Research and Innovation actions
H2020- ICT-2014-1 – Information and Communication Technologies

Collaborative Aerial Robotic Workers

AERO WORKS

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1.1 Objectives

1.1.1 The AEROWORKS Application Domain

The application domain that inspires the AEROWORKS research and innovation activities is that of civil infrastructure services, and its detectable growing necessity for high automation, improved Quality of Services (QoS) and capital-saving maintenance cycles, while retaining –or maximizing– safety and reliability. In order to clearly define the research activities and technological developments, and confine them within focused and specific boundaries, the project consortium has gathered experts from academia, robotics innovation enterprises, as well as key end-users, and aims to provide solutions to the specific –yet wide and challenging– area of civil infrastructure (power generation and distribution, oil & gas, water supply etc.) inspection and maintenance operations.

Annual investments and the overall financing of the infrastructure sector represent a significant percentage of the Gross Domestic Product (GDP) of developed and developing countries. Within the old member-states of the European Union a percentage of approximately 3.9% of the GDP in average is spent on financing infrastructure-related activities, while new member-states spend approximately 5.07% of their GDP [1], [2], [3]. Countries such as China or India spend even more, reaching percentages as high as 9% in China's case. Within the several infrastructure-related sectors, investments in the utilities sector represent a notable portion (approximately 17.5% within the EU countries during the period 2004-2009) [1], [2], [3]. Within this framework, the costs of infrastructure inspection, repair and maintenance amount to considerable sums. In the western world and the European countries in particular, infrastructure "shows" its age, hence significantly increasing the associated inspection and maintenance costs. In UK for instance, £ 10 Billion (15.15% of the overall finance for the infrastructure sector) is expected to be consumed solely for infrastructure repair and maintenance within the period 2011-15 [4]. As becomes evident by Figure 1.1, Europe –as well as the rest of the world– will face growing infrastructure needs over the coming years, especially in the fields of inspection, repair, maintenance and renewal.

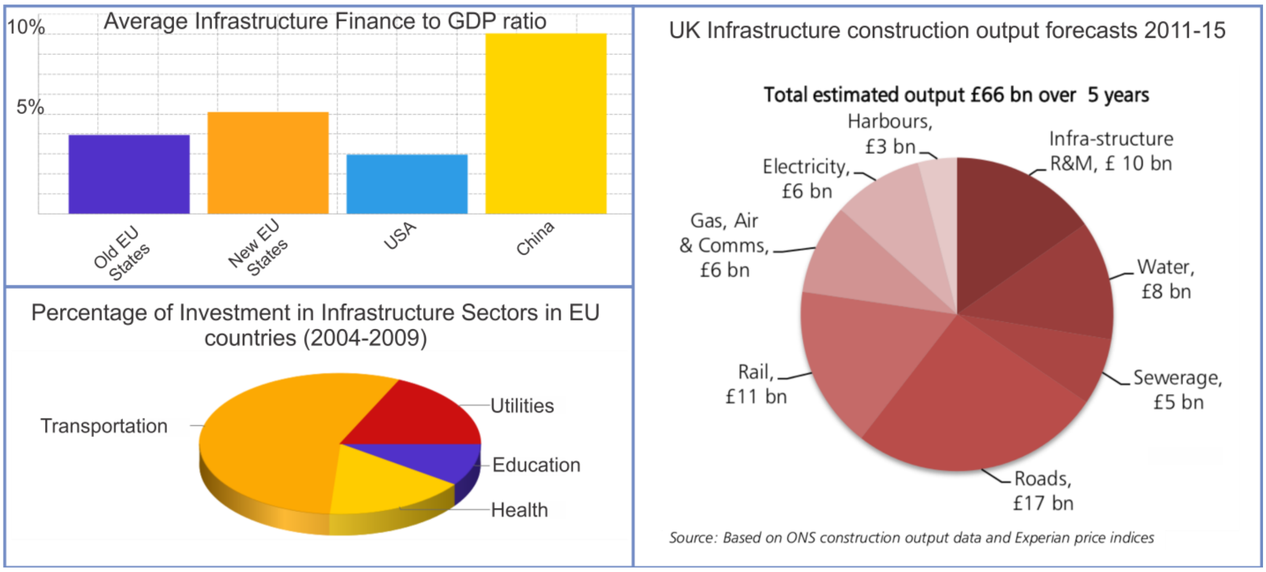


Figure 1.1: Cost of infrastructure development and Repair & Maintenance (R&M) work

Inspection, repair and maintenance works are in general complex operations, executed in several cycles and typically require time-consuming, costly and risky procedures, involving highly trained personnel who employ largely non-unified and non-repeatable methods. A variety of methods and approaches are adopted to address the challenges of infrastructure maintenance. Specialized personnel perform visual inspection, nondestructive testing and maintenance tasks using scaffolds, roping or even manned helicopters in order to obtain access to the sites of interest. According to Helicopter Association International and the "Utilities, Patrol and Construction Committee (UPAC), Safety Guide for Helicopter Operators, 2009" [5] thousands of flight hours are accumulated each day conducting manned aerial work in support of Utilities Infrastructure (electricity, gas, water), as it is now well-understood that such aerial works bring down the cost and time requirements. *Among others, one interesting example is that of power-line tower repair; before the introduction of airborne means for power distribution network maintenance, companies had to drive crews* *at each point of interest, and technicians had to climb up the structures or use cranes in order to conduct the work, and consequently climb down to repeat this process at the next point of interest.*

However, manned aerial works still require high costs, pose several hazards to humans and the safety of the assets (e.g. possible collision with structures or towers etc. [5]), while in several cases of spatially dense facilities they cannot be applied. Based on the gross capital required for infrastructure inspection and maintenance tasks (*analysis provided in Section 2*), it is readily deduced that the development of robotic assets can have a powerful impact in terms of cost minimization and work-task execution efficiency. Robots can be utilized to accomplish an important portion of the inspection, repair, and service operations, while minimizing costs and ensuring increased safety. AEROWORKS focuses on investigating the power of employing a team of aerial robots in infrastructure inspection and active work-task execution for maintenance.

The **AEROWORKS** project introduces the concept of ***"Collaborative Aerial Robotic Workers"***. The goal is to develop a team of collaborative aerial systems equipped with advanced environmental perception and 3D reconstruction, active aerial manipulation, intelligent task planning, and multi-agent collaboration capabilities. Such a team of Aerial Robotic Workers (ARWs) will be capable of autonomously inspecting infrastructure facilities and acting in order to execute a maintenance task by means of aerial manipulation, and exploiting multi-robot collaboration. The project aims to investigate the emerging scientific challenges of decentralized multi-robot collaboration, path-planning, control for aerial collaborative manipulation, aerial manipulator design, autonomous localization, as well as cooperative environmental perception and reconstruction. Emphasizing on technological innovation, AEROWORKS aims to investigate an approach with very promising returns in infrastructure inspection, repair & maintenance, leading to big savings in costs, while maximizing personnel/asset safety. With such a potential impact, AEROWORKS is at the forefront of bringing Robotics to the basis necessary in real applications, where they can make a difference.

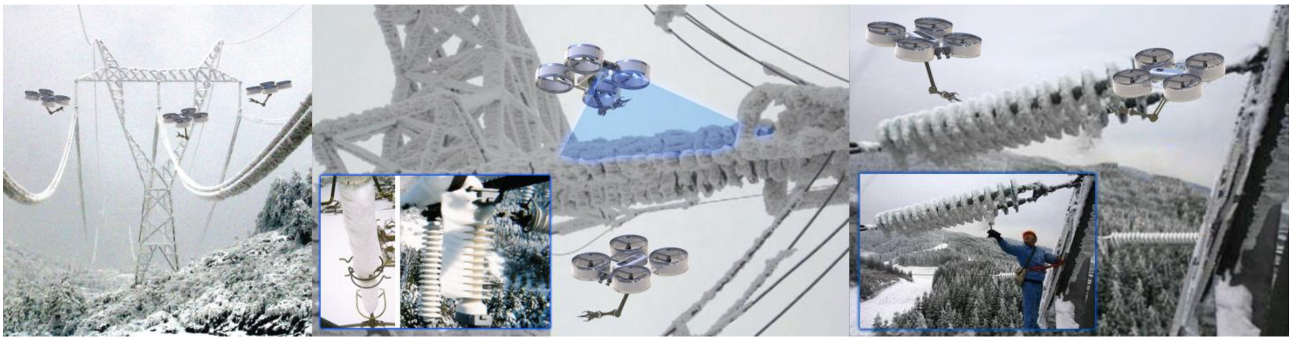


Figure 1.2: Abstract illustration of the AEROWORKS team performing power-grid infrastructure maintenance.

An illustration of the AEROWORKS concept for the case of power grid inspection is shown in Figure 1.2, while Figure 1.3 visualizes the case of wind turbine maintenance. The AEROWORKS proposal advocates that important civil applications can be accomplished efficiently and effectively by a swarm of aerial robots with unprecedented onboard capabilities, collaborating autonomously for the execution of a common task. To achieve the project goals, a balanced Consortium consisting of leading academic and private partners has been formed. More specifically, the consortium is assembled by the participation of six leading European universities (*Lulea University of Technology – LTU, Swiss Federal Institute of Technology – ETHZ, Royal Institute of Technology – KTH, University of Twente – UT, University of Edinburgh – UEDIN, University of Patras – UPAT),* two aerial robotics innovation SMEs *(Ascending Technologies – ASC, Skybotix – SBX*), as well as the service robotics specialists of *Alstom Inspection Robotics – AIR* and one of the European Power-market leaders *Skelleftea Kraft – SKL*. Each partner of the consortium has specific roles, and there is a well-defined value chain that starts from the research efforts conducted within the academic partners and goes all the way up to the robotics-related SMEs, and finally to the end-users that have specified use-cases. A clear path for market success and capitalization is envisaged. In this framework, SKL will collaborate with AIR to define the application scenarios, along with the requirements of the relevant robotic technologies. The AEROWORKS value chain then continues with the involvement of the academic partners and the research-intensive ASC and SBX, towards developing and integrating all the required components and the final robotic solutions. In close collaboration with AIR and through proper benchmarking and evaluation by SKL, AEROWORKS will continuously refine, improve and finalize the proposed solutions up to the point that the Technology Readiness Level (TRL) achieved enables their direct use by SKL and AIR, as well as the broader success in the market of service robotics, in a short time-window after the project's completion or within it. AEROWORKS initially aims to address the operations associated with power grid and wind farm maintenance, with SKL/AIR already having plans to deploy such robots in their respective operations.

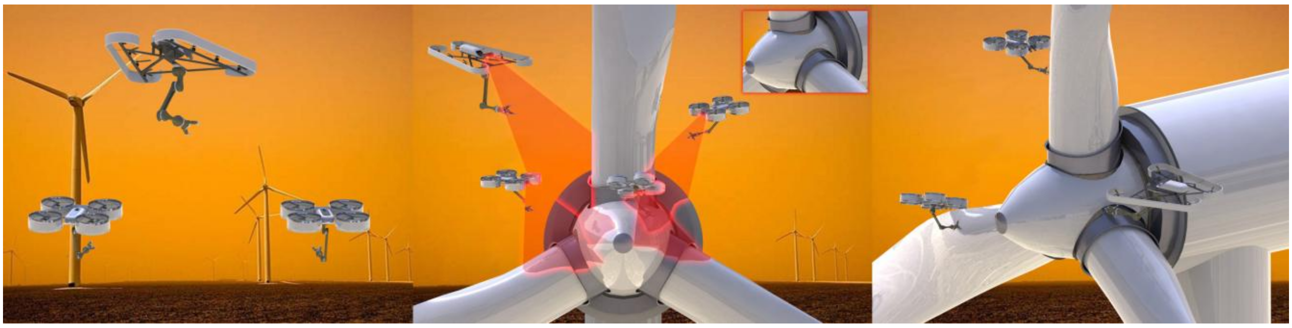


Figure 1.3: Abstract illustration of the AEROWORKS team performing wind-turbine infrastructure maintenance.

A more thorough plan on the envisaged and prioritized application domains is elaborated within Section 2. Additionally, in order to further investigate potential applications in short-term, and foster future collaborations, an Advisory Board consisting of leading private and academic entities have been formed.

1.1.2 AEROWORKS Research & Innovation Objectives

Multi-disciplinary research activities will be conducted in order to achieve the ambitious challenges proposed by AEROWORKS, encompassing the fields of dexterous aerial manipulator design, aerial robotic worker control towards physical interaction and co-manipulation, individual and collaborative perception, autonomous path-planning for inspection and maintenance, heterogeneous decentralized multi-robot collaboration, assisted and intuitive teleoperation, and human supervision. The research efforts will be integrated into robust, reliable and ready to operate technological solutions and will form the components of the AEROWORKS team. An overview of the scientific and technological objectives is provided below.

O1. Dexterous Aerial Manipulator Design and Development: Among the first main goals of the project is the realization of an aerial manipulation system that will equip the aerial vehicles in order to perform physical interaction and mutual robot-robot interaction towards collaborative work-task execution. The design of the manipulator will be such that it limits the influence on the stability of the aerial platform through the proper selection of the mechanisms and an adequate configuration and morphology. The AEROWORKS dexterous aerial manipulator will allow co-manipulation of the same object from two or more ARWs. Its control for active manipulation will rely on the observation of the energy flow between the individual systems and on the monitoring of the energy level within the overall coupled physical system. The manipulator will employ intelligent grasping techniques through adaptable mechanics and proprioceptive sensing capabilities in order to enable various and not a-priori known tools-handling. Exteroceptive sensors will be integrated in order to allow adaptability to uncertainties during the collaborative task and limited disturbing effects to the ARW. In the whole process of designing the AEROWORKS aerial manipulator, the limitations of aerial systems will be considered. Special care will be taken for the proper realization of the design concepts and the development of lightweight and robust prototypes that will equip the ARWs.

Figure 1.4: Input and synergies among various scientific areas are required for the development of the AEROWORKS scientific and technological solutions.

O2. Collaborative Perception, Mapping and Vision for Manipulation: For automated inspection and manipulation to become feasible, the ARWs need to build up the right level of scene perception to encode the spatial awareness necessary before they can autonomously perform the tasks at hand. As a result, the first step in developing the ARWs' perception is to use the sensor suite onboard each ARW (comprising primarily of visual and inertial sensors) to perceive both their ego-motion and their workspace, essentially forming the backbone of each ARW's autonomy. Following promising leads from previous work, here we will use tight sensor fusion to account for the dynamic camera motions expected by agile robots such as the rotorcraft ARWs and the challenging industrial environments of potentially featureless areas, deviating from traditional scenarios of office-like, urban or natural sceneries that the community has been addressing. Building on top of this SLAM functionality, the natural next step is to develop dense scene reconstruction algorithms to provide the information necessary for carrying out the tasks at hand (e.g. aerial manipulation). Driven by the need for such a functionality in industrial inspection and manipulation, AEROWORKS will research ways to bridge this gap between the state-of-the-art, where typically boundless processing resources are assumed, and a realistically applicable system, where careful resource management implies the need for intelligent and efficient algorithms. Finally, once each ARW is equipped with the aforementioned key perception functionalities, AEROWORKS will explore ways to combine their capabilities in a collaborative manner. Collaboration of multiple robotic agents is an idea long now perceived to come at great complexity, but with potentially drastically beneficial returns. With careful handling of cross-agent communication and information sharing strategies, AEROWORKS aims to push the state of the art in collaborative scene perception by fusing cues perceived by multiple ARWs viewing the same scene simultaneously. Exploiting the presence of multiple ARWs, all dedicated to perform the task(s) at hand, not only can boost efficiency, but also accuracy, provided that the wealth of information is combined in a consistent manner.

O3. Aerial Robotic Workers Development and Control: The aerial robotic worker constitutes a great research challenge, both with respect to its development, as well as its control, targeted for active aerial (co-) manipulation and tool-handling interaction for the execution of work-tasks. The *zero-liability* prerequisite for its intended deployment within critical infrastructure environments imposes careful investigation, in order to determine those practices that add to its dependability (fail-safe redundancy, real-time diagnostics, vehicle design aspects) that make it almost-inherently unable to cause asset damage or place human lives at risk. The control-related research efforts will focus on addressing the problems of single and collaborative *aerial robotic worker manipulation* and *work task execution*. The formulated control strategies will encompass each complete ARW's (aerial vehicle and manipulator) configuration while achieving flight stabilization, yielding increased levels of reactive safety and excellent robustness against collisions. The synthesized control scheme will focus on achieving high manipulation performance and compliant motion during work-task interaction, and allow for the manipulation of objects away from the robot center-of-mass, robustness against the induced forces and moments, and increased disturbance rejection. The manipulator's force/moment feedback estimates will be incorporated into an advanced control synthesis, which will exploit the system's distinct capability levels in a coupled sense (similarly to a human technician), generating the exerted forces with the aerial vehicle (-human body) and providing a basis for stable support of the manipulator (-human hands) during work-task execution. Moreover, high-level control strategies adding novel *natural interaction* capabilities inspired by human co-manipulation paradigms will be developed. As illustrated in Figure 1.5, *each ARW* will be capable of sensing the aiding or hindering role of externally exerted forces/moments during co-manipulation, and properly (re-)act in order to ensure stability and exploit-or-reject their effects, increasing the efficiency of the executed task. Finally, great potential for *aerial vehicle design and control* innovation is found within the concept of ARW heterogeneity: more than one unit configurations will be developed, allowing for differentiated payload capacities, sensor suites and manipulation capabilities.

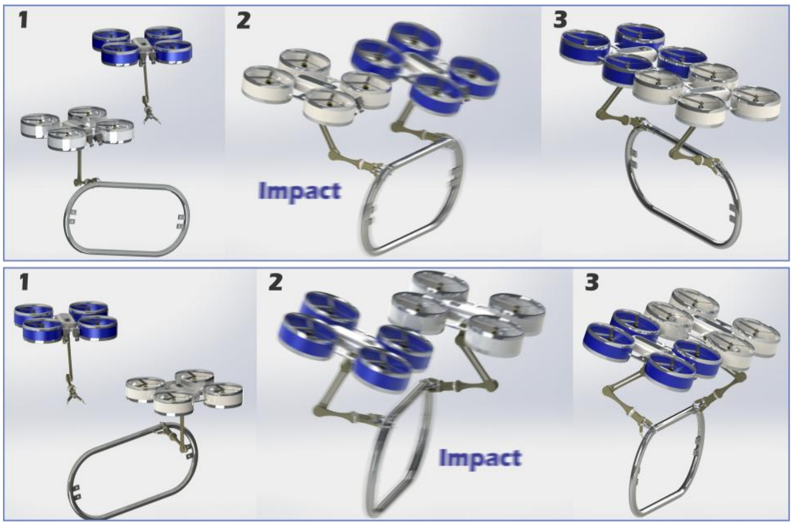


Figure 1.5: Illustration of the co-manipulation control problem: two ARWs grasp and manipulate a power-line corona-ring.

