3D laser imaging techniques to improve USaR operations for wide-area surveillance and monitoring of collapsed buildings

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Abstract

3D laser imaging systems operate at night in all ambient illuminations and weather conditions. These techniques can perform the strategic surveillance of the environment for various worldwide operations (up to long ranges). ONERA, the French aerospace lab, develops and models new active imaging concepts based on new sensor technologies. The knowledge of the relevant physical phenomena impacting on the performances of such 3D-lidar techniques is essential to face the new scientific challenges.

This talk will be illustrated by applications such as the European project INACHUS. INACHUS will improve the detection and localization of trapped victims. It aims to achieve a significant time reduction related to Urban Search and Rescue (USaR) phase by providing wide-area situation awareness solutions.

Emergencies and crisis are an inevitable fact of modern life, with extreme weather events, fires, hazmat spills and traffic accidents happening often and in every jurisdiction. The potential consequences are indisputable: serious injury and/or death to public and to responding personnel, damage to public and private property and the risk of long-term financial repercussions, among others. Under the resulting chaotic and difficult working conditions Urban Search and Rescue (USaR) crews must make quick decisions under stress to determine the location of trapped victims as quickly and as accurately as possible. The EU FP7 project INACHUS presents a holistic approach in providing a system that aims at achieving significant time reduction related to the USaR phase by advancing wide-area situation awareness solutions for improved detection and localization of trapped victims, assisted by simulation tools for predicting structural failures and a decision support mechanism incorporating operational procedures and resources of relevant actors. In the proposed approach structural damage analysis is performed based on input coming from 3-D airborne and ground-based laser-scanning, images and their subsequent analysis through advanced photogrammetric and computer vision techniques, and Structural Health Monitoring (SHM) sensors pre-installed inside the buildings. Furthermore, INACHUS involves new types of sensors and technologies for detecting and localizing trapped survivors in disaster situations (among others bio-chemical sensors, ground-based seismic sensors, infrared sensors, real-time locating systems, radars, etc.). Several miniaturized sensors are integrated into a snake robotic system capable to penetrate into the rubble and provide useful information in order to locate possible trapped survivors. Robust snake robot design together with a novel control system enable operator controlled robot operations in complex environments. This paper presents the general concept of INACHUS solution together with preliminary evaluation results of the applied techniques evincing that the proposed system could significantly contribute in successfully addressing the societal demand to increase survival rates in the aftermath of natural or man-made disasters by tackling a plethora of practical operational challenges, including increased effectiveness of USaR operations with the same number of human resources and enhanced situational awareness.

Keywords **- Search and Rescue; Survivor Localization; Structural Damage Analysis; Sensors; Remote Sensing**

I. INTRODUCTION

Natural or man-made disasters often result chaotic and difficult working conditions where USaR crews must make quick decisions under stress to determine the location of any trapped victims as quickly and as accurately as possible. Statistics show that an efficient USaR system can reduce accident human losses to 9%, compared to situations without emergency system.

INACHUS[1] contributes in saving lives by establishing an effective USaR operations framework that aim at rapidly assessing the potential of locating entrapped victims. In particular, INACHUS assists the operations of First Responders (FRs) and USaR teams by providing an integrated platform that enhances the operational effectiveness of all those involved in complex USaR and first response activities. Towards this direction, INACHUS offers deeper understanding of typical scenarios for structural failures and their damages following various types of incidents (i.e. earthquake, fire, explosions, flooding, terrorist attack), as well as integrate new types of sensors and technologies for detecting and localising trapped alive humans. INACHUS[2] tackles a wide series of practical operational challenges that include increased effectiveness with the same number of human resources, enhanced situational awareness, effective and safe tactics and uninterrupted flow of information and decision making through different levels of commandment and logistics organization, towards generating new standards for interoperability of equipment and processes. More specifically, the following technical solutions shape the INACHUS approach:

1. **Simulation tools for estimating the number and locations of survival spaces created after a structural collapse,** based on appropriate civil engineering methodologies. INACHUS introduces and adapts demolition simulation technologies to provide the structural damage projection/estimation with more effective use of earliest research findings. Through simulation the analysis of various likely scenarios of structural failures is possible for different building materials and construction types. The aimed simulations software toolset is therefore subdivided into different sub modules that support the first responders and decision makers in every time scale after the disastrous event by providing predictive information on different levels of detail. The sub modules that should support the direct response after the event is the "**fast assessment tool"** for damage assessment on the city quarters level. Main output of this module is the decision support for first responders on where to rescue first (triage) in combination with the support in evaluation of accessibility of the identified quarters. Furthermore, valuable information for the design (decision) of rescue paths is provided.

   Moreover, on the structural level of a single construction detailed mechanical analysis is delivered by the "**Progressive collapse risk assessment module**". In the sub module safe and unsafe regions within a building complex are identified and based on this rescue paths within the building are derived whereby also potential traps in the building can be located.

*1 **Inachus** was the king and -according to some beliefs- also the founder of Ancient Argos. According to the legend, Inachus settled in the kingdom of Argos many generations before the flood of Deucalion. During the flood of Deucalion, Inachus saved the surviving people by leading them from the fields to the mountains.*

2 http://www.inachus.eu/

Finally, the "**Collapse prediction and debris heaps assessment module"** supports the identification of possible survival spaces and indicates where survivors are likely to be found. 3D simulated data in combination with on-site metrology is expected to dramatically increase the chance to find obscured victims faster.

2. **Decision and Planning Components for Advanced Casualty and Damage Estimation**. This tool provides the structural damage analysis based on input coming from i) 3-D airborne and ground-based laser-scanning, ii) images and their subsequent analysis through advanced photogrammetric and computer vision techniques and iii) Structural Health Monitoring (SHM) sensors pre-installed inside the building.
3. **Integration of existing and novel sensors** as well as advanced "electronic nose" based on off-the-shelf sensors for accurate localization and detection of alive trapped humans. The sensors include dedicated Ultra-Wide-Band (UWB) radar with beam-steering capabilities, CW Doppler radar for monitoring of respiratory motion of detected victims, bio-chemical sensors as well as infrared camera with ultra-low power consumption and easy deployment. In order to aid radar-based detection and localisation of the victims by mitigating sources of vibrations, distributed, ground-based seismic sensors are deployed. The use of positioning of buried mobile phone units are pursued in the project in order to assess the likelihood of presence of trapped victims.
4. INACHUS advances the state of the art by developing a **robust snake robot mechanism together with a snake robot control system** which enables operator controlled snake robot operations with autonomous robot capabilities. The snake robots are deployed by the USaR crews in order to penetrate into the rubble and provide radar and video information from inside the rubble, in order to refine the 3-D image of the demolished building, and at the same time search for trapped survivors.
5. The **interconnection** between the developed devices; INACHUS aims to provide an integrated architecture on a network-centric scheme to interconnect all needed sensors and actors via advanced and secure communication links, able to decrease time of reaction and drastically increase the efficiency of the relevant actors. INACHUS designs a robust, resilient, redundant, seamless and interoperable communication platform to ensure that the sensors data can reach the command center; then the decision will be transmitted to first responders. INACHUS integrates also technologies, protocols and algorithms resilient to multipath errors and combine them in order to compensate the weak points and give the best-effort localisation of the targets inside the rubble.
6. **Enhanced data fusion and analysis techniques** to improve USaR operations with respect to response time and situational awareness, which are optimized through the location of the survival spaces formed under the debris, thus providing the rescue teams with a clearer picture of the situation at hand and eliminating redundant time to search for survivors. Moreover, escape routes are determined, so that rescue teams can reach these potential survivors and extract them from the debris in the minimum possible time.

