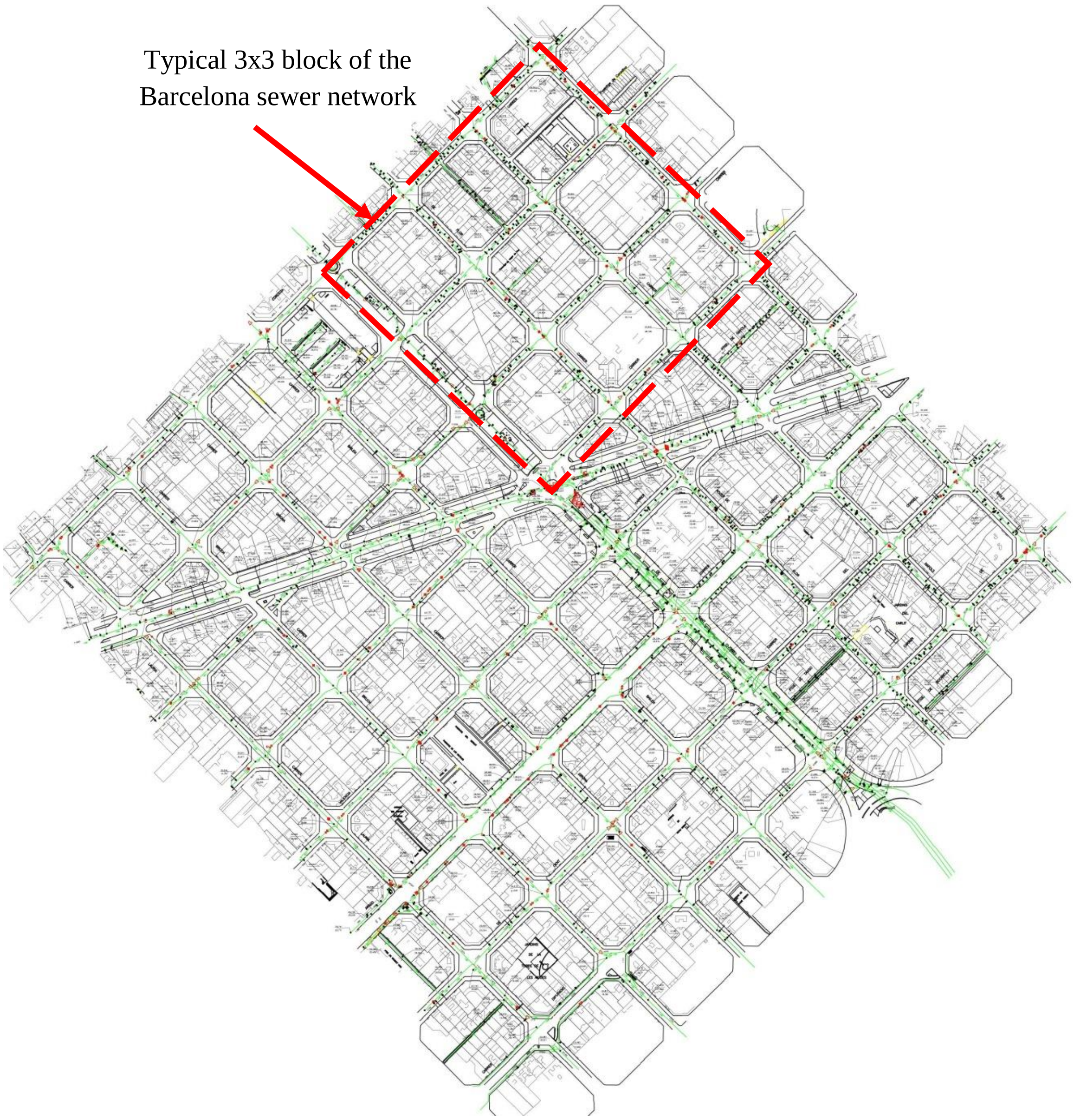
Robodillos additional weight analysis for the requirements of Phase I Evaluation:

During Phase I evaluation since many components of the final system will be missing, dummy weight will be added to simulate the final weight of the Robodillos System. The missing weight analysis is presented in the table below. From the missing weight analysis, **3599g** of additional dummy weight will be distributed to two different compartments of Robodillos robot for the needs of the Phase I evaluation test. More specifically **1668g** will be located at the central compartment and **1931g** in the upper compartment of the Robodillos robot. These values correspond to the weights of the final system as these are allocated to each compartment.

Additional Weight Required for Phase I Evaluation Test			
Item	**Unit Weight**	**Qty**	**Missing Weight**
Manipulator	470g	1	470g
Camera 180 degrees	46g	1	46g
Panoramic optics with camera	260g	1	260g
Laser scanner with mechanism	260g	2	520g
LiPo 22.2V 20Ah battery	700g	1	700g
Lipo 11.1V 6.2Ah battery	150g	3	450g
LEDs	15g	2	30g
Air/Water temperature sensor	5g	2	10 g
Relative Humidity sensor	8g	1	8g
Gastight syringe	25g	2	50g
Hydrogen sulphide sensor	9g	1	9g
Carbon monoxide sensor	10g	1	10g
Oxygen sensor	8g	1	8g
pH sensor	10g	1	10g
Sediments sampling mechanism	150g	1	150g
Computers pc-104	180g	2	360g
FPGAs	100g	2	200g
Vacuum Pump	250g	1	250g
Air Sampling Filter	10g	1	10g
Manipulator Camera	48g	1	48g
TOTAL WEIGHT			**3599g**

11 Annex VII: BCASA Sewer Network Blueprints

BCASA blueprints of a snapshot of the sewer network. This map was used as a benchmark case on which we based our analysis to determine the performance of the system.



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