O4. Collaborative Autonomous Structural Inspection and Maintenance: New methods for collaboration of multiple heterogeneous aerial robots will be developed and will address the problem of autonomous, complete, and efficient execution of infrastructure inspection and maintenance operations. The methodology will aim to provide decentralized, local control laws and planners to the individual vehicles that can accommodate heterogeneity through a model-free approach. To facilitate the necessary primitive functionalities, an *inspection path-planner* that can guide a single ARW to efficiently and completely inspect a structural model will be developed and combined with the *ARWs manipulation control laws*. Collaborative real-time decentralized algorithms for autonomous multi-robot aerial inspection will then be combined with strategies for dexterous co-manipulation of objects/tools. The collaborative team of ARWs must be able to understand the area to be inspected, ensure *complete coverage* and accurate 3D reconstruction, find an efficient way of collaborative use of tools and manipulate objects in a coordinated manner in order to accomplish complex infrastructure inspection and repair tasks. Multi-robot *online task-assignment* algorithms and schemes of team *adaptation* and *reconfiguration* will enable the online maximization of the team's collaborative performance and efficient complex work-task execution. At the same time, these features will allow for attributes such as system adaptability to unexpected events, heterogeneity and reactivity to new tasks imposed online, and further enhance the overall system. The contribution here lies in the challenging topics of: a) single and multi-robot "anytime" and efficient collaboration for autonomous structural inspection, b) navigation of mechanically connected ARWs while respecting the environment structure w.r.t the pose and morphology of the coupled ARWs/object hyper-structure, c) collaborative manipulation of tools and objects, d) complex work-task adaptation in a local, decentralized manner for multiple and heterogeneous robots, as well as e) autonomous team online reconfiguration and adaptation towards maximizing the performance of the overall accomplishment of complex infrastructure inspection and repair missions. Conceptual-representations of multi-robot collaboration are provided in Figure 1.6.

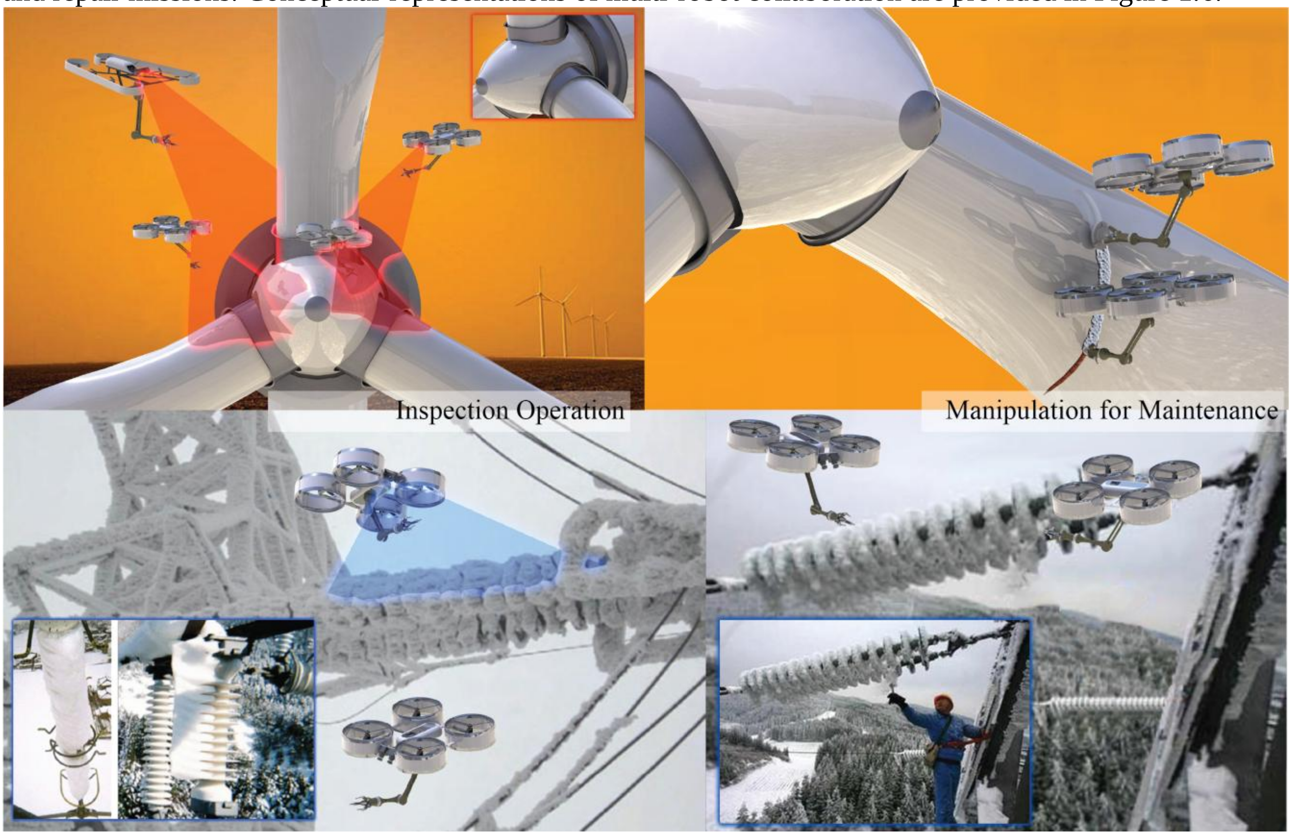


Figure 1.6: Visualization of multi-robot collaboration towards infrastructure inspection and maintenance operations.

O5. Deployment of Autonomous Aerial Robotic Infrastructure Solutions: The collaborative team of ARWs will be able to autonomously plan, execute and adapt online the plan for complete infrastructure inspection missions. This essentially corresponds to a step change that will benefit the infrastructure services market by both increasing the safety levels (reducing personnel risks and asset hazards) and reducing the direct and indirect inspection costs (mostly by minimizing the inspection times, executing certain tasks during a facility's operating times, providing repeatable tools and enabling formal analysis of the results).

O6. Aerial Robotic Autonomous Infrastructure Maintenance: The AEROWORKS robotic team will actively utilize the inspection results, and relying on its onboard manipulators it will be able to conduct typical maintenance tasks. A wide subset of the infrastructure maintenance tasks are well-defined, yet they require extreme caution from the personnel, and most times a complete shut-down of the infrastructure's operation, typically leading to significant costs, while any non-scheduled maintenance corresponds to a cost multiplier. Based on the advanced perception capabilities, the co-manipulation algorithms and the novel multi-robot collaboration and planning methods, the team of aerial robotic workers will be able to autonomously handle a large subset of the most common maintenance tasks. This essentially corresponds to a breakthrough in terms of personnel and asset safety, and a great cost reduction, while the trained crew will now be able to focus on the cognitive essentials of the mission. Figure 1.7 illustrates this vision.

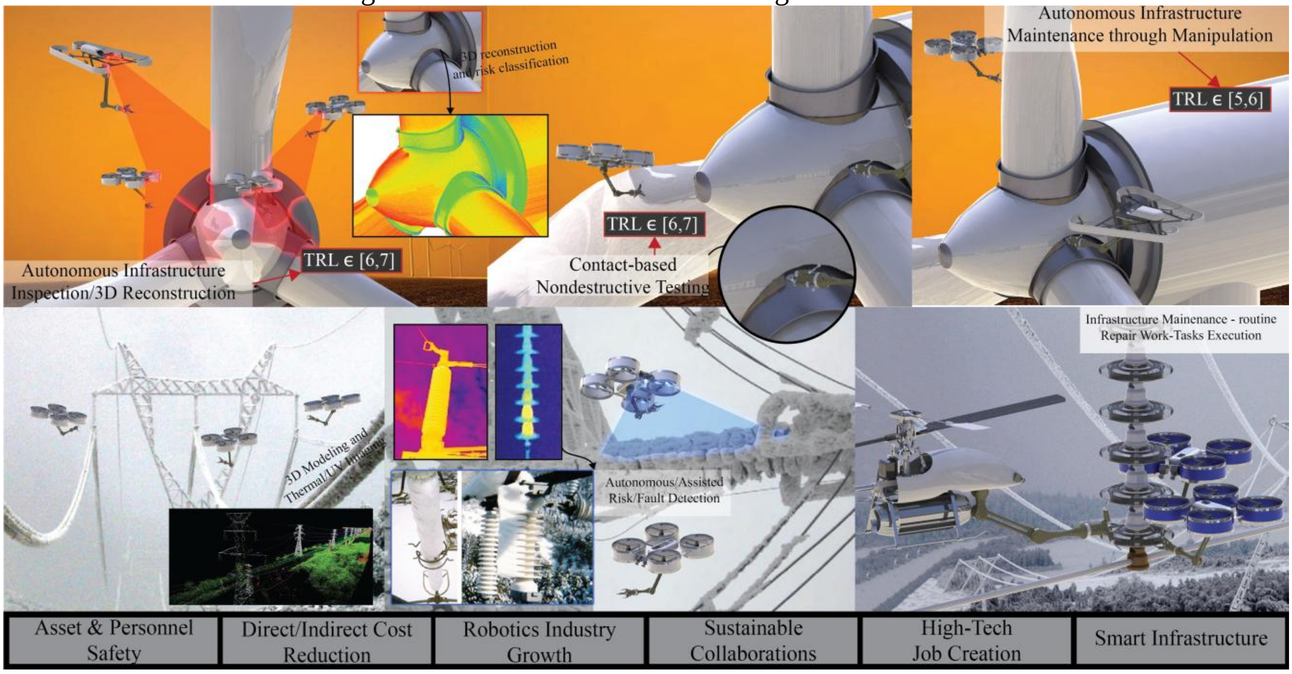


Figure 1.7: The vision of autonomous aerial robotic infrastructure inspection and maintenance and its main benefits

O7. Innovation and Commercialization of the AEROWORKS solutions: AEROWORKS aims at specific innovation and commercialization activities in order to bridge the gap between academic research, robotics innovation, and the market of large sectors such as infrastructure maintenance. A well-functioning value chain will be created to transform the AEROWORKS technologies into mature components, which will become an integral part of the infrastructure service operations. In this context, AEROWORKS will tackle specific challenges of research commercialization, such as time to market, design quality and functionality, alignment with industry levels and requirements, robustness and reliability, manufacturability and cost-efficiency, system dependability as well as adaptation in all anticipated user environments.

O8. Robots for Growth: As a final objective, AEROWORKS aims to create a significant positive impact on the competitiveness and growth of the European Robotics industry, especially in the field of service robotics. The AEROWORKS robotic team has the potential to be an integral part of infrastructure service businesses, while all the relevant technologies –either each one alone or through their combination– have the potential to provide leading solutions in a wide set of fields and applications. Our goal is to exploit all the technologies to be developed within the project and ensure that the project partners ASC, AIR, SBX and SKL, as well as further European enterprises provide leading products in this market. Towards this direction all possible exploitation channels and especially the potential collaborations through the Advisory Board will be utilized.

1.1.3 The Impact of AEROWORKS in a Nutshell

The AEROWORKS project aims to have a direct and valuable impact for the infrastructure services market and the European Robotics industry. While ***Section 2 provides a thorough description of the plan outlined by the AEROWORKS Consortium***, a summary of its key points is presented below:

Increased Infrastructure Services Personnel Safety:

The team of collaborative ARWs will be able to conduct inspection and maintenance operations in dangerous, complex and dirty environments, increasing the safety of the personnel who consequently will no longer need to conduct risky tasks such as rope-climbing, approaching power lines, etc. on these sites.

Improved and Repeatable Quality of Services:

The AEROWORKS robotic team will provide accurate, high-fidelity 3D reconstruction inspection services and well-defined maintenance work-task execution. This corresponds to higher quality services, enabling their repeatability and combination with formal methods of statistical analysis. Therefore, the cycles of prognostic and predictive maintenance are significantly advanced.

Increased Environmental Protection:

Accurate inspection and maintenance procedures lead to a decreased negative impact to the environment (especially in the case of petrochemical facilities), while more thoroughly maintained facilities have in general an environmentally greener footprint.

Economic Impact in the Infrastructure Services Market:

The team of collaborative ARWs for inspection and manipulation-based maintenance will lead to minimized service times and execution of such work-tasks, while the infrastructure facilities remain in operation. This essentially means that while the quality of services is at least as high as with manned methods, the overall required duration is smaller, leading to great cost savings. One day of unpredicted inspection/maintenance of an average-sized (~300MW) coal boiler plant leads to indirect costs of more than 1 Mil €, indicating a direct way in which robotics can lead to significant profits.

Short- and Mid-term Economic Impact Plan:

Initially, via the channels of the infrastructure business partners of AEROWORKS (AIR and SKL), and consequently through a larger network to be developed via the planned dissemination and exploitation activities, the consortium prioritizes the goal of facilitating the use of the collaborative ARWs' technologies as an integral system of the infrastructure maintenance business.

Strengthened European Robotics Sector:

Through the success in an important financial sector such as infrastructure services, the European Robotics industry will be accelerated and increased market shares will be achieved. Furthermore, through each individual AEROWORKS technology, further developments will follow and additional markets will be accessed. Our robotics development enterprises, ASC and SBX will lead these efforts.

Increased and high-tech Job creation in Europe:

AEROWORKS allows the personnel of infrastructure inspection and maintenance to focus on cognitive and potentially more interesting tasks (e.g. most repetitive processes can be automated), while enabling advancement of the technologies used. Furthermore, through benefiting robotics developments, more job positions characterized by a high-tech profile will be created.

Sustainable Research and Innovation Collaborations:

The members of the AEROWORKS consortium have been selected based on existing collaborations in several different projects and levels. Based on that, and on the persistency that will be shown in dissemination activities, networking with the industrial sector and exploitation of the project results, sustainable research and innovation networks will be created.

Overall, AEROWORKS aims to enable a step change in infrastructure inspection and maintenance. The vision of a smart, robotics-enabled, infrastructure model drives our motivation, while a special effort for increased TRLs will be invested in order to reach the target-levels indicated in *Section 1.3.5*.

1.2 Relation to the work programme

The AEROWORKS project is addressing the topic ICT23-2014 Robotics, and the presented scientific, technological and innovation objectives of the proposal correspond to a perfect match regarding the exact objectives of the current call. More specifically:

AEROWORKS addresses Specific and Prioritized Challenges:

According to the programme call, research actions should follow the euRobotics AISBL Strategic Research Agenda (SRA) and Multi-Annual Roadmap (MAR) in order to attain a world-leading position in the robotics market. Within that framework, the prioritized application areas are expected to be approached, the research goals have to be reached and the relevant Technology Readiness Levels should be improved.

AEROWORKS targets the SRA/MAR prioritized area of civil applications and especially infrastructure inspection and monitoring. Its concept and R&D&I objectives match the SRA 2020 goals especially regarding the fields of Control, Safety, Sensing, Mapping, Localization, Motion Planning, Knowledge representation and Action Planning. The expected contributions in the field of aerial robot design, *flight controls, perception systems, aerial co-manipulation, path and task planning as well as multi-robot collaboration will lead to improved robots and advanced robotic technologies. Aiming to reach increased TRLs (from 5-7) and through the central role of the industrial sector in our Consortium, AEROWORKS has the potential to put European Robotics in a world-leading position. At the same time, the envisaged potential impact in increased personnel/asset safety and cost minimization of infrastructure inspection and maintenance operations will benefit our economies and boost the European infrastructure sector.*

In addition, "a dedicated effort is necessary to close the innovation gap, allow large scale deployment of robots and foster market take-up. Robotics is very broad, both in terms of technologies and disciplines it involves, but also in terms of markets and stakeholders. It is therefore essential to address the inherent fragmentation"

Industrial utilization of the AEROWORKS robotic team is a top priority for our consortium. In that sense, AEROWORKS has a plan on addressing the identified innovation gap (thoroughly elaborated in Sections 2.2 and 2.4), by focusing on the key technological developments that will pave the way for the direct integration of such advanced robotic solutions to the infrastructure services business. These efforts will be co-organized with our partners SKL and AIR, a leading power assets owner and a service robotics expert who already have plans on how the AEROWORKS technologies can serve as an advanced, cost-minimizing and safety-maximizing tool for their tasks. Furthermore, our dissemination plan and technology exploitation strategy will pave the way for the widest possible adoption of the AEROWORKS solutions, as well as their integration with other systems.

The aim is to develop a new generation of industrial and service robots and underpinning technologies, in particular enabling robotic systems to operate in dynamic real-world environments, reaching measurable improvements of abilities such as autonomy and adaptability and interacting in safe ways with humans.

AEROWORKS plans to realize a novel robotic team capable of providing advanced services for the infrastructure maintenance sector, a financial area of great importance. This will be achieved through realizing novel cooperative perception and dense map reconstruction, active control for aerial-manipulation, autonomous path-planning and decentralized multi-robot collaboration for efficient inspection and maintenance work-task execution. As thoroughly elaborated in Section 1.3, AEROWORKS reaches advanced System Ability levels (as defined by the MAR), while each technology product and combination will be released autonomously for the benefit of the robotics community.

Collaborative projects will cover multi-disciplinary R&D and innovation activities like technology transfer via use-cases and industry-academia cross fertilisation mechanisms. Pre-Commercial Procurement (PCP) will further enable prototype development and stimulate deployment of industrial and service robotics.

For achieving the AEROWORKS goals, multidisciplinary R&D&I activities will be performed in the emerging scientific fields of decentralized multi-robot collaboration, path-planning, control for aerial co-manipulation, aerial manipulator design, autonomous localization, as well as cooperative environmental perception and reconstruction. Emphasizing on technological innovation, SKL and AIR, as well as SBX and ASC, are fully supporting and guiding the PCP towards the innovative and product-oriented technological solutions in the areas of infrastructure inspection and maintenance, leading to big savings in costs while maximizing personnel/asset safety. With such a potential impact, AEROWORKS is at the forefront of bringing robotics to the basis necessary for realistic applications of crucial importance, where they can make a difference and advance the innovation process.

Projects are strongly encouraged to optimize synergies (e.g: use of shared resources for PCP of R&D&I projects or use cases, collaboration with on-going initiatives). Priority is given to projects driven by industrial or market needs and that are expected to produce step changes in abilities.