   The structure collapse simulation tools, along with the Advanced Casualty and Damage Estimation tool provide estimation (size and location) on the formation of living spaces under the debris. The various sensing mechanisms deployed at the destruction site provide the location of possible survivors hidden under the rubble. Through the use of ontologies and intelligent algorithms the data from these two groups of data sources are fused and contribute to the overall improvement of the situational awareness and the decision support of the rescue teams. The overall end result is the faster response times and optimized operations planning, thus leading to an increase in successful rescues of survivors.
7. **System Integration** of all the above software and hardware subcomponents (INACHUS platform). The integration of the aforementioned components is based on well-defined standardisation and interoperability procedures, and all integration steps are specified and detailed at the early stages of the project. Each system component needs to be tested vigorously with respect to its functionality, and validated for integration.
8. **Contribution to standards/best practices and guidelines for the USaR operations through strong user presence.** The project facilitates interaction with relevant international standardisation organizations and public authorities engaged in the fields of interest, through an early defined and developed User Group, ensuring the establishment of strong links with the user communities and standardisation bodies**.** The ultimate goal is to conclude on pre-normative standards through modern dual path Standardisation process: Standardisation Organizations committees and workshop agreement/industrial specifications group. The conclusions reached for the pre-normative standards can be also applied as recommendations on policies development aiming at harmonizing the EU, National and Regional regulatory packages applicable to the context of USaR operations.
9. **Consideration of Societal Impact, Legal and Ethical issues of the proposed solution** whereby a legal and ethical requirements analysis is conducted at the onset of the project, feeding the technical solutions and guidelines of the use. Societal impacts and acceptability issues of the proposed solutions are analyzed and guidelines are provided to the partners in order to address them.

Section II presents the INACHUS approach where the aforementioned solutions are integrated and orchestrated.

II. INACHUS Approach

INACHUS aims to achieve a significant time reduction related to Urban Search and Rescue (USaR) phase by providing *wide-area situation awareness solutions for improved detection and localisation of the trapped victims assisted by simulation tools for predicting structural failures and a holistic decision support mechanism incorporating operational procedures and resources of relevant actors*. Figure 1 presents a snapshot of the operation of the INACHUS system where all its components are integrated, assisting the efficient localisation of possible victims.

Figure 1. INACHUS approach.

In order to achieve the efficient collaboration of the different developments, INACHUS follows a well-defined methodology that guarantees that the solution as-a-whole addresses realistic and important needs and the adopted approach is efficient and in accordance to the requirements of the end users. The INACHUS methodology is user-centric, involving end-users as much and as often as possible. End-users are regularly consulted to collect insights, needs and remarks. Based on the collected end-user requirements, the INACHUS project will carefully design, implement and evaluate, a seamlessly integrated platform which provides the appropriate tools to enable FRs and USaR crews to respond to varied abnormal events, not limited to a specific emergency case or crisis event.

A. End user requirements in SaR operations

The INACHUS project is user-driven, placing great emphasis on and dedicating close attention to the needs of end users. The INACHUS end user group is comprised of professionals within the international Search and Rescue (SaR) community and constitutes the target of the project. INACHUS started with the identification of end user requirements (EURs), consisting of the needs expressed by end users regarding the proposed system and tools. The EURs are derived from questionnaires, interviews, as well as discussions and evaluation forms. Approximately 70 end users from eight countries were consulted, efforts that resulted in the creation of 131 EURs.

The EURs were assigned a priority level based on their importance to end users, their fit within the scope of the project and their feasibility, for example, based on current technology limitations. The EURs were prioritized into three categories: first, the mandatory requirements are absolutely needed otherwise the core value of the system will be missing; second, the important requirements add functionalities to the system to deliver added technical and business value on top of the mandatory requirements; and third, the interesting requirements bring added value but do not hamper the value of the INACHUS system if not met.

EURs were categorized per each category of technical component that INACHUS will develop:

- Simulation tools for structural damage analysis and casualty estimation;
- Wide-Area surveillance tools for monitoring of collapsed buildings;
- Victim localisation solutions;
- INACHUS Emergency Support System and Common Operational Picture;
- Secure communication and positioning issues;
- Training activities;

It is important to note that in identifying the EURs, project partners have made sure these comply with international and SaR standards that regulate such missions.

The following presents a high-level description of the end users input on some of the main components of the INACHUS project:

- The simulation software is used by the commander in the headquarters and not by USaR teams on site. The 3D mapping software is seen as a useful tool in terms of planning and risk analysis before a disaster occurs. End users expressed interest in using the building modelling and collapse simulation software to determine locations of voids, rescue paths, or safest places to begin a digging operation.
- Currently, end users work with limited information regarding the safety of a building they are about to enter. End users expressed great interest in using 3D imaging in evaluating the degree of destruction of the affected buildings, and to understand the way a building collapses. In this respect, INACHUS seems to promise a very efficient tool for evaluating the risks the building poses to rescuers.
- Regarding victim localisation, end users pointed out the need to cross-check the information on the presence of a victim in order to avoid false alarms and fine-tune their location. The large panel of different and complementary sensors INACHUS proposes is of great interest to the end users. They find it important and thus request the sensor signals to be located on a virtual map and such data to be stored for further interpretation.
- During USaR operations end users encounter many challenges in operation management and information sharing. End users showed great interest in the idea of a Common Operational Picture (COP), which is an intuitive platform for collecting, analysing and sharing data in real-time, in support of USaR operations and crisis management. End users also highlighted the need to filter information so as to avoid becoming overwhelmed by large amounts of unnecessary information for their own task and responsibility. As a basic requirement, the end users insisted the interface to be simple and easy to use.
- Different communication technologies are supported by the INACHUS system. As a prerequisite for operational usefulness, the INACHUS system should be autonomous and secure regarding communication.
- Within the INACHUS project, a training package will also be developed to prepare end users for using the system. The main concern is keeping the training as simple as possible and the session as short as possible.
- End-user involvement will continue throughout the project’s scope. This means the list of EURs is not considered final, but it will be re-examined throughout the project, revising existing requirements as needed or enriching its new ones.

B. INACHUS framework design and architecture

One of the main tasks concerning the INACHUS project is to determine the framework design and architecture, the first step of which is conducting comprehensive requirements’ analysis[3], tantamount to the construction of mission-critical systems. Such systems, as is the INACHUS system cannot tolerate errors stemming from requirements and specifications, therefore great care has been taken to correctly specify technical requirements in order to generate clear and accurate system specifications. Thus, the requirements analysis undertaken in the INACHUS project commenced with the analysis of the End User Requirements and use cases produced within the project, and the pre-defined system component specifications.

Steps that lead to the completion of the requirements analysis include recognition, evaluation and synthesis, and modelling (Figure 2). Recognition refers to the end user requirements, which are evaluated (to what extent they are feasible and whether those that can be delivered are the same requirements) and synthesis of the validated requirements. Evaluation and synthesis are an on-going work in progress, which involves the end-user requirements and is done in collaboration with the INACHUS system component providers. Finally, modelling includes the creation and presentation of three types of models, namely the functional, behavioral and data model.

[3] Requirements analysis procedures are based on IEE standards for Information Technology Systems Design, namely, IEEE 830-1998 Recommended Practice for Software Requirements Specifications, IEEE 1016-2009 Software Design Specifications, IEEE 1233-1998 Guide for Developing System Requirements Specifications, and IEEE 1471-2000 Recommended practice for architectural description

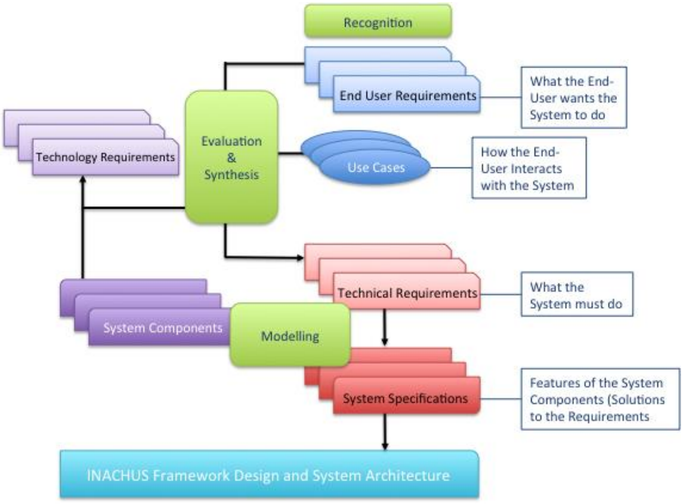

Figure 2. Methodology towards the design of the INACHUS framework.

The principles governing the requirements analysis are the following:

- Information domain of problem must be presented and understood.
- Models depicting system information, functions, and behaviour should be developed.
- Models and problems must be partitioned in a manner that uncovers detail in layers.
- Analysis proceeds from essential information toward implementation detail.

The modelling process involves three levels:

1. Conceptual Design/Data model (Shows relationships among system objects).
2. Functional model (Description of the functions that enable the transformations of system objects).
3. Behavioural model (Manner in which system objects respond to events external to the overall system).

In delivering the system's specifications the following principles must be adhered to.

- Functionality must be separated from implementation.
- Specifications must encompass the system containing the software component.
- Specifications must encompass the environment.
- Specifications must be operational (how it works).
- Specifications must be tolerant of incompleteness and easy to add to.
- Specification must be localised and loosely coupled.

The aforementioned methodology steps are used in order to build the INACHUS framework and build its architecture (Figure 3). As shown, the framework offers a simulation tool for structural damage analysis and casualty estimation. The outcomes of the simulation runs are going to be used in conjunction with the tools for the wide area surveillance for the monitoring of collapsed buildings. In this way, real pictures for the disaster area, together with the simulation results will indicate potential survival spaces (through the 3D data/image fusion functionalities) to the USaR workers. At the same time, and in the context of technical search, the USaR workers are going to deploy a number of sensors in order to find faster and more accurately survivors in the rubble.

The data from the sensors, the simulation results as well as the wide area surveillance tools (e.g., aerial photographs, laser scanning images, etc.) are going to be used by the backend services of the INACHUS framework, namely the INACHUS SaR-ESS (Emergency Support System). The core functionality of this component is to process the information, through its data fusion engine, designate rescue routes and potential survival spaces to the USaR workers, as well as provide a State-of-Art Common Operational Picture (COP) that will help towards the coordination of efficient USaR operations.

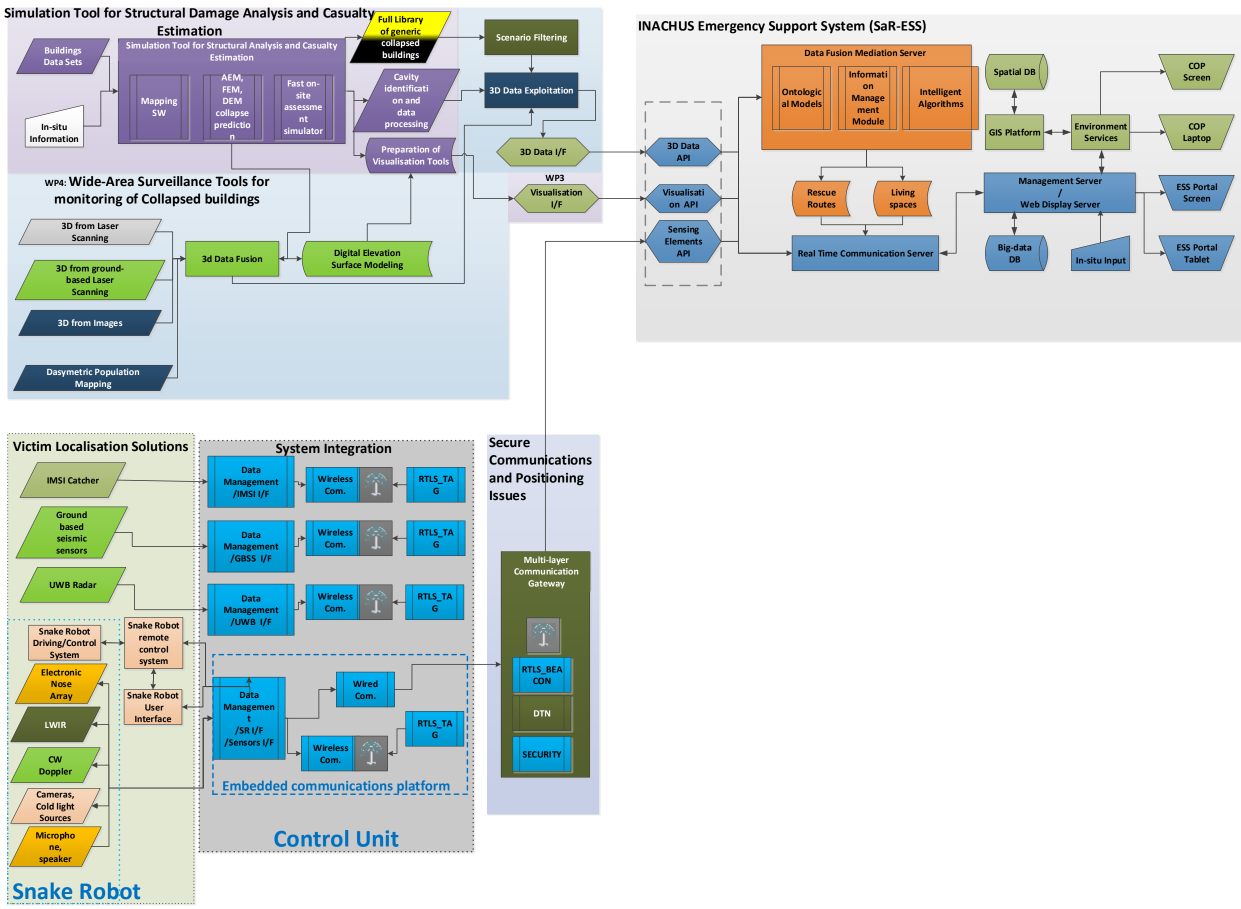

Figure 3. INACHUS framework.

C. Simulation tools for structural damage analysis and casualty estimation

Two different simulation approaches should help USaR teams during rescue operations: The assessment of damage in complete urban areas and the detailed simulation of single building collapse. Intent of the first approach is to give a quick overview of the consequences of a specific threat in whole city quarters to estimate hot spots of damage, number of affected people and free rescue routes. The second pursues the aim to give rescue teams information about the position and the size of survival spaces in particular buildings where trapped occupants may be found. Results of detailed collapse simulation can furthermore help to estimate the stability of partially collapsed buildings or debris heap.

In the first approach a catalogue of predefined building types, like “office tower”, “residential building” etc. and other urban objects will be provided to model city quarters. The number of occupants in each building is defined by a functional expression, which considers the object usage, geographic region and time of the event.

Inside the INACHUS project an existing tool [1], which has the ability to assess the damage and expected losses for explosive threats (i.e. terroristic attacks or unintentional explosions), is enlarged by an earthquake module. After specifying the threat (e.g. by defining magnitude and epicenter) two different procedures are available: The first is a rough, but very fast, semi-empirical method. Buildings are classified with help of the European Macroseismic Scale (EMS-98) [2] where a relation between earthquake intensity and expected consequences is given. For a more accurate way, buildings response to different earthquake scenarios was calculated explicitly by usage of physical models, used for the damage assessment for the specified scenario (Figure 4).

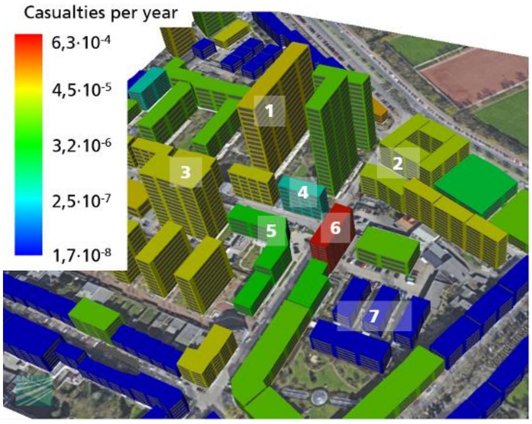

Figure 4. INACHUS approach 3D visualization of expected losses for weak spot identification with the VITRUV software for an explosive threat.

For the detailed simulation of building collapse three different numerical methods are used: the Finite Element Method (FEM), the Applied Element Method (AEM) and the Discrete Element Method (DEM). These three methods differ in terms of accuracy, speed and modelling efforts. While the FEM is very accurate, it is the slowest method and not very suited to cover the complete collapse of a large building. The AEM is very accurate in predicting building collapse, and is much faster than FEM. In the DEM rigid bodies are used to model the structural parts. This method is very fast but has deficiencies in accuracy. A database of pre-calculated collapse cases is established and give USaR teams – along with the possibility to alter and recalculate models – multiple options to use simulation results as a base for their decisions (Figure 5).