The AEROWORKS project is being driven by the real-life needs of aerial inspection and infrastructure maintenance already established at SKL, where existing manned solutions are currently being utilized with a limited performance, reduced output, a high risk for the personnel and asset safety and with non-cost efficient procedures. Moreover, AIR as a world leader in infrastructure inspection is also driving and inspiring all the technological developments in AEROWORKS, in order to cover the existing product needs and create a clear impact in the associated markets.

AEROWORKS meets the Scientific and Innovation Objectives:

In terms of market domains, the priorities are: manufacturing, commercial, civil, agriculture

The application domain that inspires the AEROWORKS R&D&I activities is that of civil infrastructure services, and particularly the growing necessity for high automation, improved QoS and capital-saving maintenance cycles, while retaining/maximizing safety and reliability.

The goal is to significantly improve the level of industrial and service robotics abilities in the context of the above mentioned market domains by addressing: adaptability, cognitive ability, configurability, decisional autonomy, dependability, flexibility, interaction capability, manipulation ability, motion capability, perception ability. To reach this ambitious goal, key robotics technologies need to be advanced in the particular fields of cognition, human-robot interaction, mechatronics, navigation, perception. This includes technology combinations such as grasping and dexterous manipulation, physical HRI, mobile manipulation, reactive planning and other combinations, in particular those that connect the key technologies above.

AEROWORKS will introduce the concept of "Collaborative Aerial Robotic Workers". The goal is to develop a team of collaborative aerial service robots equipped with advanced environmental perception and 3D reconstruction, active aerial manipulation, intelligent task-planning and multi-agent collaboration capabilities. Such a team of ARWs will be capable of autonomously inspecting infrastructure facilities, and of acting in order to execute a maintenance task by means of aerial manipulation and by exploiting multi-robot collaboration. The envisaged efforts will contribute in the fields of: a) aerial dexterous manipulation and grasping, b) control through the synthesis of controllers for co-manipulation via observation of the mutual energy exchange and model-based approaches, c) advanced real-time onboard perception systems that benefit from the multi-robot collaboration, and d) heterogeneous multi-robot collaboration for inspection and repair-tasks execution. Safety and human-robot interaction issues will be addressed in a novel way through the concept of stable and safe physical interaction, an attribute typically not encountered in aerial vehicles. According to our plan, each significant technological development will be also released as an autonomous system.

To prove the exploitation potential of the results the project outcome is to be shown in market domain-relevant demonstrations proving an increased TRL.

The AEROWORKS capabilities and overall R&D&I technological developments will be demonstrated in a progressive way and eventually with a final real-life demonstration event, where the collaborative aerial robotic workers team will be tested in autonomous inspection and repair work-task execution. SKL will lead the definition of the small and large-scale (real-life) demonstration and evaluation strategies. For this final demonstration the realistic (based on the partners' experience) targeted TRL level is 6-7. Through the AEROWORKS dissemination plan and technology exploitation strategy, the consortium will ensure that all the key stakeholders will become aware of the promising results.

It will be essential for the deployment of robots to establish systems development processes (from requirement analysis to testing and validation) and to develop techniques and technologies for system design, engineering, architecture, integration, system of systems, modeling and knowledge engineering which are applicable across market domains. One goal will be to define common hardware and software platforms (e.g.: real world test-beds, software libraries and simulators) taking advantage of existing initiatives and facilities. This will require: (a) mechanisms for sharing; (b) harmonization of system design practice; (c) the definition of standards; and (d) high quality validation, maintenance and documentation.

AEROWORKS activities cover the full range of a complete system development, from requirement analysis, scenario definition, evaluation benchmarking, to the sequential & incremental development and integration activities, as well as the real-life small and large-scale evaluation and demonstration in different TRLs that can be further adopted and applied in other robotic development projects. Based on the work-plan of the Consortium, the aerial robotic team will be based on the common AEROWORKS Sensing & Processing Unit (a prototype of which is already developed), the AEROWORKS manipulator, control, path-planning and multi-agent collaboration software libraries. The hardware and software components that set the basis for the AEROWORKS team operation will released either in the form of technological products or open-source code and hardware drawings (typically with BSD or GPL licensing) and will be integrated in widely-adopted frameworks (such as ROS).

Furthermore, activities will be supported by a benchmarking initiative to provide means for technology assessment and transfer, performance evaluation as well as of paving the way to certification of new robotics systems.

In collaboration with SKL and AIR, specific and application-oriented benchmarks regarding the AEROWORKS robotic team capabilities in terms of perception fidelity, aerial co-manipulation *dexterity, robustness, multi-robot collaboration and reconfigurability, and overall infrastructure inspection and maintenance capacity. All the benchmarking initiatives will be such that will further pave the standardization and certification processes for aerial robotic systems.*

AEROWORKS has a great impact, boosts our economies and benefits our societies

Increase Europe's market share in industrial robotics to one third of the market and maintain and strengthen Europe's market share of 50% in professional service robotics by 2020.

AEROWORKS introduces a novel concept for aerial service robotics in a world-wide scale. Infrastructure services correspond to a multi-billion market, which offers a unique potential for a new class of advanced service robots like the AEROWORKS collaborative aerial robotic workers team. Infrastructure operations are complex operations that have extreme costs mostly related with the fact that assets are shut down during maintenance while significant risks are posed both for the personnel and the facilities safety. AEROWORKS proposes a high-fidelity fruitful inspection and skilful rapid maintenance alternative, with the potential to lead to a great success in the service robotics sector.

Increase Europe’s market share in domestic service robots to at least 20% by 2020 including with new companies and start-ups in the field.

AEROWORKS R&D&I results, such as the AEROWORKS Sensing & Processing Unit (providing localization info and building the 3D map), the aerial manipulator, the software components and the overall ARWs will be as much as possible released as individual subsystems. Consequently, AEROWORKS will boost the overall domestic service robotics sector, as these technologies are fundamental for such applications. This potential will be further exploited through the advanced technology exploitation plan of the Consortium and the public demonstration of increased TRLs.

Improve the competitiveness of Europe's manufacturing sector, in particular SMEs, and address pressing technological challenges and the effect of an aging workforce.

In relation to the AEROWORKS focus, currently in Europe, Power plant Original Equipment Manufacturers (OEM) such as ABB, Alstom, Mitsubishi, Siemens and General Electric are competing to offer improved inspection services, as each day of power outage of a power plant can cost millions. The AEROWORKS concept will bring an evolution in this area, while also boosting the competitiveness of the European Industries in the power generation, petrochemical and other infrastructure sectors.

Increase Industry-Academia cross-fertilization and tighter connection between industrial needs and academic research via technology transfer, common projects, scientific progress on industry-driven challenges.

The well-balanced consortium of AEROWORKS is the product of careful planning-ahead, aiming at high cross-fertilization and tighter connection between industrial needs and academic research. It is the real-life needs, existing services and planned vision of our industrial partners and SMEs that led to the creation of the proposed aerial collaborative worker, a concept that was adopted with exhilaration by the academic partners due to its associated multiple and interesting research challenges.

Deploy robotics technologies in new application domains

The AEROWORKS project aims to have a direct and valuable impact for the infrastructure services market and the European Robotics industry. Overall, AEROWORKS aims to enable a step change in the infrastructure inspection and maintenance businesses. The vision of a smart, robotics-enabled, infrastructure model drives our motivation and all the described project activities.

Improve Technology Readiness Levels of robotics technologies and improve performance evaluation and certification of new robotic systems.

As more analytically described within all the R&D&I activities, AEROWORKS will specifically aim for increased TRLs up to level 7. The achievement of this goal will strengthen the impact of the envisaged innovations, and enable the direct penetration of these technologies in the related markets. Furthermore, proper benchmarking and evaluation will guarantee the community and the stakeholders about the overall AEROWORKS robotic team potential.

Create and maintain world class research in Europe and achieve excellent standards of publications and research outputs.

The AEROWORKS consortium contains leading universities in the field of field robotics, perception, inspection, collaboration, grasping and control. It also contains leading European SMEs in the field of aerial robotics, inspection services, and one of the biggest power industries in Europe. This combined expertise will guarantee the excellence in publications and research outputs of the project.

Ensure sufficient numbers of well-trained professionals required by the growth of the industry.
AEROWORKS will contain specific training activities for experts in the field in order to increase or retain the number of well-trained professionals in all the scientific and technological concepts of this project.

1.3 Concept and approach

Infrastructure is the foundation that connects our resources, energy flows, business, communities and people, driving our economy and improving our quality of life. For the European economy to retain and strengthen its competitiveness in the world, a new class of advanced tools and methods is required. The AEROWORKS project focuses on this need and aims to provide aerial robotic infrastructure inspection and maintenance solutions as a next-generation methodology and tool to improve infrastructure services. From the technological perspective, this goal is to be addressed based on the research contributions outlined in Section 1.1 and the implementation of the AEROWORKS Technological Platform, subsystems and components. As such, the AEROWORKS technological platform requires novel and combined research and innovation contributions in the fields of control, dexterous manipulation, perception systems, planning and multi-agent collaboration. Based on these innovations and developments, as well as the impact maximization actions, AEROWORKS targets to render such systems an integral component of the infrastructure service operations in short-term, while also a plan for long-term wider use is foreseen. Moreover, the infiltration into the infrastructure services market will have a great impact in the European Robotics industry with significant financial benefits and a series of opportunities for further developments and sustainable growth. The subsequent Sections describe the main properties of the AEROWORKS technological platform, the demonstration and evaluation principles, along with a breakdown of the final systems and their technology readiness level.

1.3.2 The AEROWORKS Technological Platform

In order to address the aforementioned real-world applications, a dexterous team of collaborative autonomous aerial workers with high-fidelity 3D reconstruction capabilities, path-planning intelligence, manipulation-grasping capabilities, and decentralized multi-agent collaboration strategies, will be developed. This advanced multi-robot system will be comprised of high-end unmanned aerial robotic platforms, capable of conducting actual aerial work-tasks, while also performing autonomous collaboration in order to complete the objectives defined based on realistic infrastructure maintenance scenarios requirements. This project aims to go beyond the level that recent research and innovation contributions have reached, where Unmanned Aerial Vehicles (UAVs) are still limited –in the vast majority of cases– to the functionality of human cognitive skills-based remote inspection, in contrast to what the great visionaries of the field have described. In particular, current unmanned aerial platforms are lacking in manipulation skills, structural high-fidelity dense reconstruction capabilities, safe navigation in unstructured dynamic environments, the ability to work in teams, sense, plan, and act in collaboration. The AEROWORKS consortium involves world-leading partners that have started paving the way in all the aforementioned domains. Based on a well-defined and specific plan, the aim within this proposal is to go one step further, investigating the scientific challenges and accomplishing the technical breakthroughs for the realization of such an advanced robotic system.

AEROWORKS proposes the development of a new technological platform, in order to address the challenges of autonomous aerial infrastructure inspection, repair and maintenance, exploiting the capabilities of aerial robots and giving birth to the concept of *collaborative Aerial Robotic Workers (ARWs).*

> *The **AEROWORKS team** will consist of multiple, heterogeneous, aerial robots (ARWs) equipped with dexterous aerial manipulation capabilities, advanced perception systems, and intelligent planning and decentralized and heterogeneous collaboration algorithms, towards visual inspection and dense reconstruction, inspection through contact, and active repair and maintenance of infrastructure.*

Each **A**erial **R**obotic **W**orker (**ARW**) will have excellent flying qualities and will implement control strategies that will allow active physical interaction and aerial co-manipulation of common objects. An integrated sensing and processing unit consisting of tightly fused inertial sensors, stereo vision modules and GPS, along with the high-level processing unit, will equip each ARW, while algorithms for simultaneous localization and mapping, collaborative map building and dense reconstruction, as well as path-planning and multi-robot collaboration, will run onboard and provide advanced autonomy and the capability for *high-*

fidelity infrastructure inspection based on a multitude of sensors and collaborative techniques. Augmenting this information with non-destructive contact-based tests of structural properties of the facilities, a complete high-fidelity assessment of the infrastructure's status will be derived. Relying on such fruitful information, the team of ARWs will also employ its dexterous (co-)manipulation skills to execute maintenance and repair work-tasks while ensuring accuracy, mission completeness and asset/personnel safety. The ARWs will operate in cooperative teams and will therefore exploit the functional primitives of each single ARW, and thus exhibit advanced operational capabilities towards complex inspection, and repair & maintenance work-task execution. The human operator is part of the AEROWORKS robotic team in multiple ways, either undertaking the role of providing very high-level commands, supervising the team's decisions towards autonomous inspection and maintenance, or by actively taking control of an ARW via a convenient interface. Within the project period, a basic "AEROWORKS team" will be developed, consisting of the ARW aerial robots, the corresponding lightweight and dexterous manipulators, the AEROWORKS advanced sensing and processing integrated module, advanced perception and estimation abilities, innovative control strategies for aerial (co-)manipulation and intelligent planning and collaboration methods. This set-up will demonstrate the main concepts and prove the potential of aerial robotic workers in convincing close-to-real-life demonstrations or real operational environments.

"We claim that through the development of the AEROWORKS framework, we will be able to provide a platform that is flexible, robust and adaptable to the application and to the environment, which will be able to fully demonstrate the ability of autonomous robotic systems to cognitively operate, interact and collaborate to perform a challenging task in the form of infrastructure inspection and repair, setting new standards in the areas of configurability, cognition, perception, decisional autonomy, scalability and adaptability."

The AEROWORKS technological framework is based on a novel approach to develop a collaborative aerial fleet of aerial robots with dexterous manipulators, and will exhibit the following main System Abilities:

- **Configurability:** the AEROWORKS robotic team will be able to adapt on changes of its team members and characteristics (e.g. different sensor-suites on different ARWs) or dynamic environments, based on advanced decentralized heterogeneous multi-robot collaboration techniques. In relation to the euRobotics Multi-Annual Roadmap (MAR), the minimum ability level that AEROWORKS will achieve is that of *Run-time Self Configuration,* while the consortium targets to achieve *Autonomous Configuration*.
- **Adaptability:** the collaborative ARWs will ultimately adapt their tasks online, according to a set of varying parameters including the time horizon of the mission, the desired inspection fidelity or changes of the manipulation-related tasks. This higher-level of adaptability will also rely on several adaptation mechanisms in the lower levels, including state estimation adaptation, control adaptation, reactive planning and more. In relation to the MAR, the minimum ability level that AEROWORKS will achieve is that of *Multiple Parameter Adaptation,* while the consortium targets to achieve *Task Adaptation*.
- **Human-to-Robot Interaction:** the project focuses on providing intuitive to use robotic tools to the infrastructure services personnel, tools that will improve how the inspection and maintenance tasks are conducted and allow operators to focus on high-level tasks. In relation to the MAR, the minimum ability to be achieved is that of *Supervised Autonomy,* while the consortium aims for *Mission Goal Setting*.
- **Dependability:** The collaborative ARWs' team will rely on a) its robust control and state estimation/localization methods along with the reconfigurable planning and multi-agent collaboration methods to provide a high-level of fail-safe operation and mission/functional dependability. In relation to the MAR, the minimum ability level that AEROWORKS will achieve is that of *Fails Safe Dependability,* while the consortium targets to achieve *Mission Dependability*.
- **Motion Capability:** Aerial robotic solutions such as those to be developed within AEROWORKS correspond to the ultimate motion-capable solution for a large subset of infrastructure inspection and maintenance operations. In relation to the MAR, the minimum ability level that AEROWORKS will achieve is that of *Reactive Motion,* while the consortium targets to achieve *Dynamic Motion*.
- **Manipulation Ability:** The ARWs will be characterized by dexterous manipulation and co-manipulation capabilities that will allow the execution of work-tasks using tools on infrastructure facilities. In relation to the MAR, the minimum ability level that AEROWORKS will achieve is that of *Compliant Placement* while the consortium targets to achieve *Object Manipulation*.
- **Perception Ability:** Autonomous inspection operations such as those envisaged to be autonomously executed by the ARWs will require a whole new level of self-localization accuracy and 3D dense reconstruction fidelity, using tight sensor fusion and collaborative techniques. Moreover, understanding

key properties of objects is fundamental to the work-task execution goals. In relation to the MAR, the minimum ability level that AEROWORKS will achieve is that of *Grouped Feature Detection,* while the consortium targets to achieve *Property Identification*.

- **Tracking Ability:** Accurate path-tracking, agile maneuvering and reactive collision avoidance is essential for the ARWs in order to navigate safely within the confided areas of infrastructure facilities. In relation to the MAR, the minimum ability level that AEROWORKS will achieve is that of *2/5 Tracked Feature Perception,* while the consortium targets to achieve *Dynamic Object Tracking*.
- **Scene Perception:** The team of ARWs will be able to interpret the context of a wider scene, identifying static elements in the scene relevant with infrastructure maintenance operations. In relation to the MAR, the minimum ability level that AEROWORKS will achieve is that of *Combined Structures,* while the consortium targets to achieve *Object Arrangement Detection*.
- **Location Perception:** Robust self-localization based on tight integration and optimization over a fruitful suite of sensors is an area where AEROWORKS will contribute generic and reliable solutions. These methods will also act on the multi-robot team level towards optimized efficiency. The minimum MAR ability level to be achieved is that of *Self Location,* while we target to achieve *Object Coupled Location*.
- **Decisional Autonomy:** the AEROWORKS team will be able to autonomously plan its (collaborative) mission to ensure complete inspection of the infrastructure facilities and execution of maintenance tasks. Intelligent and autonomous operation is among the prioritized directions of the project. In relation to the MAR, the minimum ability level that AEROWORKS will achieve is that of *Multiple Task Autonomy* while the consortium targets to achieve *Distributed Autonomy*.
- **Action Ability:** the highly autonomous AEROWORKS robotic team will be capable of planning and executing its designed actions in order to fulfill its mission and overcome changes of the environment or of the robotic team. In relation to the MAR, the minimum ability level that AEROWORKS will achieve is that of *Optimized Action,* while the consortium targets to achieve *Dynamic Planning*.
- **Object Interaction:** each ARW will be able to use cognitive knowledge to improve object handling and manipulation towards advanced work-tasks. The minimum MAR ability level to be achieved is that of *Composite Object Manipulation,* while the consortium targets at *Generalized Object Manipulation*.

To fulfill the mentioned attributes and in compliance with the relevant *H2020-ICT-2014-1* call, the proposed project will contribute to the general development of the next generation of intelligent robotic systems for Civil Applications, more specifically related to Infrastructure Maintenance and other commercial applications. The AEROWORKS project essentially corresponds to a strategic development effort, and the consortium contains academic institutes, technology providers, service providers as well as asset owners, and aims to enable and directly –or indirectly– lead to market solutions within few years after its completion.