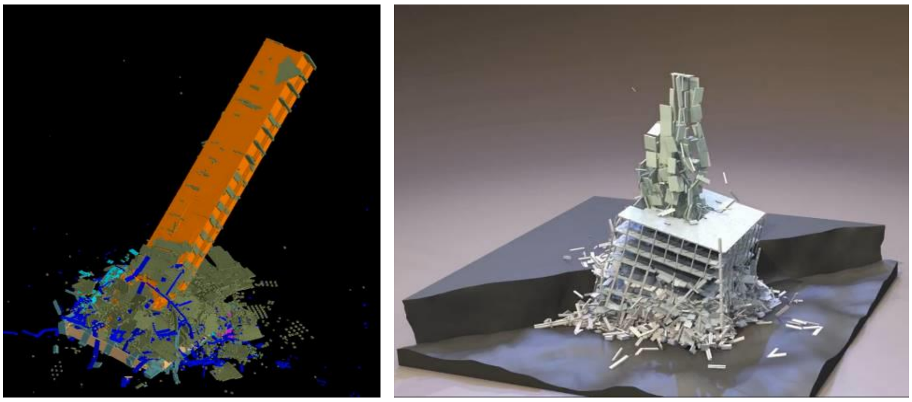

Figure 5. Collapse simulation of a 16 story office tower with Applied Element Method (AEM; left) and Discrete Element Method (DEM; right).

D. Wide-Area surveillance tools for monitoring of collapsed buildings

The INACHUS systems is primarily aimed at facilitating the work of USAR teams, allowing for a more surgical and efficient response. This, however, requires detailed information on the likely location of victims. In terms of the response timeline following a significant disaster event, the first available element of the INACHUS is the synthetic modelling of the likely consequences, using a building model library and known scenario parameters (e.g., the epicentre and magnitude of an earthquake, or location, type and estimated strength of a blast). For such a significant event the International Charter "Space and major Disasters" is activated, and provides a situation assessment and structural damage estimation based on satellites imagery, with first results typically being available within 6-12 hours of an event. This information provides critical guidance to the decision making process of whether to deploy USAR teams. However, in terms of where specifically to deploy those efforts the maps are insufficient, as the focus of the USAR teams is not to evaluate the damage but to find victims. Therefore, the damage information must be further modulated with population information. The first step in the wide-area assessment procedure will thus be to couple the satellite-based damage estimation with dasymetric mapping. This will include a day-time/night-time assessment of people presence in specific neighbourhoods or even buildings, with the concept being based on the use of census data but also image-based urban functional modelling [3, 4]. Such approaches will help to avoid rescue crews digging in collapsed structures that likely did not contain people at the time of the event (e.g., a school at night).

Once the USAR teams deploy and activate the INACHUS system in the disaster area, further detailed intelligence is needed, since the synthetic collapse assessment, the satellite-based damage mapping, but also the dasymetric mapping are model based, and thus serve as approximation only. The detailed information will come from terrestrial and aerial remote sensing information, specifically from unmanned aerial vehicles (UAV). INACHUS will make use of both large (ca. 100 kg) and small (<5km) platforms as depicted in Figure 6.

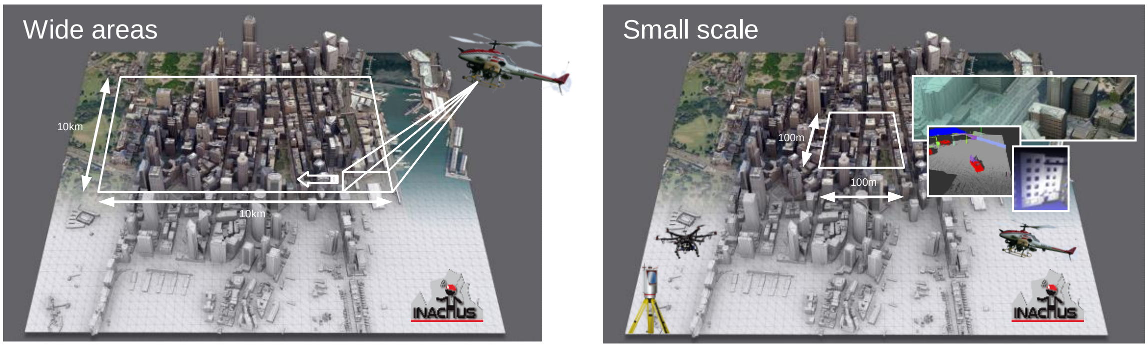

Figure 6. Wide and small areas are considered to select the associated UAV and imaging systems to be embedded. The resolution of the mesh depends on the scenario. Ground measurements are associated to 3D and coloured data acquired by small and large aerial platforms. The information displayed to the USAR teams is also correlated to the 3D data fusion and post processing algorithms.

Aerial platforms should be considered to allow a 3D reconstruction of the area in all bad weather (DVE) and all visibility conditions. The suggested compact drones operate by day and night (H24) and are easy to deploy and operate in less than one hour. A wide variety of sensors can be considered in the optical domain to acquire images from an aerial platform. For each pixel of the sensor, we identify an incident photon flux from a direction of observation with a given solid angle and a given spectral sensitivity. There are two ways to obtain images: *(i)* push-broom sensors where a linear array detector is scrolled for creating an image and, *(ii)* matrix sensors where a large area is simultaneously acquired from a single array detector. INACHUS distinguishes two scenarios following the scale of the collapsed area of interest.

For wide areas (up to a large city), a 3D laser system is embedded on a drone. An airborne lidar mapping system also known as an Airborne Laser Scanner system (ALS) is a complex technique exploiting time signals. A lidar system measures the time of flight of photons between the initial emitted laser pulse and the collected signal by the sensor. The synchronization of the signal provides the measurement of the distance between the drone and the ground. The 3D data are geo-referenced in real-time. For an airborne lidar system, the laser scanning mechanism is continuously moving in a three dimensional space. The global position system and its orientation (*ie*. position) must be known at any time to process the 3D georeferenced data. The ALS systems are classified into two main families depending on the size of the footprint on the ground. INACHUS considers small footprint, high-resolution and, multi-echoes systems. The quality of the Digital Terrain Model (DTM) is enhanced thanks to the full wave form capabilities of such 3D laser systems. Moreover, a 3D vision through bad weather conditions (rain, fog, haze…) is achieved by post processing. The resolution is limited to 1m for wide areas cases. The maps of rescue paths, the classification of the typologies (building, road, tree, vegetation…), and the classification maps of buildings with associated survival probabilities are computed and can be displayed to the USAR teams in common software.

For small areas (from the quarter to the building levels), INACHUS considers an autonomous outdoor flight done by *(i)* light-weight drones (<5kg) coupled with cameras and, *(ii)* large platforms coupled with ALS systems. 3D Laser ground measurements are also used. All the collected data are processed in a global georeferenced system. These second scenario provides a high resolution map (<10cm). A precise 3D reconstruction is displayed for the visual analysis of buildings operated by the USAR teams. A specific data fusion algorithm from terrestrial and airborne measurements (coloured visible images and precise 3D geometry from laser based solution) increases the operator interpretation by 3D / visible data fusion for damage evaluation. The UAV-helicopter system can provide synoptic coverage, providing information to be used to refine the initial model-based assessment and to identify specific damage and population presence hotspots. A further refinement is then provided by smaller multi-copter UAVs that carry a consumer grade camera, and that can carefully map a building from all sides [5, 6]. The overlapping images acquired by the camera will be processed photogrammetrically, resulting in highly detailed coloured point clouds of the affected buildings and their immediate neighbourhood. Figure x illustrates such multi-perspective images (obtained with a manned system, though similar to what UAVs can acquire) and resulting point clouds. In INACHUS methods are being developed to make use of the information from both the original images and the geometric data to identify indicators of damage (such as damage-related holes and gaps in a structure, spalling or debris), as well as actual structural deformation. Even subtle signs, such as minor façade inclinations can be detected in this way. Given the information on the building surroundings also debris piles, such as those blocking a road, will be identified. In principle a small UAV can even enter a building and obtain further data, which can be merged into a common visualisation. The INACHUS research efforts will focus on methods for automatic optimisation of such 3D models, whereby ideally on-board pro-processing establishes a rough 3D model of the environment that is used to identify model gaps (e.g., due to occlusion), resulting in an adjusted flight path obtain further images to patch those gaps. The analysis can be further strengthened by incorporating point clouds models based on pre-event data where they exist (e.g. Figure 7), and methods are being developed to detect damage based on pre- and post-event model comparison.

Since the data obtained by the small UAV will be fully georeferenced, they will later be integrated with the data from the helicopter-UAV, as well as data obtained at street level with a terrestrial laser scanner, resulting in a detailed, multi-level nested 3D dataset combining the best from both laser and image-based point clouds.

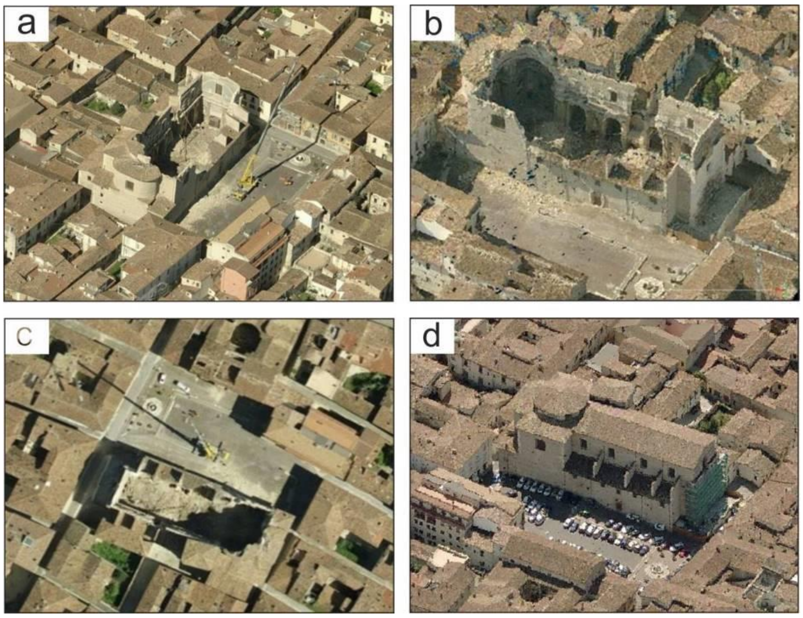

Figure 7. Multi-perspective images of central L'Aquila (Italy) obtained with the Pictometry© system by C.G.R. (Parma, Italy) after the 2009 earthquake (a, c), and resulting point cloud (b). Similar images were also acquired in 2008, and used to construct a model of the pre-event situation (d). Ground sampling distance of the images is ca. 11 cm (nadir) and 14 cm (oblique).

E. Victim localisation

Several different sensors will be used to detect and locate survived victims buried in the rubble. The sensors use different physical principles to maximize the detection probability and to narrow the identified volume of interest and include mobile phone detectors gas detectors (chemical sensors for human biomarkers), IR (infrared)- and video cameras, seismic and radar sensors. In addition, a prototype of a snake robot mechanism is developed in the INACHUS project.

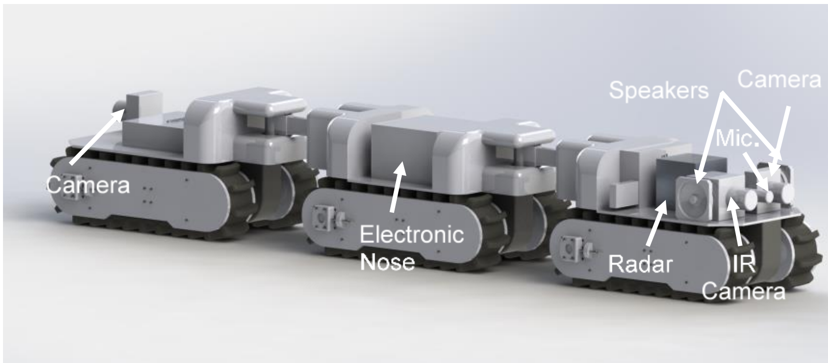

Figure 8. Conceptual design of the snake-like robot.

Snake robot

Snake robots are mechanisms inspired by the shape and motion of biological snakes, see [7] and references therein. Biological snakes are able, after millions of years of evolution, to move efficiently on different types of terrain. The research on snake robots focuses on developing prototypes, which could be used in particular environments where long and thin robots have advantages on more conventional ones, such as legged robots or crawlers. For example, such type of robots could be used for pipe inspection [8, 9], search and rescue, industrial inspections, military intelligence [10].

The main goal of the INACHUS robot is to help USaR teams localising victims. The robot will integrate and transport different sensors such as, long-wave infra-red camera, electronic nose, continuous-wave Doppler radar. The snake robot operator will be able to maneuver the robot and operate the sensors via a portable control unit. Two video cameras and a microphone will be installed on the snake robot and will be the "eyes and ears" of the operator. In addition, a set of two speakers will allow the operator to communicate to the victims. An illustration of the concept is given in Figure 8.

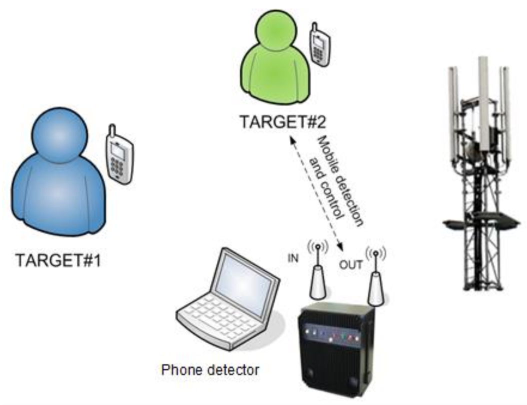

Figure 9. Principal sketch of the personal handset positioning sensor system.

Personal handset positioning

INACHUS consortium has developed a product (IMSI catcher) that is capable of localising mobile phones even without network coverage. Assuming the mobile phone is switched on, the IMSI catcher can detect the signal within a 2km range and can give an estimate of the location (direction and distance) of the phone. During testing, civil security teams have been able to localize signals under 2m of snow or other material from a distance of 500m – a larger range than a ground searcher receives with an avalanche beacon. The research challenge of this topic in INACHUS is to adapt, enhance, and evaluate the mobile positioning system to provide exploitable results within the different dense built environments selected for the project test beds. Figure 9 presents the system concept.

Electronic Nose Sensor Array (e-nose)

The Electronic Nose Sensor Array (ENSA), or e-nose, is one of the sensor modules located on the snake robot. Its purpose is to assist in the victim localisation efforts of Urban Search and Rescue Teams and, more specifically, help detect living humans trapped in voids inside building rubble. The e-nose works in a similar way a canine does, by being able to detect select gases originating from human metabolic activity. The e-nose, as the search dog, can only provide information about the air it samples. Localisation or positioning information is generated when the air is scanned with a search pattern. The area covered by the search pattern in conjunction with real time interpretation of the readings and knowledge of the rubble environment can lead to the victim's location. The e-nose is transported in the snake robot and its operator must follow the trace. The e-nose contains logic that helps the snake robot's operator to efficiently navigate towards the source of the trace by indicating, with visual or audible alarms, important sensing status or events. Important status could be the rising (or falling) of the concentration of the target gases which could indicate that the snake robot is moving in the correct direction. An important detection event is when the concentration reading changes from rising to falling (or the opposite) indicating that the snake robot is not heading in the correct direction and possibly should have entered an opening it just crossed.

Currently, a proof of concept prototype has been developed and tested supporting a subset of the intended target gases. The prototype is designed to operate in a laboratory test apparatus developed as a simple simulation of a void in rubble where a victim is trapped. The apparatus (**Erreur ! Source du renvoi introuvable.**0) is built around a gas chamber that has two air ports and the e-nose is placed inside. The air ports can be used to connect an air sample container and an air relief container, or be sealed off. The e-nose is connected to a computer that displays, in real time, the measurements in the form of plots and also stores the results for further analysis. The intended purpose of this apparatus is to serve as a proof of concept of the followed detection approach as well as to provide rough measurements about the limits of detection and the response time of the system. This is achieved by placing variable amounts of exhaled air effectively altering the concentration of target gases in the gas chamber. The test procedure for determining the limit of detection involves collecting a known amount of exhaled air in the sample container, and transferring it into the gas chamber after it reaches the labs environment temperature. While the sample container's contents are transferred into the chamber, the relief chamber's air content increases from zero to the volume contained in the sample container. Air is oscillated between the sample container - gas chamber - relief chamber in order to rapidly mix the air and acquire the same concentrations of gases throughout the system. With this method, a good, for the purposes of the experiment, estimation of the concentration of the gases inside the chamber can be produced without raising any ethical concerns regarding the health of the test subject that provided the exhaled air samples. The response time of the prototype is also determined with this procedure by marking the time the sample air was introduced into the chamber and offline processing of the measurement data.

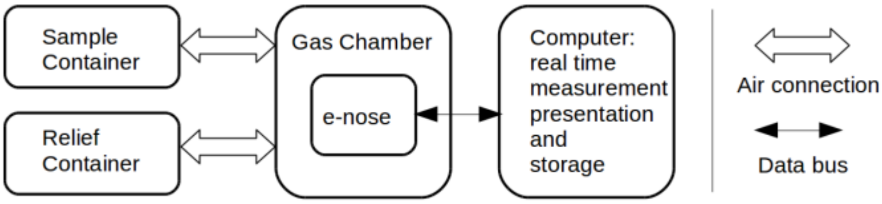

Figure 10. A high level block diagram of the apparatus.