1.3.4 The AEROWORKS Benchmarking, Demonstration and Evaluation Strategy

AEROWORKS contains an extensive and thorough ***evaluation and benchmarking*** process in order to validate the flying qualities, state estimation accuracy, 3D reconstruction fidelity, risk classification abilities, aerial co-manipulation dexterity, inspection completeness and overall infrastructure maintenance potential. A progressive and complete demonstration and evaluation process will take place as described in *Work Packages (WP) 2 and 8*. During the last phases of the project, the AEROWORKS robotic team will demonstrate its ultimate capabilities in public demos in environments relevant to civil infrastructure applications ***[TRL=6]*** while a smaller subset – the more mature and more feasible in terms of legislation – will be demonstrated in real operational environments ***[TRL=7]***. The consortium end-users SKL and AIR will be

Figure 1.8: Demonstration sites already being used by members of the consortium. Within AEROWORKS, demonstrations will take place in environments that mimic those of civil infrastructure inspection or even in real operation.

responsible for providing and arranging the access to demonstration environments and operational facilities, as well as for defining the benchmarks for the systems' evaluation. Figure 1.8 provides indicative demonstration environments already being used by members of the AEROWORKS consortium.

1.3.5 The AEROWORKS Integrated Solutions and Subsystems Technology Readiness Levels

The Table below summarizes the currently achieved and targeted TRLs by the AEROWORKS consortium, for the aerial robotic workers solutions for infrastructure inspection and maintenance, as well as for the project technological contributions and combinations. The TRLs indicated in this project follow the guidelines of the European Commission Project Call and the guidelines with the SRA and MAR.

Technology	Current TRL	Target TRL	Plan
AEROWORKS Integrated Solutions			
Single Teleoperated semi-autonomous ARW-Inspector	6	7	The operation of a single teleoperated semi-autonomous aerial robotic worker for inspection operations has been demonstrated by ETHZ and AIR in the Narcea Power Plant at November 2012 [6] in collaboration with UEDIN. Within AEROWORKS, this concept will be further improved and optimized regarding its 3D reconstruction techniques, accuracy of flight as well as the incorporation of obstacle avoidance capabilities. These technologies will be demonstrated in a real operational environment in collaboration with SKL and AIR.
Single Autonomous ARW-Inspector	4	7	The operation of a single fully autonomous ARW for inspection operations has been validated in the ETHZ lab facilities [7] [8]. Within AEROWORKS, the improved perception capabilities and obstacle avoidance algorithms will be combined with new and novel autonomous inspection planning strategies. The result will be demonstrated and operated at least once in an operational environment (power grid, wind turbine etc).
Collaborative ARW-Inspector	2	6	Consequently, the collaborative ARW team will be formed and the overall autonomous inspection capabilities will be demonstrated in a relevant environment. Significant work has been conducted regarding this problem formulation and relevant algorithms have been evaluated, especially by KTH [9] [10]
Single Teleoperated ARW-maintainer	4	6	The operation of the teleoperated ARW has been validated in the lab facilities of UT [11] as well as UPAT [12] Within AEROWORKS the improved aerial robot and manipulation will be demonstrated in relevant environments, where manipulation tasks for infrastructure maintenance will be conducted.
Single Autonomous ARW-maintainer	2	6	As a follow up of the previous developments, the ARW will be combined with the relevant algorithms for manipulation towards infrastructure maintenance operations. The results will be demonstrated in a relevant real environment. So far only the technological concept has been formulated but since teleoperated manipulation is achieved by UT [11], one can only expect that autonomous tasks will improve the results.
Collaborative Autonomous ARW-maintainer	2	6	Several autonomous ARWs will form a team, and collaborative manipulation tasks will be executed. This operation will be validated and potentially demonstrated to end-users in relevant real environments. So far only the technological concept has been formulated. The basis for the multi-agent collaboration algorithms is already part of the research contributions of KTH [9] [10]
Single Teleoperated semi-autonomous ARW-Inspector	4	6	The technologies that form an ARW that is able to both inspect infrastructure facilities and conduct maintenance tasks have been partially and preliminarily demonstrated in real-life and validated in the lab respectively. The relevant AEROWORKS developments will lead to the teleoperated ARW-Inspector+Maintainer, the capabilities of

+ Maintainer			which will be demonstrated in real environments.
Single Autonomous ARW-Inspector + Maintainer	2	6	Based on the aforementioned developments towards realizing the teleoperated ARW-Inspector+Maintainer, the planning algorithms for inspection and manipulation will be combined to form the autonomous ARW-Inspector+Maintainer. The results will be demonstrated in real environments.
Collaborative ARW-Inspecting + Maintaining team	2	6	Finally, the AEROWORKS efforts will lead to the autonomous ARWs team capable of conducting infrastructure inspection and maintenance operations. All the relevant results will be demonstrated in real-life environments in a series of public events.
Generic AEROWORKS Technological Contributions			
AEROWORKS 3D Reconstruction Solution	4	7	The AEROWORKS Sensing and Processing Unit with the onboard 3D reconstruction algorithms will be released as a technology module that may be utilized in further robotic developments. Starting from its current status (validated in the lab), it will be demonstrated in an operational environment.
AEROWORKS Dexterous Aerial Manipulator	3	6	As aerial manipulation becomes a research trend, the AEROWORKS team will focus on releasing its manipulator hardware and software setup as an open-source project that will enable further developments by researchers and robotic development enterprises.
AEROWORKS Aerial Manipulation Controls	2	6	Similarly, the ARWs aerial manipulation control laws will be released as an open-source contribution. The performance of these controllers will be demonstrated in an environment relevant to that of real-life infrastructure inspection operations.
AEROWORKS Single-Aerial Robot Inspection Planning	4	7	The theoretical and algorithmic properties of the ARW-Inspector planner will be generalizable to a wider class of robotic inspection applications. Therefore, the corresponding algorithms will be released under an open-source license and effort will be put to integrate them common middleware interfaces like ROS. The results will be demonstrated in a real-life operational environment in collaboration with SKL and AIR.
AEROWORKS Multi-robot collaboration strategies	2	6	Similarly, the AEROWORKS multi-robot collaboration algorithms will be extendable to a wider class of problems. Therefore, the formulations will be generic and the corresponding architectures will be released, when possible, as open-source contributions. As the results will be demonstrated in an environment relevant to that of real-life infrastructure inspection operations, it is expected that evaluation analysis on their robustness and efficiency will be available.

1.3.6 Relevant Projects and Research Efforts

A list of the most relevant national and international research and innovation activities is provided below as well as the connection of the AEROWORKS consortium with the corresponding efforts.

Project Description	Key difference with AEROWORKS
EuRoC (European Robotics Challenge - EU-funded FP7)	The EuRoC/Plant Servicing and Inspection (PSI) Challenge aims at targeting the open problems in existing MAV solutions (especially in multirotors) to enable their deployment in real-life scenarios. The competing teams will try to provide solutions to the problem of safe navigation within complex structures, such as those of infrastructure facilities. Therefore, there is a potential for synergies, especially taking into account that the AEROWORKS ETHZ partners host the EuRoC PSI Challenge.
PETROBOT (EU-funded FP7) PETROBOT intends to develop and	PETROBOT deals with the problem of petrochemical industry facilities inspection. It is a project that is at its initial phases and the

validate new robot inspection technologies for a) Internal inspection of pressure vessels, b) Inspection of storage tanks	AEROWORKS partner AIR is also a participant there. Through this channel, synergies and further collaborations will be developed.
ARCAS (Aerial Robotics Cooperative Assembly System - EU-funded FP7) The project started in 2011 and aims at realizing a robotic system which involve the transportation of parts, and the placement and assembly of the parts using manipulators to build a structure or assembly an object. Project site: http://www.arcas-project.eu/	ARCAS is an FP7/IP project that puts its research efforts in developing manipulator-endowed UAVs towards the deployment of a robot system for assembly and structure construction, following a rather centrally coordinated methodology. Therefore there is potential synergy with AEROWORKS which will be thoroughly investigated. However, the main focus of AEROWORKS is different from that of ARCAS since it focuses on: a) strategies for autonomous decentralized heterogeneous multi-robot collaboration to execute non strictly predefined complex tasks, b) collaborative environmental perception towards autonomous complete infrastructure inspection and repair, c) investigation of active mutual aerial interaction tasks, in terms of monitoring the energy flow between co-manipulating aerial robotic workers, both from the side of the manipulator and the aerial vehicle control, d) development of motion and manipulator task primitives, based on which the ARWs will be able to accomplish complex work-tasks that are not described in detail beforehand. Our consortium will make use of its expertise to investigate these directions, while building synergies whenever needed with the ARCAS team.
AIROBOTS(Innovative aerial service robots for remote inspections by contact - EU-funded FP7) The goal of the AIRobots project is to develop a new generation of aerial service robots capable to support human beings in activities that require the ability to inspect remote environments through contact. Project site: http://www.airobots.eu/	The labs at ETHZ and UT also participated in this project and have gained the experience of the ground-setting research efforts conducted within this framework. AEROWORKS goes even further, focusing on cognitive strategies for autonomous complex task accomplishment using collaborative aerial robots that make use of their advanced manipulators. Additionally, AEROWORKS will perform research on collaborative mapping and control of UAVs that use their manipulators to pick up and use tools and objects, as well as on the control aspect and coordination of aerial robots coupled through the mechanical links of their manipulators and via the mutually grasped objects.
International Projects and Research Efforts	
Drexel Autonomous Systems Lab – Prof. Paul Oh - National Science Foundation (NSF) project to develop “Mobile Manipulating UAVs”.	This project aims on understanding the effects of manipulators on aerial vehicles and optimize the design and control aspects. The AEROWORKS consortium will strengthen the link with the DASL lab, since the research efforts achieved on control may potentially lie within common fields.
Yale University – the GRABLAB – Assist. Prof. Aaron M. Dollar: at GRAB lab the aim is to develop unmanned aerial vehicles that are able to interact with the environment through the utilization of compliant manipulators.	This project aims on analyzing the effects of induced forces and torques from grippers attached on existing helicopters. The main focus is on how to design a manipulator that can suit existing helicopter designs and controllers. Prof. Aaron Dollar, director of the GRABLAB is a member of the AEROWORKS advisory board and we aim to create fruitful collaborations and exchange of ideas.

Overall it is highlighted that in most of the European projects related with structures inspection, at least one of the AEROWORKS partners participates. Essentially, AEROWORKS will be the research and innovation avenue following which, all the previous contributions will be combined with new developments that will lead to a whole new class of more advanced and technology-ready systems.

1.4 Ambition

Within this Section, a brief overview of the State of the Art along with explanations of the AEROWORKS ambition to go beyond the currently achieved results is provided.

1.4.1 Dexterous Manipulation for Aerial Robotics

State-of-the-Art:

Within the AEROWORKS scenario context, multiple ARWs will perform tasks, such as infrastructure maintenance, via collaborating both in a turn-based sense and in a cooperative way. The tasks the ARWs have to perform therefore require active robot-to-robot physical interaction. To achieve such goal, the AEROWORKS aerial robotic workers should embed basic new functionalities of robust and precise aerial manipulation. These require that the final robotic system will be characterized by high dependability and interaction capability by employing novel manipulation and design concepts.

Aerial manipulation is a new field of research and only a limited group of researchers have already focused in this direction (with the AEROWORKS UT and UPAT and ETHZ partners being among them). Among the most recent works, aerial manipulation is a research topic that is addressed both focusing on the capabilities of the aerial platform to perform manipulation tasks, and by the development and utilization of manipulators aimed at increasing the manipulation capabilities and precision while performing the manipulation task.

Aerial robots *without* dexterous manipulators have shown their potentials in applications such as object picking and transportation, both as single and as collaborative group [13], in construction building [14] and assembling [13] [15]. Nevertheless, when the aerial robot is equipped with a manipulator, the augmented dexterity allows performing tasks that drastically increase the performances in both precision and physical interaction. Is has been demonstrated in the laboratories of UT that a manipulation system, as the custom-developed manipulator connected on an quadrotor UAV, allows increasing both precision and the interaction capabilities of the aerial manipulator, compared to the case of a fixed tool [16]. Moreover, relevant work of UT has demonstrated that, due to the physical properties of most aerial robots available –being floating-base and underactuated–, the control of the aerial manipulator should allow a degree of compliance, that can be achieved via passive control as in [17], or by force feedback as in [18]. Recent works along the same research lines have demonstrated the capabilities of a fully actuated redundant lightweight arm mounted on the bottom of an unmanned helicopter. This work shows the challenges that are introduced by a manipulator on the aerial vehicle due to the coupled dynamics between the systems and proposes a control solution.

Among our latest relevant works, UPAT/ETHZ have proposed a solution to the development of innovative mechanics for the aerial vehicle to perform increased force-exertion tasks [12].

The AEROWORKS contribution and progress Beyond the State-of-the-Art:

AEROWORKS will move beyond that state. The envisaged scenarios generally refer to collaborative interaction tasks involving single or bilateral aerial manipulation. The main contribution of AEROWORKS as compared to the current state-of-the-art and existing literature will be the introductory force in the fields of: a) active manipulation of objects or tools aiming to their practical usage, not confining in carrying and placement tasks, as well as b) mutual physical interaction and co-manipulation using aerial robots. In terms of manipulator design, the work beyond the state of the art will consist in proposing a framework to the development of innovative mechanical solutions, as well as control strategies, to guarantee the robust execution of dexterous aerial manipulation and mutually assisted actions from the collaborating robots team.

The achieved manipulation capabilities will provide the primitive operations necessary to accomplish complex higher-level collaboration-requiring tasks. The use of lightweight design techniques and compliant mechanisms will guarantee both safe interaction of the robotic system and a high level of dependability, due to the intrinsic capability of compliant elements to adapt to the interaction. The designed systems and control schemes will incorporate the extended study results in: a) the physical interaction between an object and the environment, b) the impact on the aerial robot during manipulation, as well as c) the physical interaction between the co-manipulating aerial robotic workers. Of particular importance is the in-depth analysis of the influence that mutual dynamic interaction has on each singular aerial robotic worker platform. The envisaged novel mechanical solutions will allow the aerial robot to grasp and actively utilize non-predefined objects and co-manipulate together with other aerial robots, while minimizing the mutual dynamical impact on the vehicle's dynamics. Additionally to that, the manipulation system will be developed such that the energy exchange between two or more collaborating robots, and the collaborating team's sum effort, are minimized. Issues emerging from robot-to-robot interaction, such as switching contact and dynamical impact, will be specifically addressed. Of particular interest is the minimization of the disturbance effects at the initial grasping phase, especially when two or more robots are coupled through a commonly manipulated object.

Within the proposed research, energetic approaches to the control of the mutually physically interacting systems will be used to propose a formal methodology that guarantees the passivity of the system during the dynamic interaction between aerial robots. Specifically, novel effective solutions, both mechanical and algorithmic, addressing the control challenges related to the aforementioned aspects will be developed.

1.4.2 Perception, Mapping and Vision for Manipulation

State-of-the-Art:

Visual-Inertial Simultaneous Localization And Mapping (SLAM): In recent years, a considerable research effort has been focusing in automating UAV navigation. The now well-established combination of visual and inertial cues has been employed successfully in various systems [19], [20]. Moving away from traditional loosely-coupled fusion approaches, recent work showed that tightly coupled optimization over inertial and visual error terms can lead to better performance [21], [22], [23]. An excellent example is that of the latest SLAM results by members of the AEROWORKS consortium, demonstrating the power of these fusion strategies on loosely coupled [24] and tightly coupled frameworks [22], [25], which have employed on very relevant frameworks aiming towards inspection of industrial boilers and underground mineshafts using UAVs [26], [27], [28]. The technological platform of our perception module is shown in Figure 1.9 and has been specifically designed to allow effortless visual and inertial data capture. This sophisticated sensing unit comes with a default setup of a stereo rig of cameras, while it allows data capture of up to four cameras interfaced through a modern ARM- FPGA system. Along with the visual sensors, it features an Inertial Measurement Unit (IMU) providing high-quality rate gyro and accelerometer measurements, calibrated and hardware-synchronized with the images. The latter is specifically interesting to the SLAM capabilities we aim to develop within AEROWORKS, as it facilitates a tight fusion of the visual and inertial cues captured during the motion of each ARW.

Place recognition and loop closure: While accurate frame-to-frame estimation is our goal as it is key to high-fidelity SLAM, inevitably small estimation errors accumulate over time, as visual odometry is prone to drift. For this purpose, visual dictionaries can be used to retrieve locations with high probability [29]. Inspired by text retrieval techniques, the pioneering work in [30] proposed to describe an image as a set of visual words, giving rise to what is widely known as the Bag Of Words (BOW) approach. The success of BOW approaches in searching for similar images in a database has led to their wide use, however, it was soon realised that their performance increases with the size of the vocabulary [31], not only affecting complexity, but also encouraging misclassification. The FABMAP framework (*presented in* [32]), partially alleviates the latter by learning the dependencies between visual words, in a framework that is currently considered the highest performing pipeline for place recognition, reporting remarkable performance on large datasets with strong perceptual aliasing. However, the performance of FABMAP and any such system is bound by the precision-recall characteristics of the features it uses to identify salient image regions (e.g. FABMAP 2.0 uses SURF [33]). The high performance of sophisticated features such as SURF and SIFT, typically comes at the cost of speed, driving many systems to rely on the availability of GPUs for practical computational time, albeit prohibiting the applicability of such methods on lightweight systems.

Dense 3D reconstruction: While SLAM comprises the first step towards the spatial awareness of a robot, it is well-understood that for a robot to navigate in its environment, the traditionally *sparse feature-based* SLAM maps are not sufficient for tasks, such as sophisticated obstacle avoidance or manipulation. Recently, *dense visual odometry* approaches demonstrated the feasibility to jointly estimate the camera pose as well as the full scene depth given the intensity values of the full images [34]. This novel approach is in contrast to traditional SLAM approaches which only use sparse image features instead of the full intensity image. Most impressively, [35] pioneered high-quality real-time dense reconstruction with "*KinectFusion*" using an RGBD camera, while [34] demonstrated the first real-time dense reconstruction pipeline using a monocular, visible-light camera. On the flip side, the amount of computation required by these techniques is immense, necessitating the use of extremely power-consuming GPUs and restricting the mode of operation to very small spaces. Given the power and weight constraints of a UAV, the AEROWORKS consortium focuses on dense reconstruction approaches based on stereo vision. Based on available, open-source implementation of depth reconstruction algorithms [36], local scene reconstruction was demonstrated and subsequently fused into a global voxel-grid based map [37] by incorporating the pose from our state estimation framework [22].

Collaborative robot sensing and mapping: Once each ARW is employed with SLAM functionality enabling perception of its individual motion and workspace, the next step is to consider the bigger picture of the AEROWORKS paradigm. Namely, the presence of multiple ARWs employed for a common task, such as inspecting a given area. Enabling collaboration across multiple ARW agents to exploit this information can enable more efficient and effective perception of the environment – for example, mapping a scene from different viewpoints can eliminate the effect of occlusions and boost accuracy when considering the two views as comprising a stereo-image setup. The challenge of matching across different aerial views to enable collaborative mapping has been addressed very little in the literature, with our previous work being the most relevant [38]. However, akin to this problem is Place Recognition, which has been troubling the Robotics community for quite some time.

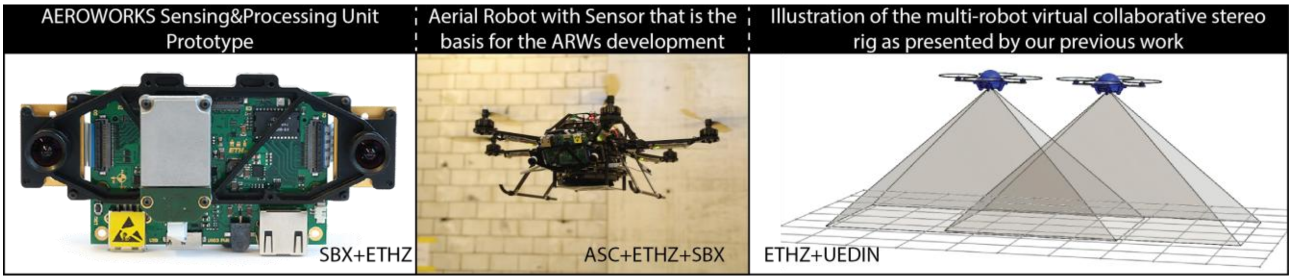


Figure 1.9 Photo of the current AEROWORKS Sensing and Processing Unit as well as its integration on an ASC Firefly aerial robot. Furthermore, the collaborative perception by two UAVs viewing the same scene as addressed in our previous work in [38] is visualized. While only demonstrated on simulated visual data, the idea of treating two UAVs (here ARWs) as forming a variable baseline stereo-rig can be a very powerful and useful basis in addressing the collaborative perception and mapping for industrial inspection within AEROWORKS.

<u>The AEROWORKS contribution and progress Beyond the State-of-the-Art</u>

Visual navigation for aerial robots: While SLAM is a well-studied problem, we are yet to see fully autonomous navigation for agile robots such as UAVs. In a bid to enable autonomous operation outside the controlled laboratory environment, we aim to build on our previous work [22], [39] to address the challenges on visual-inertial SLAM for truly autonomous operation. While [39] has pioneered vision-based UAV operation, the approach requires cumbersome initialization necessitating human interaction at take-off and landing, while the quality of estimates has never been put to test (i.e. via interaction of the UAV with its environment). In [22] we demonstrated the benefits of tight vision-IMU fusion in SLAM tested on generally smooth camera motions (e.g. sensor-suite strapped on a car roof). However, the applicability of this method is yet to be tested for the jerky camera motions we expect in AEROWORKS, as the sensor suite here is carried by highly agile and dynamic ARW rotorcraft. Adding on to the challenge, the type of environments to be mapped in the industrial inspection AEROWORKS paradigm is far from trivial, as the potentially large featureless areas and the ambiguity caused by erroneous corner features arising from pipework occlusions can prove fatal for any existing SLAM pipelines. However, with the great interest in automated visual inspection in such industrial applications, the potential impact of the research in robust visual navigation planned within AEROWORKS is great.

Dense 3D reconstruction: Current monocular dense reconstruction pipelines are mostly implemented on power-consuming GPUs, which make them impractical to be used onboard UAVs. As a consequence, we follow a two-fold strategy in dense reconstruction. For robust dense reconstruction, here we intend to use the sensing capabilities of the stereo module onboard each ARW to develop a suitable dense reconstruction pipeline building on existing work. To increase robustness with respect to reconstruction outliers, it is planned not only to enforce *spatial* photo consistency in between a stereo image-pair as already done today, but also to incorporate *temporal* photo consistency. Incorporating the stochastic properties of the depth reconstruction process as well as the covariance of the estimated pose, a robust outlier detection scheme based on temporal photo-consistency will be studied. As a subsequent step, we intend to evaluate dense reconstruction algorithms based on monocular vision. Contrary to traditional monocular dense mapping alternatives, here the focus will be on techniques that can realistically be applied on the envisioned scenario of a power –and computation– independent ARW. As a result, our study into denser mapping strategies will avoid the power-demanding GPUs and rather aim for a methodology employable on CPUs. While the use of a more powerful ground station for post-processing of information will not be excluded, our goal is to enable the acquisition of at least a first ‘draft’ of a dense map in real-time by each ARW.

Collaborative ARW perception and mapping: With little work in the literature on collaborative perception and mapping from multiple UAVs, there is great potential for innovation in AEROWORKS. Addressing this as an extreme case of place recognition, the aim here is to investigate the applicability of recently emerged binary features (e.g. FREAK or our previous work on BRISK [40]) in place recognition pipelines. While FABMAP [41] is probably the highest-performing place recognition pipeline to date, it has been devised for use with high-quality power-demanding visual features (SURF [42]), which feature floating point descriptors (as is the case in most feature types). As a result, in order to make the most of the qualities of binary features within such a pipeline, extensive investigation needs to be performed towards the realization of the methodologies involved (e.g. clustering and classification of binary descriptors). Moreover, given that image matching within AEROWORKS needs to be performed for images captured from different platforms, the viewpoint change can be drastically different, which can be a limiting factor in today's place recognition pipelines as they consider the world as a set of discrete locations. To this end, AEROWORKS will study the graph structures used to represent the world and as a result, the graph matching techniques used in order to allow a more continuous representation of the world. Effective image matching across views captured from multiple ARWs will enable collaborative perception and mapping, which is key in efficient and effective multi-agent inspection of a scene.

Vision for aerial manipulation: The AEROWORKS project will use vision also for manipulation as a part of the vision-guided manipulation control structure. So far this problem has been approached for ground rovers and some research efforts have developed algorithms to servo manipulators in the Cartesian space [43], [44], while others worked in the image plane using intensity-based approaches to vision-guided manipulation [45]. However, most of this work has assumed a robust dexterous manipulator mounted on a robust platform on the ground. The limited dexterity compared to industrial manipulators will be compensated from the aerial robot degrees of freedom, while the limited positioning accuracy will be improved based on novel vision-based algorithms and the special manipulator design. One additional challenge is related with the fact that the same vision module will be used for mapping and manipulator control. As it will be rigidly attached to the aerial robot, several challenges arise (occlusions due to the manipulator motion) and for the final phase of the object grasping the system will have to rely heavily on the remaining sensors. Vision-based aerial manipulation will mark an additional contribution of the AEROWORKS project.

1.4.3 Aerial Robotic Workers Development and Control

State-of-the-Art:

A pivotal point has been reached in the field of airborne robotic systems, with a notable research turn marking the passage from the era of aerial observation/navigation, to direct physical interaction with aerial robots. Established research groups worldwide progressively adopt this vision and address the challenges of aerial robots that do not regard their surroundings only as a set of navigation obstacles *to be avoided*, but *aim to interact* with their environment, substantially increasing their possible functionalities.

From the control point-of-view, the research labs of ETHZ and UT (AEROWORKS partners) participated in the EU AIRobots project, identifying the challenges and successfully demonstrating the utility of aerial vehicles that conduct inspection missions which require direct physical contact [17], [46], [6] , [18]. Efficient control strategies for approaching, collision, and stable docking were developed, controlled sliding/maneuvering while docked were achieved, and high-end robust manipulators were incorporated onto the vehicles in order to allow for increased-inspection precision. Beyond this, ETHZ has reached the level of autonomous aerial [28] and contact-based [47] inspection, as shown in Figure 1.10, with minimal system-design but utterly effective solutions. UPAT has developed a reconfigurable aerial robot which generates and exerts forces exceeding its own weight –while maintaining operational stability–, achieving pushing-manipulation of objects on the ground, and simple but forceful technical task-execution (surface-grinding) [12] while UT has progressed with active aerial manipulation.

Further advances include GRABLAB's (Yale University) [48] , [49], demonstrated potential in controlling a UAV which is subjected to the forces and moments introduced by a compliant gripper. The ARCAS European Project [13], also dealt with the control of a UAV, coupled with a medium-scale KUKA-DLR manipulator, while performing visually-driven manipulation. The GRASP lab has followed the direction of nature-inspired paradigms and achieved avian-like grasping of small objects, employing quadrotor UAVs equipped with a gripper. Also the same lab focuses on cooperative grasping [50], but with limited focus in the system's autonomy, manipulation efficiency, and the decentralization of the cooperative strategy. The CSIC research institute has developed motion-planning algorithms for aerial collaborative 6-DoF towed-cable manipulation. Regarding the aerial robot – manipulator carrier platform, several research groups are using systems from the AEROWORKS partner (UT,ARCAS Project, GRASP Lab and more) while within

AEROWORKS the most recent developments on multirotor systems –such as an advanced Firefly hexarotor– will be utilized. Figure 1.6 presents recent results of aerial robotic physical interaction and manipulation presented our project partners.

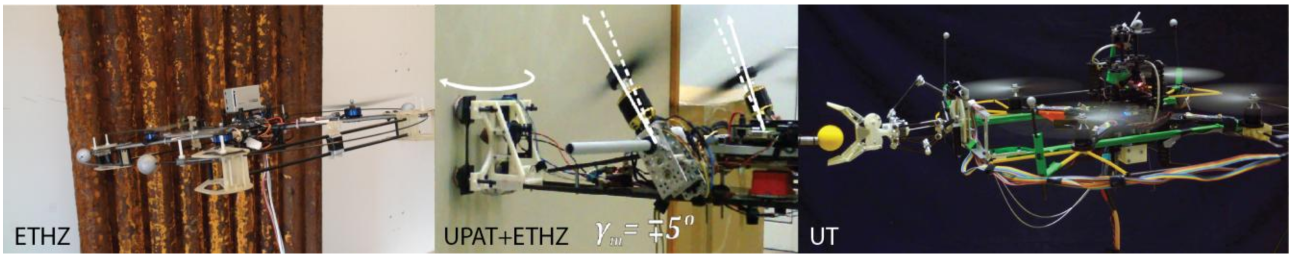


Figure 1.10: Examples of physical interaction and manipulation control already achieved by the consortium: an ETHZ quadrotor performs inspection through contact manoeuvres (*left picture*), a UPAT tilt-rotor executes a grinding task (*picture in the middle*) and finally a UT quadrotor equipped with a dexterous manipulator for complex contact-based inspection operations (*right-side picture*). Both the ETHZ and the UT aerial robots are based on ASC UAVs.

The AEROWORKS contribution and progress Beyond the State-of-the-Art:

Despite the recent progress, it is believed that the approaches followed up to this point have only begun to scratch the surface of the full potential lying in aerial robotic manipulation. The AEROWORKS vision requires increased technological maturity levels and numerous control challenges need to be addressed:

Ground-Up Approach for Dependability and Configurability: The development of all the integral parts of the ARW will follow a structured approach, providing seamless component interfacing, scalable functionalities, fail-safe/redundant subsystems, multi-modal (autonomous/tele-operated) control, and an overall architecture that will contribute to the area of field robotics. Additionally, the development of UAV platforms and manipulators of different sizing/capabilities will allow for task-tailored configurability at the ARW level (lightweight UAV & manipulator combination for small-scale tasks, heavyweight combination for demanding tasks, heavyweight UAV & lightweight manipulator but with heavy sensor suite such as LiDAR, thermal cameras, etc. for advanced sensing), while also adding increased operational versatility at the heterogeneous collaborative team level.

Analytical Methodology for Stability Analysis and Low-Level Control: AEROWORKS aims to have a direct impact on aerial robotic applications. Methods and tools needed to analyse the stability and assess the performance of the attitude-controlled platform, while operating under the presence of forces and moments introduced from a manipulator, will be developed. Existing attitude controllers and schemes will be examined, aiming to make the derived results transferable to the aerial robotics market. The developed tools will aid the derivation of the maximum manipulator workspace and force/moment margins that do not compromise the aerial platform's stability, while further research effort will be invested in novel model-based attitude control synthesis which accounts for the introduced forces/moments.

Novel Motion Capabilities based on Coupled Aerial Robot-Manipulator Dynamics: The ARW is envisioned as a proficient robotic technician in the air, executing manipulation activities with robustness and stability, while benefitting in its performance in the same sense that a human utilizes their body to aid their arms and hands. This tightly coupled system operating in the air requires the development of: a) a novel multi-body modelling approach, b) regard for the operating environment in the control sense (for safe navigation and in the worst case collision robustness), and c) novel model-based control synthesis that exploits estimates of the induced forces and moments and dynamically/ kinematically combines the UAV's actuation capabilities with the manipulator's dexterity. AEROWORKS will exceed the limited concept of compensation-only during aerial robotic manipulation, and will innovate by developing controllers for multi-body collaboration achieving maximum effectiveness in challenging task execution.

Natural Interaction and Efficient Manoeuvring for Robust Co-Manipulation: Research directions derived from nature/human-inspired paradigms will be incorporated in a high-level control synthesis. The aim is to achieve unprecedented collaborative manipulation by focusing on the ARW control level in order to attribute a level of natural interaction potential. Employing the force/moment-feedback of the manipulator, and relying on the advanced multi-body control of the aerial worker, each unit will have the capability to sense the aiding-or hindering role of the effects induced during co-manipulation, from one robot to the other and via the commonly manipulated object, and adaptively compensate or benefit from them. In this sense, the ARW will act in a similar way to a human operator within the group paradigms of table-carrying and double saw tree-cutting, where the task execution efficiency does not rely on constantly communicated coordination, but comes as a product of the human sensing abilities and motor skills. Additionally, the challenges of co-manipulation include the capability to execute near-optimal maneuvers in order to initiate/terminate the tasks. Grasping and releasing objects already manipulated by other ARWs requires in-depth investigation, in order to identify the crucial parameters and the proper strategy that yields trajectories with minimally-destabilizing effects, while efficiently exploiting the advanced mobility and compliant motion capabilities of the UAV-manipulator combination.

The aforementioned contributions will mark a cornerstone in aerial robotic manipulation and will provide a reliable basis for the effective integration of higher-level, intelligent multi-robot collaboration strategies.

1.4.4 Collaborative Navigation and Planning for Inspection and Manipulation

State-of-the-Art

Navigation of multi-agent systems is an area of increasing interest both from a research, as well as an application viewpoint. When it comes to robots or vehicles, collision avoidance and decentralization are two important design specifications for guaranteeing safety and scalability. Thus, there has been a growing demand for the development of decentralized navigation methods with guaranteed collision avoidance. In recent years the application of potential field-based methods has been explored [9], [51] as a promising alternative for such algorithms. A common problem with potential field-based path planning algorithms in multi-agent systems is the existence of local minima [52]. The seminal work [53] involved navigation of a single robot in an environment of spherical obstacles with guaranteed convergence. The closed-loop single robot navigation methodology of [53] was extended to multi-agent systems. In particular, in [54], [10], [9] this method was extended to take into account the volume of each robot in static environments, yielding the tool of Decentralized Navigation Functions. The latter were also used for multiple UAV guidance in [55].

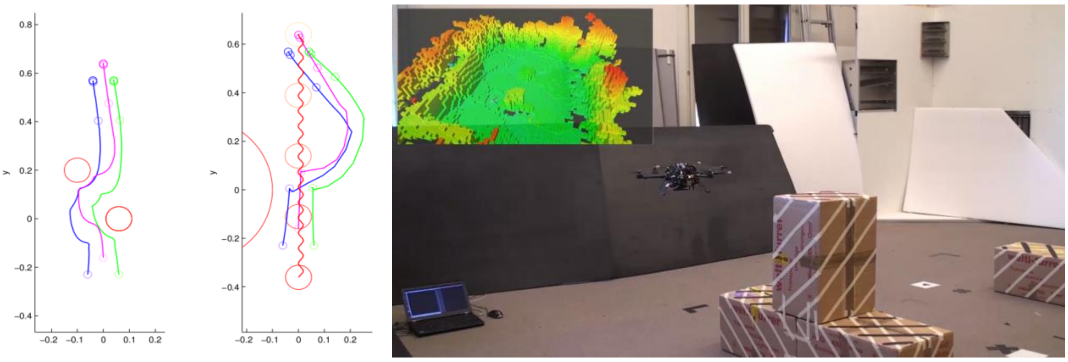


Figure 1.11: Multi-agent Collision-free navigation algorithms (KTH) and experimental evaluation of an inspection path-planning algorithm (ETHZ)

A second feature of the inspection mechanism will involve the coverage of the area of interest in a 3D setup. While coverage control in the plane has been extensively studied since the pioneering work of[1], the three-dimensional case has up-to-now mostly been considered for the cases of robots with homogeneous dynamics[2],[3] while no collision avoidance properties between the members of the multi-robot team were accounted for. When the goal involves grasping the target object of interest, collaborative approaches have mainly considered predefined contact points, and agent dynamics & motion while navigating towards them are not taken into account [56], [57]. A framework that considers both agent dynamics and adjustment of contact points as the robotic team approaches the object of interest may be of essence.

While navigation control approaches guarantee safe convergence without collisions, task-related specifications were addressed using discrete representations such as automata [58] and formal methods from computer science. The current effort is oriented towards unification of these two complementary approaches [59]. Up-to-date multi-agent control approaches at the task-planning level are mainly centralized [59], while

[1] J. Cortes, S. Martinez, T. Karatas, and F. Bullo. Coverage control for mobile sensing networks. *IEEE Transactions on Robotics and Automation*, 20(2):243–255, 2004.

[2] Andreas Breitenmoser, Jean-Claude Metzger, Roland Siegwart and Daniela Rus, Distributed Coverage Control on Surfaces in 3D Space, IROS 2010.

[3] Du Xiaoyu, Sun Lijuan, and Liu Linfeng1 Coverage Optimization Algorithm Based on Sampling for 3D Underwater Sensor Networks, International Journal of Distributed Sensor Networks, Volume 2013 (2013).

attempts for decentralization [60] rely on global information, thus lacking in scalability and adaptation to local changes in the environment. The AEROWORKS partners and especially KTH, UPAT and ETHZ have conducted extensive research in this area (Figure 1.11 presents some results) providing a great basis for the challenges aimed to be tackled in AEROWORKS.