Infrared (IR) camera

In the recent past, infrared (IR) spectrum has been an active research topic in the video surveillance community. The growth in this area is due to promising applications in both day and night times monitoring. As these systems often operate 24 hours a day, there are difficulties dealing with images captured with little or no light (at night or very deep inside the building debris), limited daily visibility (in cases of dust caused by the building collapse) and images captured during the sudden change of scene illumination. A solution for this problem is the use of IR imagery. IR cameras operate on the principle that all objects emit IR energy as a function of their temperature. In general, the hotter an object is, the more radiation it emits. An IR sensor collects the IR radiation from objects in the scene and creates an electronic image. Since they do not rely on reflected ambient light, thermal imagers are entirely ambient light-level independent. In addition, they are able to penetrate obscurants such as smoke, fog and haze.

The “interesting objects” (trapped people or/and objects) are natural IR ray emitters regardless of the presence of visible light. Usually, the temperature of the human body is different from the background temperature. This leads to different energy distributions and grayscale differences between background and human body in thermal images. INACHUS aim is to build an automated surveillance system with reduced human intervention and a high level of scene understanding. In principle, such a system requires the use of a high level description which often relies on tracking and analysing moving objects trajectories, classifying these objects, or even detecting the presence of a human among buildings ruins. In INACHUS, thermal data and motion parameters are employed as reliable features to develop a system that automatically generates relevant video surveillance scenarios from low quality infrared imagery. The INACHUS system relies on real-time activities detection using a single stationary infrared camera. The accuracy of the infrared camera can be improved by exploiting fusion mechanisms with other cameras types and information coming from other sources.

Initially, an object segmentation process takes place to identify humans from other types of objects. The object segmentation process is performed using a dynamic background-subtraction technique which robustly adapts detection to illumination changes. Segmented objects are tracked by a two phase function: prediction and correction. During the tracking process the objects are classified into two categories - humans and non-human objects, based on features like size, velocity and temperature. With the objects correctly segmented and classified using features like velocity and time stood in one spot, it is possible to identify suspicious events occurring in the monitored area.

A miniaturized IR-camera in combination with robust and reliable detection algorithms developed in this project will be mounted on the snake-like robot to detect humans by thermal radiation. In Figure 11 the IR-camera to be used and an example of processed results of an IR-image identifying three humans.

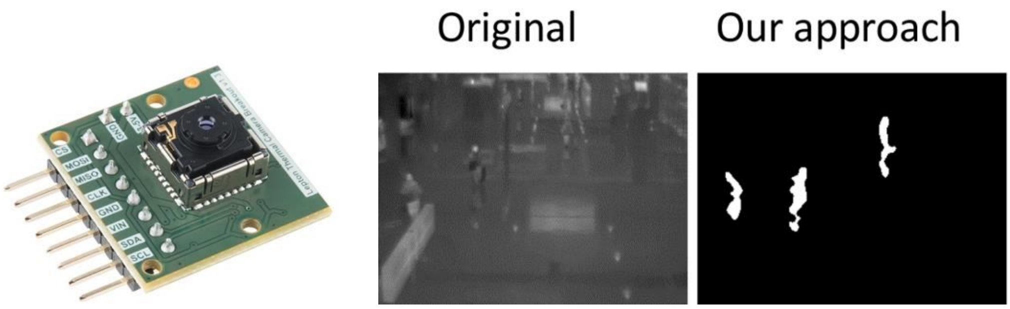

Figure 11. Left: the IR-camera to be used and right: an example of measured and processed results of an IR-image.

<u>Ground-based seismic sensors</u>

Sensors that detect mechanical vibrations e.g. microphones and geophones can detect movements and shouting of trapped people. Sensor kits that exploit this for the sake of finding humans in the debris after an earthquake are commercially available today, although they typically provide very basic signal processing. INACHUS uses a network of distributed vibrational sensors (ground sensors) that pick up vibrations at different points and associate the different contacts to one or more singular sources. The ground sensors can be deployed in the ground around buildings, but also attached to the rubble and/or descended into rubble cavities. For ease of deployment, the ground sensors can be wireless and self-positioning. By fusing associated contacts at distributed positions, propagation models can be used to deduce the vibration source. Depending on the ambient noise this localization can of course be done with different levels of accuracy. Primarily, geophones with standard cases like the land case are used, but special geophone cases suitable for attachment on debris are also considered. INACHUS develops automated algorithms that use distributed ground sensors to detect and localize trapped victims. INACHUS contributes with efficient mechanical interference rejection in challenging environments, and also propose robust propagating models and automated algorithms that provide a useful support to the radar sensor as well as to the rescue personnel. The seismic sensors study the detection of human made vibrations in the rubble (by knocking). Results from the first test trials using 15 geophones in an array (Figure 12) presented in map of the energy density in the area and can be used to indicate the location of humans in the rubble.

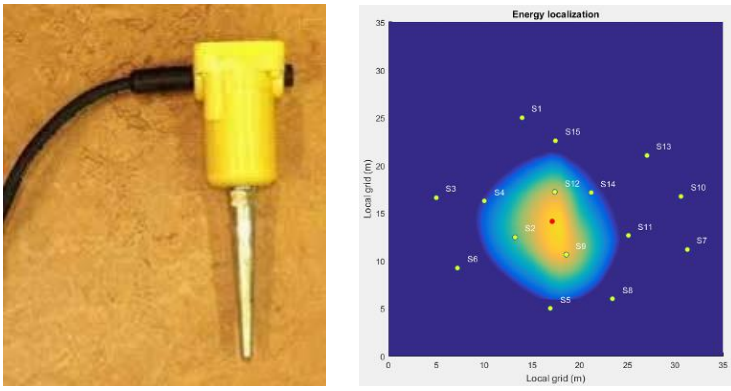

Figure 12. Picture of the geophone (model SM6) used as seismic sensor (left) and results in terms of an energy density map (right).

<u>Snake and surface radars</u>

The aim of the two radar sensors used, one on the snake robot and one from the surface, is to detect breathing movements of victims buried in rubble. The surface radar consists of nine antenna elements (in a 3x3 configuration) for transmit (Tx) and receive (Rx) resp. and use beam steered radar technology to scan the radar beam. A more precise direction to the victim can hence be obtained. By the use of the close to 500MHz wide bandwidth the distance to the victim is expected to be measured in the accuracy order of 30cm. The radar on the robot is narrow band and consists of one Tx and one Rx element on each panel. This radar gives an indication of movements within the radar beam, but not the distance to the victim. The antenna elements are however intended to be placed at perpendicular directions on the robot which will give the possibility to indicate the direction to the victim approximately. In Figure 13 the surface radar is presented and in Figure 14 the antenna element design.

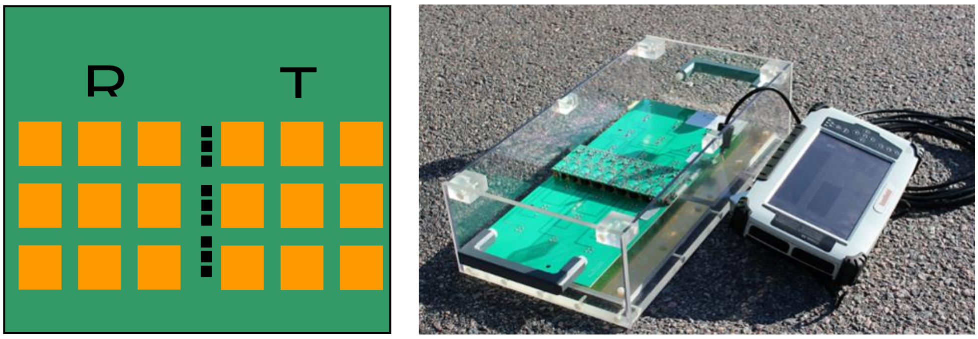

Figure 13. Drawing of the surface radar antenna arrays (left) and a photo of the system (right).