The AEROWORKS contribution and progress

While decentralized navigation for multi-agent systems has been addressed in recent literature, most works consider a static environment where certain knowledge of existing obstacles and features of interest is given a priori. When it comes to the specific applications of AEROWORKS, an approach that goes beyond up-to-date trends should be considered. More specifically, the tool of Decentralized Navigation Functions is going to be enriched in order to cope with online knowledge of the environment each agent obtains through its own visual perception, as well as potential communication with other agents and the end user. Additionally, all provably correct works consider homogeneous agents and simple kinematic models for the agent motion. It is expected that the model of each aerial worker carrying a manipulator will possess a level of complexity far beyond the motion models that have been considered up to now in robot-navigation literature. This and the heterogeneous nature of the multi-agent group calls for more sophisticated tools for control design and analysis of the decentralized system that goes certainly beyond the state of the art. At the same time, we will consider algorithms for coverage control in three dimensions that build beyond the state of the art, both due to the fact that they will tackle heterogeneous robot dynamics, and also due to the fact that they will take into account collision avoidance requirements.

At the same time, the robotic workers we have in mind will possess collaborative manipulation capabilities. The envisioned framework goes beyond the current state of the art in the following ways: a) it will consider both agent dynamics and real-time adjustment of contact points for optimal grasping, and b) it will take into account the issue of navigation towards the object of interest in a synchronized manner. Such temporal constraints have not been considered up-to-now in decentralized multi-robot systems and thus constitute yet another research issue in this task. An initial attempt for a dual arm robot was considered in [61], but the crucial extension to multiple robots is yet to be explored.

Last but not least, a further feature we are going to address is the issue of online task reconfiguration for each individual robotic agent. Online information may have an effect both at the discrete and the continuous levels of planning and control. For example, when an agent meets an obstacle an issue is whether it would be more suitable to change the discrete objective by choosing another goal point, or to update the continuous controller in order to avoid the obstacle and keep the same target at the same time. This hybrid nature of task reconfiguration has not been considered in decentralized multi-agent systems and more specifically, in the case of aerial vehicles. Initial results for kinematically homogeneous agents are found in [62] but the case of coordinated control of multiple robotic workers with more complicated dynamics requires a fundamentally different approach

1.4.5 Integrated Robotic Infrastructure Inspection and Maintenance Solutions

State-of-the-Art

Robotic systems have been introduced to the infrastructure inspection and maintenance business. So far, specific systems have been developed to address several challenging problems with the vast majority of them having the form of a ground robot or a system that slides along a surface or navigates through a pipe etc. In some cases, underwater systems as well as remote-controlled aerial vehicles have been employed. Especially regarding the utilization of aerial systems, the great scientific developments on self-localization, control, path-planning and 3D reconstruction had not reached the required maturity levels or hadn't managed to convince the infrastructure service operators. Only few companies that use unmanned aerial systems for such operations exist, and they essentially rely on the skills of human remote-control operators. Furthermore, no real-life applications with manipulator-endowed UAVs have so far been realized.

The AEROWORKS contribution and progress Beyond the State-of-the-Art:

The introduction of the Aerial Robotic Worker, with its robust and reliable operation, safe navigation and multi-robot collaboration capacity towards advanced inspection and maintenance work-tasks corresponds to a breakthrough in the way robots are used in infrastructure services operation. A thorough analysis on the expected step changes is provided in the Impact Section 2.

2. Impact

2.1 Expected impacts

Infrastructure is the foundation that connects our resources, energy flows, businesses, communities, and people, driving our economy and improving our quality of life. A first-class infrastructure system, in terms of quality, distribution and long-term operation, is necessary if the European economy is to retain and strengthen its competitiveness. Within recent years, the scientific breakthroughs and technological developments in the area of robotics have been progressively bringing robots closer to real-life challenging applications, and some first demonstrations have already shown a promising potential. The AEROWORKS consortium involves the required key-players from the academia, robotic development SMEs, infrastructure service providers, and asset owners, sharing the vision and aspiring to develop aerial robotic systems with increased technology readiness level, capable of full operational integration within industrial environments and ready to increase the safety standards, improve environment characteristics of the maintenance business, provide advanced tools, lead to increased high-tech job creation and significantly reduced costs.

2.1.1 The Infrastructure Inspection and Maintenance Market: an overview

As highlighted in Section 1.1 and Figure 1, the annual investments on infrastructure inspection and maintenance correspond to a very significant portion of the generally large investments on infrastructure. As Figure 2.1 recalls, this can reach up to 15.15% of the overall financing for the infrastructure sector in a developed European Country such as UK. In recapitulation, Europe, as well as the rest of the world, faces growing infrastructure inspection and maintenance needs in the coming years, especially due to the age of its facilities, the required regulations and the cost of renewal.

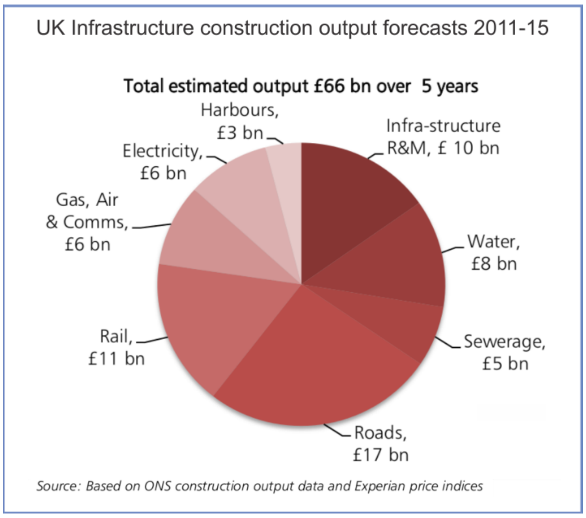


Figure 2.1: Cost of infrastructure development and Repair and Maintenance (R&M)

Infrastructure Inspection and Maintenance services refer to assessing the state of a facility, building, structure or overall network, and to the execution of specific maintenance tasks. Typically, an inspection expert initially needs to have visual data of specific components like linkages, joints, wires, ladders, isolators, sensors and actuators. Visual and non-destructive testing-based assessments of the mechanical integrity, corrosion, pollution and impurity of such components allow deducing the general state of the structure. Often, whole surfaces and supporting elements on an installation need to be inspected for potential cracks using visual methods as well as non-destructive testing devices. In case substantial defects are discovered, maintenance work like repainting or replacement of components is executed.

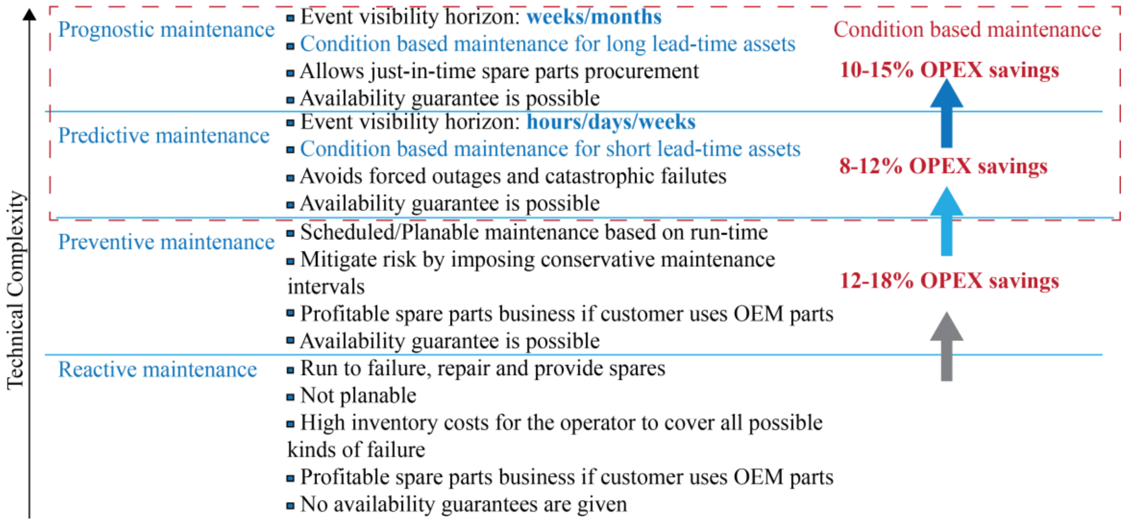


Figure 2.2: Infrastructure maintenance cycles – AEROWORKS focuses on the prognostic and predictive cycle

Inspection and maintenance services address a wide class of facilities and structures, both indoors and outdoors. Typical examples include those of wind farms, power grid network and high voltage power masts, power boilers, chimneys, cooling towers, mines, tankers, marine structures, flare stack inspections, oil rigs, bridges or water dams. Maintenance is conducted in several cycles (Figure 2.2), with those of *predictive* and *prognostic maintenance* being those mostly related with robotic applications.

Infrastructure services correspond to a large market which offers a unique potential for a new class of advanced robots like the aerial collaborative robotic workers. They essentially correspond to a multi-billion market of dirty-and-dangerous jobs, which however require great cognitive skills and dexterous manipulation capabilities. As the most fundamental cost of inspection and maintenance lies in the fact that facilities typically have to be shut down, reducing their operating times, maximizing the "availability" of the installations is among the most important goals. Even a few statistics reveal the size of this market:

- The Operations & Maintenance sector of the wind power market amounts up to 25% of the total energy production costs, and is expected to rise from *$ 7.3* to *$ 19 Billion* by 2020 on a global scale. Germany accounts for 12.9% and Spain for 7.2% of the global O&M market, and the UK is expected to grow to 15.6% by 2020 due to its heavy investment (1GW London Array with dedicated monitoring & maintenance facilities established nearby), and with European companies striking new contracts in-house and off EU-ground (Alstom in Turkey, Gamesa in the US, Siemens in Japan), while commonly (90% of contracts) offering guaranteed availability clauses, a need for high-quality, reduced-cost, and easily-deployable prognostic inspection & micro-maintenance solutions is rising.
- SGS, the Petrochemical management services company spent *$1,046 Mil.* during 2012
- Power plant Original Equipment Manufacturers (OEM) such as ABB, Alstom, Mitsubishi, Siemens and General Electric are competing to offer improved inspection services as each day of power outage of a power plant costs multiple millions. One day of outage of one of the coal boilers of the average-sized Narcea Power Plant in Spain leads approximately to *€ 1Mil.* Similarly, during the recent shutdown of the Swiss Leibstadt Nuclear plant due to a generator failure in the non-nuclear part of the plant, each outage day caused commercial losses above *CHF 1Mil.* In general, ALSTOM indicates that the basic rule of thumb of *€ 1Mil./day* for a 300MW grid undergoing unplanned maintenance applies.
- On average each bridge is inspected once every four years, while 4.000.000 of them exist worldwide and the inspection operations are mostly visual and nondestructive testing based.
- Metal-structure inspection businesses in total correspond to a *$ 276 Billion* market annually

Aerial robots correspond to an excellent alternative approach to infrastructure inspection. Even today where almost solely teleoperated and GPS-based solutions have been used in very few cases, companies such as Cyberhawk have conducted operations that saved *£ 4.6 Mil.* after their UAVs inspected a drilling derrick while it was still operational (http://www.thecyberhawk.com/)

However, current UAV technologies have not yet managed to become an integral part of the infrastructure inspection and maintenance operations, and skills such as high-fidelity 3D reconstruction or aerial manipulation are a very recent field. Since the inspection expert is interested in acquiring sharp and detailed visual, laser, thermal or other data, conducting piloted flight very close to structures is very dangerous, while GPS-based solutions cannot deliver the required accuracy. Furthermore, such approaches do not actually provide advanced inspection methods but are limited to provide an easier "eye-in-the-sky". AEROWORKS significantly exceeds this direction by providing autonomous inspection capabilities, high-fidelity 3D reconstruction based on multi-sensor fusion, cognitive representation of the results, automated contact-based non-destructive testing as well as execution of lightweight –yet very common– maintenance operations using the onboard manipulators, and finally high-level mission autonomy along with a framework for intuitive, interface-based teleoperation. Essentially, AEROWORKS corresponds to a game-changing revolutionary approach to infrastructure inspection and maintenance that provides time-efficient solutions along with improved inspection results, repeatable methods, statistical data and rapid, versatile maintenance tools.

2.1.2 Key drivers for the use of robotics in Infrastructure Inspection & Maintenance and the AEROWORKS plan

As AEROWORKS targets to provide advanced robotic solutions that can revolutionize the Infrastructure Inspection and Maintenance businesses, our first effort was to understand the key drivers that –if addressed–

can pave the way towards achieving such an ambitious goal. Based on the input of the AEROWORKS end-users SKL and AIR, the analysis conducted by Quasset on the perspective of petrochemical industry on robotic solutions [63], as well as a series of reports, the identified key-drivers for the use of robotics for inspection and maintenance operations are considered to be the following:

1. Safety first: Safety of personnel, asset and technology safety are fundamental priorities that have to be perfected in order to enable the possible use of robotic solutions in infrastructure service operations. Asset owners and infrastructure service enterprises put personnel safety as their first priority, and robotic solutions should aim in this direction and by no means introduce any new hazards. The health of the personnel and its protection from hazardous situations, and the zero tolerance on accidents (http://www.alstom.com/) are considered among the top priorities. Asset safety is also of paramount importance: the asset must be kept safe as any potential damage leads to unpredicted shutdowns and typically poses new risks for the personnel safety. Finally, any robot that is to be deployed in an industrial environment has to be robust, safe and reliable in order to avoid being damaged, which could in turn lead to further implications.

The AEROWORKS robotic team fully accounts and respects the aforementioned ***safety considerations****. The team of collaborative robotic workers will a) be able to conduct inspection and maintenance operations in dangerous and dirty environments* ***increasing the safety of the personnel*** *that will consequently be able to focus on the essentials of the operation, b) will be robust, fault-tolerant and fail-safe, eventually* ***harmless to the infrastructure facilities****, while c) its technological characteristics will reach the required robustness, reliability and readiness level that will allow its* ***"anytime" operation****. Among others, effort will also be put to investigate the required platform adaptations that will allow operation in explosive environments (ATEX qualifications etc.).*

2. Environmental Protection: Inspection and maintenance operations are essential to minimizing the negative impact of infrastructure assets on the environment. Moreover, the several inspection and maintenance procedures of an asset can in several cases (e.g. cleaning of petrochemical facilities) affect the environment. This impact should be minimized through the utilization of robotic solutions.

Towards this direction, the AEROWORKS robotic team will first of all improve the inspection and maintenance cycles, which consequently ***decrease the environmental imprint of the infrastructure*** *under operation, and also provide more regulated and accurate procedures allowing for minimization of the impact of service operations to the environment.*

3. Economic Impact: Infrastructure inspection and maintenance is a procedure that involves significant costs. Among the most cost-inducing factors is the need to take the asset off-line for inspection and maintenance, and the associated downtime and loss of production. Depending on the type of facilities, the required off-line time ranges from one day to several weeks, costing millions of Euros in lost production. Therefore there is a clear effort towards "**maximized infrastructure facilities availability**" and robotic solutions should aid in this direction.

The AEROWORKS collaborative aerial robotic workers team will be designed having this goal under consideration. The overall concept of fully (or if desired by the users semi-)autonomous inspection and active robotic maintenance using the team of aerial workers will exactly enable ***minimized inspection times –potentially also during– operation and faster and easier execution of several maintenance procedures****. The AEROWORKS consortium understands that for the infrastructure service sector, robots are essentially a means to an end: for acceptance it needs to perform equally or better than other alternatives with better economic costs. This potential will be shown and proven in the envisaged challenging and exhaustive demonstration and benchmarking process. Enabling the utilization of aerial robots and the particular concept of the aerial robotic worker as an integral part of the infrastructure inspection and maintenance operations is the absolute focus of the AEROWORKS team.*

2.1.3 Example Applications and Scenarios for the AEROWORKS robotic team

This section provides basic examples of identified and targeted applications of the collaborative ARWs:

AEROWORKS Example Scenario 1: Inspection of Wind Turbines [SKL, AIR priority]

The wind turbine inspection and maintenance field holds great potential for aerial robotic automation, since a major part of this business revolves around scheduled inspection & on-site maintenance operations. More specifically, greatly reduced profit losses can be achieved by frequently conducting inspection and micro-maintenance services of the turbine components (mainly the blades), as they can prevent future catastrophic failures which require taking down the entire nacelle. Detailed inspection maps provided by the AEROWORKS team can be used to accurately reveal: a) Erosion and damage -due to harsh environment exposure (rain, hail, ice, sandstorms) or material fatigue- of the blade trailing/leading edges and their protective coating, which causes loss of aerodynamic efficiency and reduced/uneven power generation. b) Accumulation of deposited material in crevices -such as sand and salinity- which can penetrate into the nacelle and cause catastrophic gearbox damage. c) Blockage of the blade draining holes, which can result in accumulation of water and oil inside the blades, leading to rotor mass imbalance and consequently main bearing wear or gearbox damage, or even explosive decompression after lightning strikes which causes the accumulated water to instantaneously evaporate. In this sense, the AEROWORKS team will provide template-based verification of the blade morphology and reliable assessments of the turbine status. Furthermore, the usually conducted micro-maintenance tasks of: a) clearing deposited material, b) opening/freeing the blade draining holes from blockage, and c) application of specialized filament to locally restore the blade coating, are almost a perfect match for the work-task execution capabilities of the proposed aerial robotic workers, since they are nowadays carried-out by human workers ascended on cranes. The AEROWORKS team is envisioned to be capable of undertaking this complete range of operations, and reliably guaranteeing the longevity and profitability of wind-power farms. Figure 2.3 presents this concept.

Figure 2.3: Wind turbine inspection and maintenance operations

AEROWORKS Example Scenario 2: Inspection of the Power Network [SKL, AIR priority]

Power transmission lines inspection services consists of surveys for collecting images, laser data, thermal and ultra-violet (UV) captures to allow classification of pylons, transformer stations and the calculation of catenaries, detection of thermographic-related faults and insulator damages or contact-based corrosion inspection. In several cases the maintenance operations are related with a) insulator washing, b) live line maintenance, c) insulator testing, d) marker ball instillation, e) spacer repairs and replacements, f) removal of surrounding vegetation to avoid flashovers, g) installation of corona rings and more. Such operations are nowdays conducted using expensive manned helicopter-based operations or slow ground teams. Especially when helicopters are not used, the ground crews have to reach each point by vehicle, ascend the structure by climbing or by using cranes, conduct the work, descend and repeat at the next point. Therefore, the costs are in general very high and the risks for the personnel as well as for the asset (especially in case of a helicopter crash) unavoidable. AEROWORKS will correspond to a step change and will address the growing need for high-precision, maximally-safe and easily deployable solutions. The team of collaborative ARWs is considered to be an excellent alternative to the current means of power network maintenance, providing a) complete high-fidelity, multi-layered 3D maps that fuse multi-sensor data (e.g. vision, LiDAR, thermal and UV imaging) based on which human operators can make risk assesments, b) semi- or fully-autonomous non-destructive testing on areas with increased probability of structural faults, and c) aerial robotic automatic maintenance based on collaborative manipulation by multiple ARWs. In collaboration with the our end-users SKL and AIR, relevant demonstrations will take place where both the inspection and maintenance capabilities of the ARWs will be evaluated. Figure 2.4 depicts the concept.