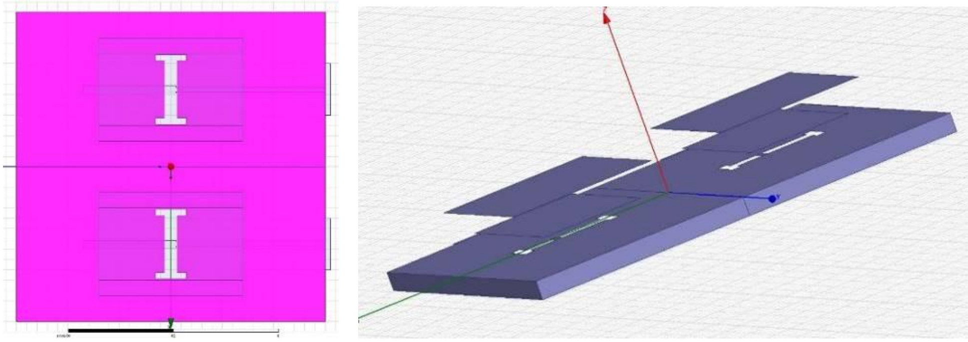

Figure 14. Design of the antenna elements (one Tx and one Rx) of the snake radar. Top view to the left and 3D-view to the right.

F. Common Operational Picture System (COPS)

The most advanced operation centres are today designed as "map-centric" systems (Figure 15) where the cartographic representation of the environment is a central component enabling an easiest and fastest understanding of the situation as well as the sharing of a Common Operational Picture (COP) between different users, from potentially different organisations.

Figure 15. Sitaware Mobile Operation Centre.

INACHUS proposes to adopt the same concept for its Operation Centre and to extend it in two directions:

1. The INACHUS COP is effective for 3D environments, namely urban areas and indoor areas
2. The INACHUS COP is not limited to the visualisation of the environment but will also be the visual interface to operate the system, configure and control simulation, and plan and command operations

Most of the existing COP systems (Figures 16 and 17) are based on a GIS system with poor performances. Such systems are suitable only for top-down visualisation of the situation, which proves to be totally ineffective for operations within urban environments and within buildings in particular. The most advanced COP systems are based on 3D globe viewers (i.e. Google Earth). Such systems enable a correct 2,5D consideration of the environment. In other words, the topography of the terrain as well as building envelopes can be supported. However; these fail short to provide an exploitable and legible representation of the operational situation within high density urban zones or indoor environments where info is highly concentrated, sometimes hidden behind occluders, and distributed in 3D.

Figure 16. INDIGO COPS.

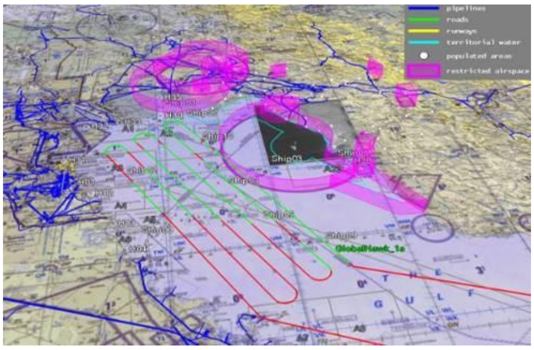

Figure 17. AGI's COPS.

INACHUS addresses these roadblocks by researching and implementing new techniques enabling the legible representation of critical situations and operations within 3D environments. The issues to be addressed are the following:

- The interconnection with the INACHUS environment service that will provide the information to display
- The interoperability with other INACHUS sub-systems
- The representation of the different data provided by the other INACHUS modules (e.g. FEM or SaR datasets)
- The legible visualisation indoor environments including building floors and walls, which will require visual metaphors (e.g. hiding information behind a wall may be photorealistic but does not make sense for the managing operations)
- The optimal positioning of information in the view (i.e. 3D decluttering)
- The representation of simulation results and sensor measurements

INACHUS extends the environment visual representation to a user-friendly visual interface to control the system.

Decluttering

When visualising maps enriched with tactical or operational information, it often happens that several displayed data (e.g. icons, labels, indicators) are located at the exact same place, or very close, in the visual representation. This causes a visual artefact known as "cluterring" where some map elements are hidden by others, which can make the central map completely unusable. Although several basic techniques, such as multiresolution approaches, exist for declutering static 2D maps, this feature still represents an open research issue as reported by the recent scientific literature (Figure 18).

Figure 18. The "split" declutering approach.

It is however dramatically more complicated for dynamic environments (with mobile elements or mobile viewpoint) and even more challenging for 3D representation of built environments where buildings can add more complication, hiding some elements or lowering the legibility of the display. The INACHUS project researches a solution using the latest GPU acceleration techniques, namely visibility volumes and occlusion maps initially introduced to accelerate the 3D rendering of complex worlds, in order to optimise the legibility of the visual display by minimizing occlusions and overlaps. This approach is expected to enable the support of transparent surfaces that may be used in the visualisation system to provide an insight view of buildings. This technique will also enable the grouping of information according to their distance and their consistency.

Video re-projection

The INACHUS project investigates also an innovative feature that would enable real-time re-projection of video streams and pictures within the 3D environment. This feature promises to dramatically increase both the immediate localisation and understanding of the images coming from the field in the COPS (Figure 19). In current Operation Centers, video streams or pictures are usually displayed in separate windows which require users to mentally map the displayed images to the COPS. This requires certain training and quite some attention from operators to remap the videos. Recent researches have demonstrated that it is extremely effective to project the video stream directly in the visual representation of the environment.

INACHUS experiments the feasibility add added value of a similar technique, connecting the COP to the available video streams, coming from instance from surveillance cameras pre-installed or deployed after a crisis event, and re-projecting them in the displayed environment.

Figure 19. Video stream mapped on terrain & buildings.

Concentration maps

During advert events, punctual information is available (number of users connected localised by an IMSI catcher, sensor measurements, simulation results, etc.). However, it is sometimes difficult to mentally extrapolate the geospatial implications of such sparse and punctual information. For that purpose, end-users would greatly benefit from a function presented by the MIT that turn a set of punctual data into density 3D maps (Figure 20).

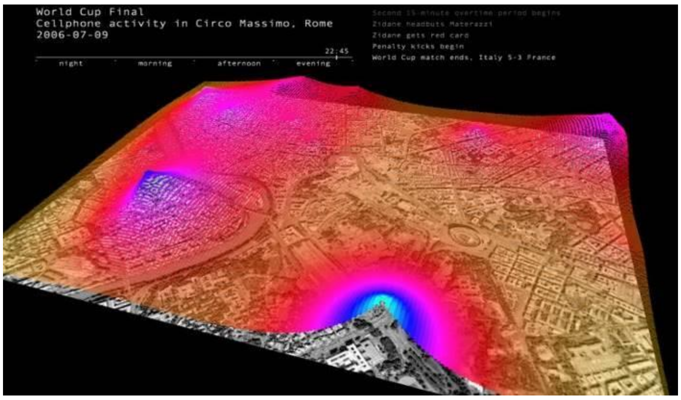

Figure 20. Map display of population density.

INACHUS proposes to implement such a feature and to extend it to 3D environments. This could turn any set of local measures into an overlaying 3D texture representing extra- or interpolated data. This will be done in addition to the dasymetric interpolation, where interpolation is guided and constrained by local lands use information to achieve a de factor disaggregation.

Visual interface

The INACHUS COP is much more than the display of a situation within a 3D environment. A central and visual interface to select items, query information, define simulation parameters, prepare plans and create commands will be pursued. For this purpose, the support of advanced devices is envisioned such as tactile surfaces to input info and to enable the user to draw directly by hand on the visual representation of the environment, the information she/he wants to input.

G. Communication for SaR operations

When an emergency occurs, the ability to communicate is vital. This capability is needed for the general public but also for authorized professionals who are involved in any of the different emergency phase such as prevention, mitigation or recovery. Unfortunately, real-time communication becomes a difficult task under crisis situations. Existing communication solutions exhibit restrictions to provide response in real-time conditions and additionally they cannot automatically enable mechanisms to overcome congestion problems or network unavailability issues.

A node architectural communication platform plays a central role in the topology envisioned by the INACHUS project, it manages the seamless interoperation, the interconnection between other wireless and wired networks, as well as provide redundancy and recovery functionality. A multi-layer architecture is adopted for the communication and the routing as well as the gateway functionality. The gateway could be accessed by the operator, from the control centre as well as locally by the first responders, when/if needed; as well as remotely controlled and maintained by specialized maintenance staff.

For extending the capabilities and range of the crisis network in case of failures and/or congestion and to provide a distributed architecture, portable gateways are used. These gateways should be positioned according to relevant and appropriate network dimensioning, even deployed by personnel where needed (i.e. mobile gateways) and they could be automatically or manually switched on. The gateways support the interfaces and functionality of any other mobile USaR centre as an alternative and cost effective solution in an integrated ad-hoc manner but with redundancy, extendibility and security capabilities to assure robustness, flexibility and reliability. Furthermore, relevant routing and gate-keeping functionalities are integrated at the various monitoring USaR vehicles (incl. snake robots) as well as the Personal Area Network (PAN) of the USaR personnel, supporting a truly co-operative and autonomous architecture and platform.

Regarding mobility management, the use of a central network manager positioned at a higher management layer, is required, positioned at the gateway. Location awareness for discovery and configuration of unmanned vehicles as well as their individual sensors/local devices is essential.

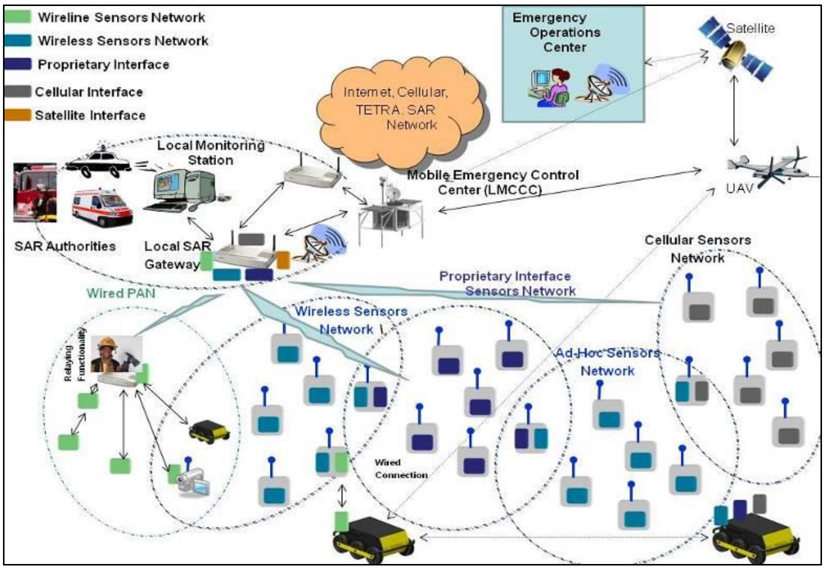

Figure 21. Overview of the INACHUS communication architecture.

In addition, the communication at the crisis site is facilitated as well as controlled by the INACHUS multi-layer, multiple-gateway, access point & ad-hoc connective architecture (Figure 21) for providing additional redundancy and resilience at the crisis scenarios. Specifically, the following alternative networks and/or scenarios of the crisis site are supported:

- **Wired Network:** It is “old technology” but wired communication is reliable, robust and appropriate at crisis scenarios, wherever and whenever available.
- **Wireless Networks:** Different type of networks could be formed according to USaR specific needs such as: IEEE 802.15.4, Bluetooth, IEEE 802.11.
- **Public Cellular/Wireless Connectivity:** Cellular and wireless networks such as GSM, 3G, WiFi are advantageous and can be used by the crowd as well as the first responders, if they are still available and not congested.

- **Personal/Community Area Crisis Network:** This type of networks are formed by sensors/users, users/users, users/gateway when a crisis scenario occurs. These are ad-hoc connected networks supported by the INACHUS architecture for the crisis needs.
- **Cellular/Wireless Crisis Network:** Different type of networks could be utilized by the INACHUS architecture at the crisis site according to the interfaces available and selected such as a crisis Wi/Fi, crisis 2G/3G Cell, Bluetooth assisting network, etc.
- **FRs/Proprietary Connectivity:** The INACHUS gateway can facilitate communication with the local FRs. This can be achieved if the gateway is supporting and is compatible with the first responders' communication interface.

H. Security

Within INACHUS, different actors need to exchange information such as sensor readings and measurements in a secure and reliable manner. INACHUS provide end-to-end security and privacy for the involved heterogeneous wired and wireless networks of sensors/devices, using current best practices in data security. Security solutions designed for different types of networks are evaluated, analysed, customised and integrated into a unified framework addressing the INACHUS requirements, providing overall security level interoperability for heterogeneous network environments. Thus, INACHUS provides a security middle layer to ensure interoperability and seamless communication between heterogeneous devices/networks.

The security protocols in the INACHUS project targets fundamental security issues such as key distribution and authentication. Data exchange between different actors requires interoperability of security mechanisms and communication. However, existing architectures do not address properly the secure interconnection of heterogeneous networks with different resource and QoS constrains. INACHUS evaluates, customizes and integrates state-of-the-art security protocols with resource efficiency in mind. This includes methods such as limiting security data exchanges as well as using lightweight cryptographic primitives. End-to-end security approaches are researched and relevant solutions for the specific INACHUS USaR requirements are considered as well. As a matter of fact, most of the security protocols developed for resource constrained networks focus on providing efficient link layer encryption techniques, without considering key distribution and entity authentication. INACHUS addresses efficient authentication and key distribution schemes in order to assure the required privacy level. For all involved protocols the best trade-offs between resource efficiency and security are provided as well. The mechanisms for authentication, authorization and key management are added to the INACHUS security layer. This approach leads to the best trade-off between energy efficiency and the required security level.

III. IMPACT IN THE SOCIETY

Command and control operations of complex USaR missions based on innovative simulation tools, wide-area surveillance systems of areas affected by large-scale disasters and advanced sensors for detecting trapped alive humans under rubble stand to gain the most from the INACHUS system. At present, individual emergency services enjoy the use of the latest technological means and operational protocols to conduct their tasks with the utmost effectiveness. INACHUS' holistic approach in providing a system to monitor and control USaR operations will significantly reduce the level of ambiguity governing the operational environment of USaR crews. Thus, USaR crews, fire brigades, and medical emergency teams that currently use outdated mechanisms to interface with each other will be turned, using INACHUS, into one coherent force, eliminating the duplicate application of force, sharing intelligence and information as it becomes available. INACHUS contribution, however, will not be limited to this—its decision support features will help decision makers at command and control centers not only exert more centralized control over their forces, but to use this control in better ways in order to make better more educated decisions. Better decisions, in this context, can be characterized as decisions that are based less on assumptions that need to be made in the absence of concrete information, and more on information deduced through advanced data analysis.

INACHUS will do much to ameliorate the high costs of disasters, since it can be said almost without fail that an effective crisis response also translates to substantial monetary savings. These savings may be realized in a myriad of ways: direct disaster costs may be reduced through the limitation of disaster impact by its limitation to a specific geographic locale, by the reduction in medical costs through the effective eviction of the population from danger zones, or through the reduction in subsequent insurance claims. Emergencies and crises are an inevitable fact of modern life, with extreme weather events, fires, hazmat spills and traffic accidents happening often and in every jurisdiction. In the end, the potential consequences of emergencies are indisputable: serious injury and/or death to responding personnel and the public, damage to public and private property and the risk of long-term financial repercussions.

The effectiveness of USaR activities following emergency events is to a large extent determined by the performance of emergency workers who rush to the scene. Many factors may inhibit the effectiveness of USaR crews, including bad preparation, under-funding, malfunctioning equipment, or situational circumstances (think of extreme weather). The most pertinent factor determining success or failure is the quality of information and communication processes, which should provide USaR crews with an adequate and common picture of the situation. Therefore, through the provision of an end-to-end platform for USaR operations INACHUS will be the necessary development to enhance the operational effectiveness of USaR crews while reducing civilian casualties and loss of life among crew members.

INACHUS justifies its existence by addressing the societal demand to increase survival rates in the aftermath of natural or man-made disasters using novel search and rescue methods. However, the primary goal cannot come at the expense of transgressing cherished EU values and fundamental rights; they don't have to be mutually exclusive events. It will be the role of the consortium to ensure that the work of INACHUS is delivered without negative impacts on society.

Two of the areas that may potentially raise societal impact issues will be in the technology design stage and particularly in the capturing of building images. Here, data privacy and protection will be adhered to wherever applicable (e.g. concerning personal data of the building occupants). Furthermore, the topic of data fusion can be ethically contentious depending on the sources (for example, data that can identify humans is different to temperature data) of interaction between different strata of data. These examples offer an insight into the role that the consortium will play to ensure that upon delivery the INACHUS body of work can withstand societal impact scrutiny by taking all necessary steps to ensure that the construction, implementation and maintenance of the technology doesn't infringe fundamental EU human rights and data protection laws.

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