Figure 2.4: Power grid inspection and maintenance operations as envisaged to be conducted using the aerial robotic team along with photos of the currently used methods

AEROWORKS Example Scenario 3: Inspection of Pipework [AIR priority]

Apart from the internal inspection of the pipe network, pipework inspection also requires assessments of the external condition of the pipe facilities. The cost of the overall services is mostly determined by the cost of scaffolding (with more risk, roping is also used) and the need to remove the insulation layers. The team of collaborative aerial robotic workers corresponds to an excellent and powerful alternative that can rely on its airborne characteristics and the autonomous path-planning, and exploit multi-robot collaboration to provide rapid inspection and 100% structural coverage, and consequently use the onboard manipulators and novel penetrating inspection tools to derive all the required information needed for a complete assessment of the condition of the outer surfaces of the piping systems. This automated aerial robotic approach to pipework inspection and maintenance corresponds to a significant cost reduction as the inspection times are minimized. This, combined with the increased personnel safety as robots are used instead of ground crew using scaffolding in risky environments, reveals how AEROWORKS can benefit the infrastructure service business in this particular application scenario. Figure 2.5 illustrates how aerial robots can simplify such works.

Figure 2.5: Pipework inspection and maintenance operations

AEROWORKS Example Scenario 4: Inspection of a Power Plant Boiler [SKL, AIR priority]

Boilers of thermal power plants are large, rectangular chambers made from carbon steel tubes within which water or steam is transported, usually 15 to 35 meters wide and 50 meters high. Inspection usually focuses on corrosion and crack detection, particularly on the tube welds. Moreover, condition assessment of the injection nozzles and the super- and re-heater pipework is required. The inspection process typically starts with a visual pre-inspection, where all structures must be visually scanned. For this, often scaffolds are installed in the boiler. Subsequently, the combustion deposits on the boiler walls are removed and non-destructive testing is performed on all areas of interest. As such operations require that the boiler is shut down, and every day of missing operation corresponds to ~*€ 1Mil.* (for an average coal power plant boiler), improving the inspection quality while minimizing the overall time is of paramount importance. The AEROWORKS collaborative aerial robotic workers can provide a

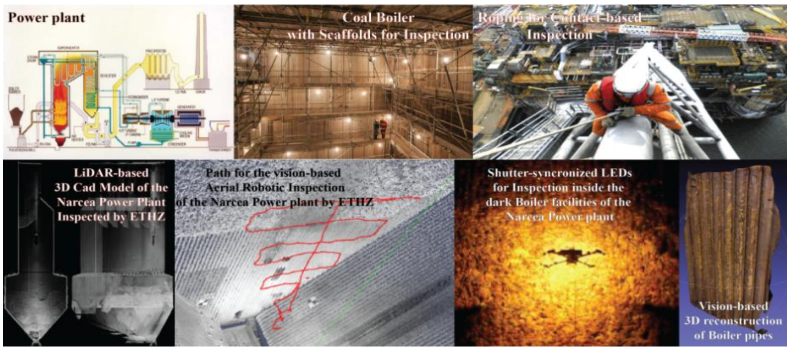


Figure 2.6: Boiler Power Plant Inspection and relevant aerial robotic inspection tests conducted by ETHZ at the Narcea Power Plant (Spain)

asset/personnel safe and rapid (no scaffolding, no roping) alternative that can provide the tool of high-fidelity 3D reconstruction, rapid & versatile nondestructive testing, and maintenance operations using the onboard dexterous co-manipulators (e.g. cleaning, brushing, polishing or even welding). Figure 2.6 shows instants of how the task is conducted so far and some initial inspection results our ETHZ partners have presented. AEROWORKS will build on top this experience and will ensure that a TRL-high product will be delivered.

AEROWORKS Example Scenario 5: Water dam Inspection [SKL priority]
In collaboration with the hydroelectric sector of our partner SKL and AIR, the case of Water dam inspection and maintenance is considered. Water dam inspection consists of identifying degradations in terms of structural cracking, erosion, sinkholes, vandalism effects, animal burrows, boils, depressions and more. Non-destructive testing has to be done, typically requiring several hours due to the challenging environments. Inspection records should be well-documented and provide statistical insights, while maintenance tasks are mostly related with local repairs. In that sense the AEROWORKS robotic team corresponds to a tool that will boost inspection, advance its fidelity with 3D maps and fused multi-sensor feeds (visual, laser, thermal), rapid non-destructive testing and yield fast execution of the lightweight subset of the repair work-tasks.

2.1.4 AEROWORKS contributes to overcome the technical capabilities gap

Integration of aerial robotic solutions into the infrastructure inspection and maintenance applications may only become possible as long as the challenging technical capabilities gaps are overcome. Towards this direction, AEROWORKS contributes in specific and important ways into the most prioritized and fundamental technical challenges and aims to provide solutions that will set the standards in the area. AEROWORKS technical contributions are aligned with the industry requirements [63], the MAR as well as the overall conclusions and directions of the scientific community [64].

AEROWORKS Contribution: **Aerial Robots for Inspection and Work-Task Execution**
The new concept of the aerial robotic worker requires innovative design methodologies and accordingly synthesized control schemes to provide the capability of ***active aerial manipulation*** in combination with ***advanced/robust perception modules*** for accurate and safe navigation, as well as ***intelligent planning and multi-agent collaboration strategies***. In that sense, AEROWORKS firstly contributes with the introduction of a novel robotic system characterized by increased levels of autonomy, capacity to perceive and model the environment, intelligence and the capability to execute physical work tasks on its environment.

AEROWORKS Contribution: **Control for dexterous (Co-)Manipulation**
AEROWORKS aims to have a significant impact in the field of aerial systems control by addressing the problem **of active aerial manipulation using multiple robots with a close integration of the reactive control actions and the deliberate planning algorithms**. Of particular importance is the problem of the mutual influence between the manipulator and the aerial vehicle body, especially when multiple aerial workers act on the same object, as well as the stability issues and the control limitations towards the development of robust and reliable aerial co-manipulation. The solutions that will be proposed will pave the way for wide use of aerial systems equipped with such capabilities. Within AEROWORKS, the problem of control will be approached in a way that stability and near-optimal performance can be ensured. Extensive demonstration will increase confidence in the field and present high TRL validation.

AEROWORKS Contribution: **Advanced Localization and Collision-free navigation**
AEROWORKS contributes in all the fields relevant to accurate ego-motion estimation, and will deploy a **robust and versatile collaborative simultaneous localization and mapping framework that will enable safe and accurate maneuvering within crowded, unstructured and uncertain real-life environments.** Relying on the *AEROWORKS Sensing and Processing Unit*, tightly integrated sensor fusion algorithms and multi-agent fusion of perception data, along with reactive path-planning methods for collision-free motion will allow the aerial robotic workers to gently and safely navigate within the challenging environments of infrastructure facilities. The planning algorithms will also account for the coupling between the motion primitives and the estimation confidence, and will adapt the planning commands accordingly. All the relevant capabilities will be demonstrated in relevant and actual environments, while the key elements of these solutions will become available to the community.

AEROWORKS Contribution: **High-fidelity Multi-Aerial Robotic Map 3D Reconstruction**
Automated infrastructure inspection relies on the capability of the robotic team to derive high-fidelity 3D models. Through **dense reconstruction algorithms** that rely on the tight fusion of inertial sensor readings,

stereo camera feeds, as well as (optionally on some robots of the team) LiDAR inputs or thermal/UV camera imaging, a dense representation of the structures of the environment overlaid with texture information will be computed. Such algorithms will run online, while further improvements will be possible with algorithms executed on the ground station. The resulting 3D-reconstructed model will offer a new and advanced tool to the infrastructure inspection operators, a tool very accurate, as well as repeatable over time. The proposed technologies will be demonstrated to achieve a high technology readiness level (at least TRL 6), and the key elements will become available to the international community.

AEROWORKS Contribution: **Autonomous Path-Planning for Inspection**
Relying on the accurate state estimation as well as dense reconstruction capabilities of the collaborative aerial robotic workers team, algorithms for the autonomous inspection planning that will ensure full coverage (mission completeness) and fast computation times (team readiness and dependability) will be designed. Furthermore, the mission-oriented planning algorithms will be integrated with the reactive safe-navigation planners and control laws. As AEROWORKS aims to increase the TRL for autonomous infrastructure inspection, demonstration on relevant as well as real environments will take place.

AEROWORKS Contribution: **Multi-robot collaboration and task planning**
Among the main characteristics of AEROWORKS is that of collaborative work-task execution and coordinated navigation. Novel solutions will be developed to address the problem of **autonomous multi-aerial robot collaboration for manipulation,** in order to execute a complex work-task. Addressing this challenging problem can have a significant impact from both a theoretical, and an applications-related point of view. Of particular importance is also the *heterogeneity* of the different robots. Finally, it is worth mentioning that addressing the problem of multi-robot collaboration is coupled with that of vision-based collaborative map building towards the achievement of an integrated solution.

The aforementioned contributions close the gap in the most important technical challenges as identified by key opinion leaders of the infrastructure inspection and maintenance businesses *(such as MAR*, [63]*)*

2.1.5 The AEROWORKS targeted Economic Impact

AEROWORKS aims to realize innovative solutions for the infrastructure inspection and maintenance market. According to the consortium plans, three different levels of success are foreseen:

1. **Short-term** utilization of the AEROWORKS robotic team by AIR (*as part of the services they offer*) and SKL (*as a tool for maintaining its assets*).
2. **Mid-term** wide integration of robotic products based on the AEROWORKS contributions to the infrastructure inspection business, and adoption of such tools by key service providers and asset owners.
3. **Strengthening of the European service robotics sector** by leading in such an important civil applications market.

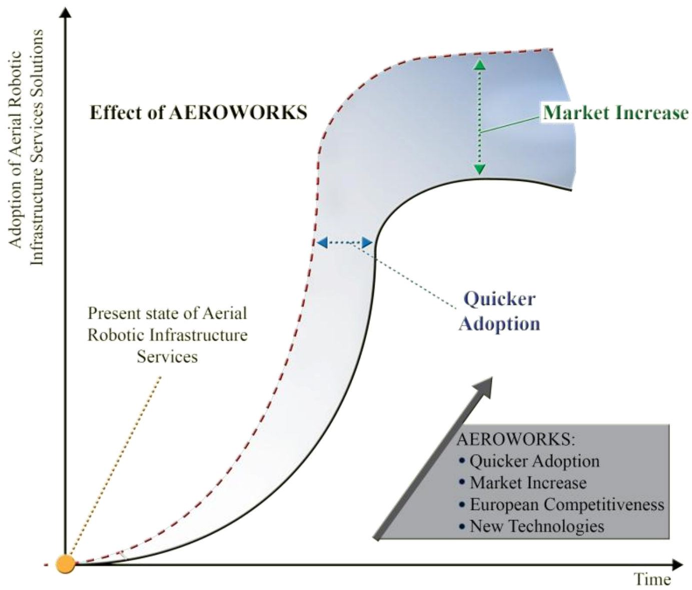


Figure 2.7: Drawing of how AEROWORKS will lead to added values, technology developments and earlier adoption of them.

Consequently, AEROWORKS aims for: a) an increased take-up of marketable robotic technologies, b) rising awareness across the community about what robotics can accomplish, c) creation of a sustainable value chain between academia, robot developers, service providers and asset owners, d) positive economic impact on the competitiveness and growth of infrastructure service businesses in Europe, e) strengthened competitiveness of the European Robotics Industry, f) increased high-quality Job Creation without endangering job positions, and finally g) a significant contribution to the society-critical infrastructure sector.

Short-term AEROWORKS Economic Impact and Focused Infrastructure Areas

In short-term, AEROWORKS focuses on demonstrating the capabilities of the team of collaborative aerial robotic workers, and on equipping AIR and SKL with a team of such robots. These two partners of AEROWORKS will lead the way of the utilization of such aerial robotic infrastructure service solutions while an "*early adopters*" program will also be initialized for those enterprises that are directly interested to adopt a subset of the AEROWORKS technologies. Consequently, **a revolutionary robotic tool will be available to a significant set of infrastructure service providers and asset owners, therefore paving the way for the widest possible use of such solutions**. Regarding the infrastructure fields, those of wind farm, power network and power plants inspection and maintenance will be prioritized.

Mid-term AEROWORKS Economic Impact and Focused Infrastructure Areas

Our mid-term focus is **to attract increasingly more asset owners and infrastructure service providers** and extend the application of aerial robotic solutions that rely on the AEROWORKS contributions, into a wide set of infrastructure inspection and maintenance operations. This will be accomplished by extending collaborations of the AEROWORKS consortium as a whole or individually, through the follow-up developments of ASC, SBX and AIR as well as through the adoption of the AEROWORKS algorithms and design concepts by the scientific and robotic technologies community. Towards this direction, the extensive dissemination and exploitation plan of the project will set the basis for success. Furthermore, the additional channels of the Advisory Board Members (see Section 3), from both the academic sector as well as those that represent asset owners/managers and service providers, are going to be used. Figure 2.7 illustrates expectation on the adoption of aerial robotic infrastructure services solutions based on the AEROWORKS contributions.

AEROWORKS Economic Impact on the European Service Robotics Sector

Overall, AEROWORKS aims to create **a significant positive impact on the competitiveness and growth of the European robotics industry, especially in the particular field of service robotics**. The AEROWORKS robotic team has the potential to become an integral part of infrastructure service businesses, while all the relevant technologies have –each one alone or through their combination– the potential to provide leading solutions in a wide set of fields and applications. Each one of the encompassed fields of: manipulator design, control, sensorial systems and perception, path-planning, autonomous inspection as well as multi-agent cooperation, and eventually the AEROWORKS platforms and team, can find their way towards successful commercialization.

Based on the fact that new systems and methodologies will be developed, as well as the fact that challenging demonstration and benchmarking will be held, AEROWORKS will have a significant impact in the European robot-manufacturing and services industry. ***This is especially important accounting for the rapidly increasing character of the service robotics market.*** Service robots are sold in large quantities, while a substantial part is related with civilian applications. Our goal is to exploit all the technologies to be developed within the project, and ensure that **the project partners ASC, AIR, SBX, as well as further European enterprises provide leading products in this promising market**. Towards this direction all possible exploitation channels, and especially collaborations through the Advisory Board, will be utilized.

AEROWORKS benefits Job Creation and high-tech employment in Europe

AEROWORKS aims to contribute in achieving increased job creation in Europe along with an overall improved level of high-tech employment. This is achieved via three different methods:

- By advancing the job of infrastructure inspection and maintenance, providing personnel with advanced –yet intuitive to operate– robotic tools. AEROWORKS does not put job positions at risk, as instead of aiming to replace personnel with robots, it provides them with advanced robotic tools to utilize.
- By developing new products and technologies that will lead to an increased share of the robotics market by European companies, a fact that consequently leads to more highly-skilled job positions.
- By distributing the knowledge and the developments within a large subset of the European countries and fostering collaborations among them.

Overall, the AEROWORKS consortium puts a strong focus on sustainable development for the society.

2.1.6 The AEROWORKS consortium and its value chain

The AEROWORKS consortium and project plan is focusing on ensuring its effectiveness in terms of scientific excellence and market uptake. This is vital in achieving the goals stated by the European Commission, regarding the strengthening of European competitiveness within the global market. The

AEROWORKS project essentially corresponds to a strategic development effort, as the consortium contains academic institutes, system integrators, service providers, as well as asset owners, and aims to enable and directly or indirectly lead to market solutions within 5 to 10 years from its starting point.

> *Upon successful completion of the project, it is expected that key-players in the fields of infrastructure development, inspection and maintenance will be interested in the capabilities of the platforms, especially due to their robust and safe operation, advanced and game-changing ways they introduce for inspection and repair, and extremely low-cost as compared to the current state-of-the-art in the field. This, together with the participation of ASC and SBX within the consortium, as robotic solutions development SMEs, AIR as an infrastructure services provider, and SKL as an asset owner, the challenging demonstration process and the extensive dissemination, we aim to contribute in increasing Europe's market share in aerial robotics and boost the infrastructure services sector.*

The AEROWORKS consortium contains all the key elements and connections to lead to research and innovation actions of excellence that will strengthen the leading role of Europe in the field of service robotics, and ensure market-successful solutions that will make the aerial robotic workers an integral part of the infrastructure inspection and maintenance businesses. Figure 2.8 illustrates the complete value chain that is formed within the project consortium. Within this framework, the academic partners put their efforts to propose novel solutions and new knowledge, to be integrated in collaboration with ASC and SBX, and produce robotic technology solutions to be used by AIR and SKL. Accordingly, AIR and SKL provide knowledge and experience input to the academics, ASC, and SBX, while AIR serves as a channel to translate the more high-level requirements of SKL, as requirements of the collaborative aerial robotic workers team.

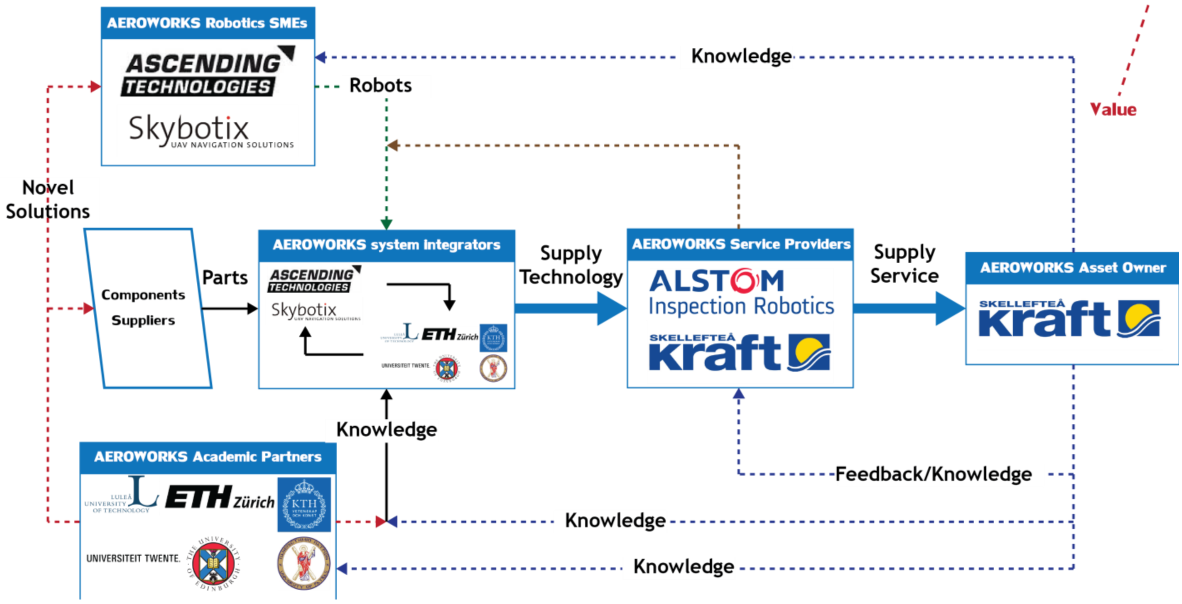


Figure 2.8: The value chain of the AEROWORKS consortium

All the AEROWORKS members contribute with their expertise, while several partners already had the opportunity to deploy their solutions in real applications, therefore increasing the consortium readiness.

2.1.7 "Anytime" operation and Flight Regulations

As the regulatory framework for unmanned aerial systems is in the long process of being fully established in Europe and worldwide, the consortium will focus on ensuring that an easy regulation procedure will be required for the ARWs team. This will be achieved by a) promoting the safe, reliable, robust properties of the systems and b) by going through all the regulation procedures within the project framework. With successful Permissions To Fly (PTF) being held by the AEROWORKS partners for at least two European countries (e.g. Sweden and Switzerland), the legal precedent for flight allowances will be established.

2.1.8 AEROWORKS beyond AEROWORKS

In summation, the AEROWORKS consortium and project plan have already put significant effort to identify the appropriate methods that can boost infrastructure inspection and maintenance missions, ensure the safety of the personnel, and provide new, advanced, and accurately repeatable methods and tools. Specific goals have been set, and the prerequisite experience and background are available. Directions have been set, while the consortium already has accumulated experience in all the fundamental scientific, technological as well as financial challenges.

However, AEROWORKS aims to pave the way for even further. Observing all the recent trends, the distributed character of infrastructure facilities, the requirements for long-term sustainability, as well as the need for advanced monitoring techniques, the members of the AEROWORKS consortium would like to investigate the concept of "***smart infrastructures***". In such a conceptual scenario, infrastructure facilities would have robotic teams – *like that of AEROWORKS or further extended* – as an integral embedded part. Through a distributed network of sensors and robots, fixed inspecting systems and mobile inspection & maintenance agents would regularly assess the quality of the facilities and conduct repair tasks. Such smart facilities will be characterized by a new class of maintenance quality and efficiency, with advanced predictive and prognostic cycles as well as reactive functions for the unpredicted events that may appear. Furthermore, the on-site permanent presence of robotic agents with excellent perception capabilities can provide further benefits: With asset-theft/liquidation crime rising (e.g. reported wind-farm vandalisms due to soaring copper cable prices, causing severe downtimes and up to 20,000 lt. of oil-spills), an additional potential for their utilization during idle inspection/maintenance periods as surveillance agents is exposed. In total, the establishment of such "smart infrastructures" will increase the reliability and predictability (organized pre-scheduled downtimes for inspection/maintenance) of the infrastructure network, allowing for its maximally efficient exploitation based on advanced schemes (e.g. energy markets that incorporate dependable power-generation models). By building upon the results of AEROWORKS, maintaining the collaboration of the consortium, utilizing the additional channels of the Advisory Board members and all the networking and dissemination activities that will take place, we aim to bring this ultimate scenario to life for the benefit of the European and worldwide societies, the strength of European industry and academia.

2.2 Measures to maximise impact

2.2.1 Dissemination and exploitation of results

The ***AEROWORKS consortium and project plan*** is designed in a way that simultaneously ensures the widest possible scientific and technological impact of the project, along with creating opportunities for market success at the European as well as on an international scale.

Within AEROWORKS, a special effort will be made to disseminate as much as possible the obtained and developed knowledge, the designed and demonstrated robotic systems. The project consortium has identified four groups of target audiences that will significantly benefit from the dissemination activities:

- Target Customers such as **infrastructure asset owners and service providers**
- **Robotics SMEs** in Europe towards further commercialization of the AEROWORKS technologies, as well as key subsystems and components
- **Technical and Scientific communities** at the European and International level with a special focus on strengthening synergies with other EU projects
- **Standard bodies and organizations** that are in charge of defining the robotic technology standards
- **General public** towards attracting its interest in the emerging robotic technologies, as well as raising awareness about: a) what robots can do and how they can help us, b) the positive role of Horizon2020.

A major objective of AEROWORKS is to facilitate Europe-wide benefits from the project outputs and results. The dissemination plan outlined in WP8 will ensure the demonstration and R&D&I outputs along with the publications, code releases and the project deliverables. Within this framework, all possible methods and channels including ***a)*** **scientific conferences, journal publications, technical symposia, industrial exhibitions**, ***b)*** **the internet in all its trending forms**, ***c)*** **summer schools and other educational activities** *(focusing on the infrastructure services personnel)*, as well as ***d)*** **public events, demonstrations and talks**, will be employed. Especially regarding the scientific and peer-reviewed publications, the project partners will focus on high-calibre publications, while it will also support the open-access publication framework. Furthermore**, open-source code releases** and **public sensor/robots datasets** will be yet another method for the consortium to disseminate its results, and pave the way for further collaborations. The AEROWORKS consortium will make use of all its channels and the project advisory board to reach further interested asset owners or service providers, as well as to create further and sustainable research collaborations.

Technology exploitation is among the fundamental targets of AEROWORKS. By stimulating the knowledge exchange and efforts, collaboration between stakeholders facing technical challenges (infrastructure asset owners and service providers) and stakeholders that can provide solutions (SMEs and research institutes), a powerful innovation engine for creating and demonstrating new robust, efficient, safe and cost-effective methods in the area of infrastructure inspection and maintenance will be started.

The AEROWORKS **Technology Exploitation Strategy** (TES) will be developed within WP8. Within this framework, the main exploitation goals of the consortium are:

- The *asset owners and service providers* (SKL, AIR) will benefit from the new automated aerial robotic infrastructure inspection and maintenance solutions, and will have a direct gain for their own businesses.
- New market opportunities and job openings will be created, as the *robotic SMEs-Technology Suppliers* will come with new products and systems that have a great potential in large markets, namely those of infrastructure services as well as robotic technologies.
- New knowledge will be developed, broader visibility and raised awareness of the general public will be achieved, and sustainable collaborations and synergies will be established among the project partners.

The planned activities will also generate access to further and new markets, new channels and new business applications related with inspection and aerial robotic manipulation. Furthermore, the commercialization of the AEROWORKS robotic team, as well as of the individual technologies will create advanced opportunities and collaborations between European enterprises, as well as international partners. In total, the project is expected to increase Europe's market share in domestic service robots (contributing to the overall EU Commission goals) and improve the position of European companies within the overall robotics market.

Furthermore, the project activities and results will be continuously evaluated from a business perspective using the "business models generation canvas", a methodology specially designed in order to identify new business opportunities and associated business models. The AEROWORKS approach for **mutual benefit from collaboration and innovation impact** is visualized in Figure 2.9.

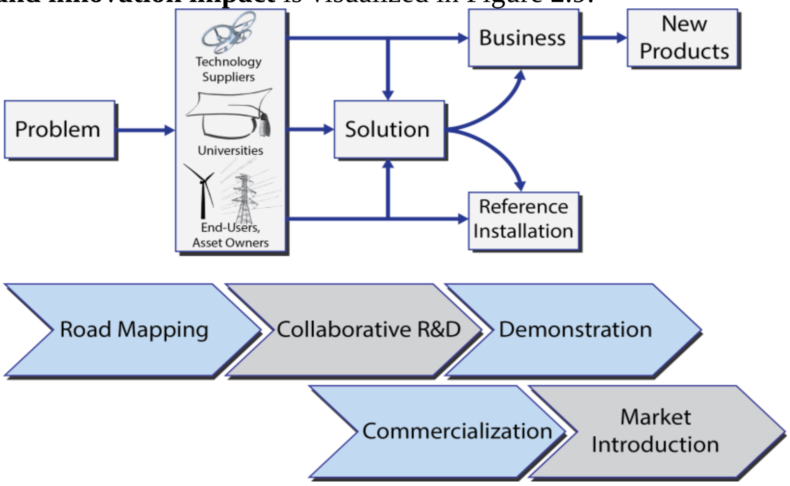


Figure 2.9: Technology Exploitation Strategy

The TES will be synchronized with the ***AEROWORKS Consortium's Business Plan*** and aims to provide recommendations in order to give the AERWORKS technological platform a strategic advantage and improve its market entry potential. *The intended structure of the business plan is outlined below:*

1. Executive Summary	2. Organizational Plan
1.1 Consortium Overview 1.2 Market Opportunity / Objectives 1.3 Relation to Work Programme 1.4 Capital Requirements, Breakdown of Uses of Funds 1.5 Vision and Mission Statements 1.6 Management board (profiles of participants) 1.7 Financial Projections (for the next 3 years)	***2.1 Summary Description of the Consortium*** 2.1.1 Mission (short- and long-term goals) 2.1.2 Business model 2.1.3 Market Strategy 2.1.4 SWOT Analysis ***2.2 Products and Services*** 2.2.1 R&D process description 2.2.2 Product/services description 2.2.3 Manufacturing process description ***2.3 Administrative Plan*** 2.3.1.IPR Management - Copyrights, trademarks, patents 2.3.2 Location - Available facilities
3. Marketing Plan	
3.1 Market Analysis 3.1.1 Target Market 3.1.2 Competition 3.1.3 Market Trends 3.1.4 Market Research	

3.2 Marketing Strategy 3.2.1 General Description 3.2.2 Methods for Sales and Distribution 3.2.3 Pricing 3.2.4 Branding 3.2.5 Database Marketing (personalization) 3.2.6 Sales Strategies 3.2.7 Promotion 3.2.8 Advertising Strategies 3.2.9 Public relation 3.2.10 Networking ***3.3 Implementation of Marketing Strategy*** **4. Financial Plan** 4.1 Summary of Financial Needs 4.2 Fund Dispersal Statement 4.3 Cash Flow Statement 4.4 Three-Year Budget Projection 4.5 Projected Balance Sheet 4.6 Financial Statement Analysis 4.6.1 Liquidity Analysis 4.6.2 Profitability Analysis 4.6.3 Measures of Investment	- Costs associated with the facilities - Supporting documents 2.3.3 Legal Structure - Description of the legal structure and its advantages 2.3.4 Management Structure - Corporate officers - Responsibilities of the consortium management body 2.3.5 Personnel - Number of dedicated personnel per consortium partner - Qualifications of required personnel - Breakdown analysis of man months with corresponding rates per consortium partner - Future needs for adding employees 2.3.6 Accounting & Legal 2.3.7 Insurance

2.2.2 Management of Knowledge and Intellectual Property

The knowledge management approach of AEROWORKS will ensure that the project findings will be protected and covered in a separate Consortium Agreement (CA). For this purpose, the Intellectual Property Office (IPO) will be established within the Management Support Team. The main task of the Intellectual Property Rights (IPR) manager will be the regular update of the Consortium Agreement, as well as consulting with the partners on any issues related to the protection of their know-how. More specifically, the IPO will deal with:

- Access to the background knowledge
- Joint ownership and use of foreground knowledge
- The transfer of foreground knowledge
- Detailed rules for dissemination-related activities and measures
- Various access rights

2.2.3 Communication Activities

Communication activities include both internal and external communication channels to promote the project and its results to the public, the scientific community, the European industry and potential business users. The overall objective is to ensure that value is created within the targeted audiences, and that EC funding leads to further advancements in society and industry. Hence, keeping the European infrastructure services business and robotics industry at the leading edge within the global marketplace is an essential goal. In summation, the communication plan for the project will be constituted of the following activities:

- Internal communication within the consortium and the Advisory Board
- External communication towards the scientific community
- Communication towards the European and International society
- Technical dissemination towards the Infrastructure Asset Owners and Service Providers
- Educational activities towards raising the awareness of infrastructure services personnel on how robotic solutions can help them in their work.
- Technical dissemination towards the Robotics Industry at the European and International level
- Demonstration events where a set of potential end-users and other interested collaborators will be invited and round-table discussions will be held.
- Other dissemination activities which aim to provide background education and awareness to society.

The Project Coordinator and the Management Support Team will be responsible for coordination and implementation of the communication plan described in detail within WP8.

3. Implementation

3.1 Work plan — Work packages, deliverables and milestones

3.1.1 Overall Strategy

The overall work plan is divided into 8 Work Packages (WPs); 1 is dedicated to the project management-related necessities (WP1), 5 to research and development activities (WP2-WP6), 1 to integration, demonstration and evaluation activities (WP7) and 1 is dedicated to dissemination purposes (WP8).

For each WP, and for each WP Task, one consortium partner is assigned as a leader. The relation between a WP and a Task leader is a hierarchical one. The leader role signifies the final responsibility for the successful execution of the required tasks, achieving the milestones while abiding by the global time-schedule, and the timely provision of the respective results, in terms of project reports and WP deliverables. The milestones set within the timeline of the Work Packages mark the completion of critical project-progress phases, and as such represent progress control points.

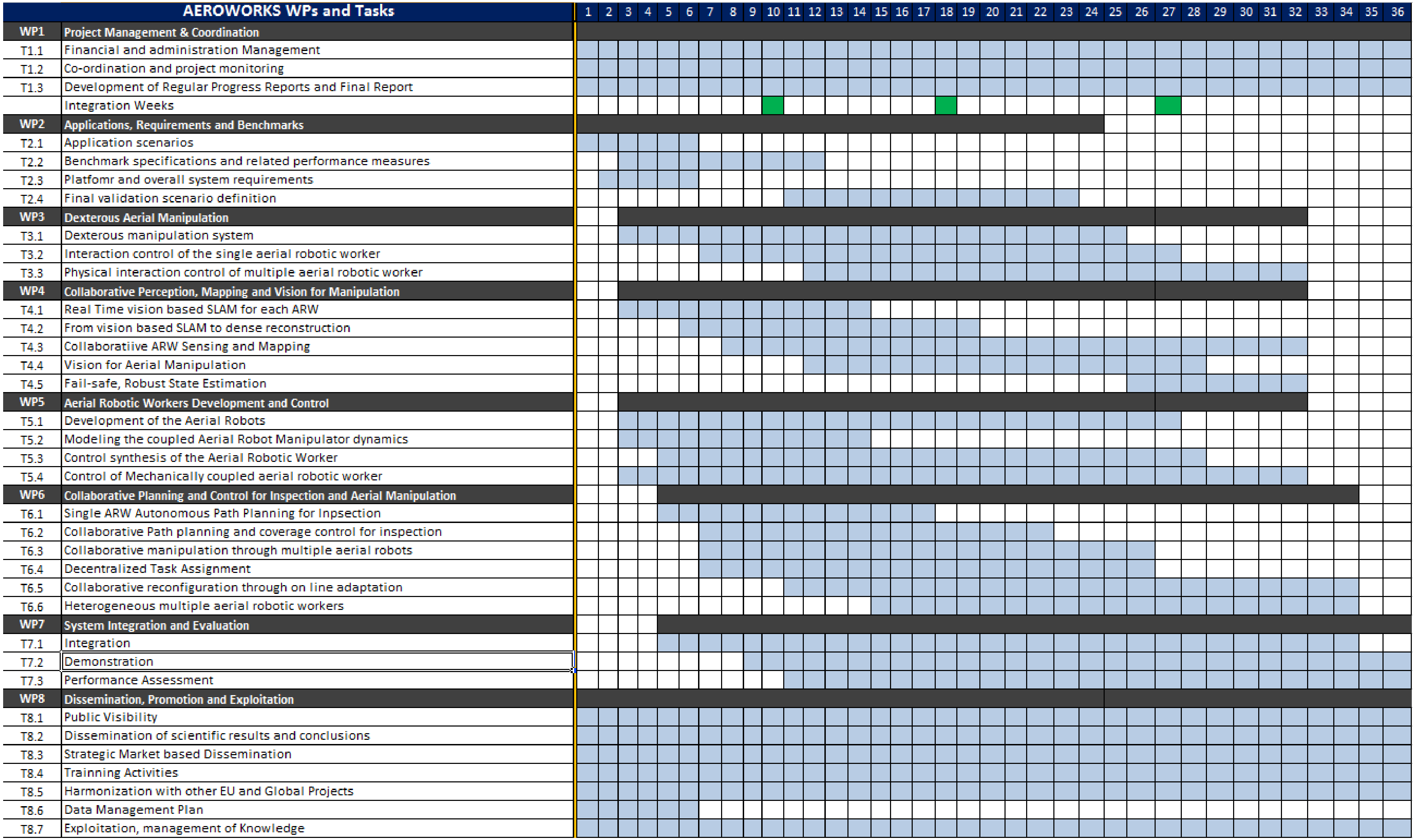
From the research and development Work Packages, WP2 serves a central role, namely to establish the common ground upon which the sum of the project's specifications and consequent activities will be based. This will be achieved via the full-scale inter-partner involvement, such that the end result is the product of the mutual exchange of application and research-critical information, and the achieved consensus reflects a clear picture of all necessary project-related specifications in their detail.

The core research package consists of WP3-WP6, which are focused in the development of each of the AEROWORKS subsystems, according to the common specification-basis set by WP2, but in a self-contained approach, each fulfilling their own unique research directives and requirements. These are appropriately organised, so that each one contains the relatively independent scientific and technological advances and subsystems, which following proper integration will allow for the realization and assessment of the final AEROWORKS system. An important feature of these WPs is the proper incorporation of directives set by WP2, so that the developed hardware/software implementations allow for less future integration effort.

The AEROWORKS platform will be derived from the integration of the aforementioned subsystem primitives, a task handled in WP7 which also involves inter-partner collaboration and contribution. The complete system demonstration and consequent assessment are also activities incorporated in the same Work Package. The especially challenging goal of full system integration will be greatly aided by the directive for common-interface software subsystems and predetermined hardware requirements, as per the consensus in WP2 and the related requirement in WP3-WP6. This is especially the case regarding the aerial robotic platforms, the AEROWORKS Sensing and Processing Unit, Communications hardware and protocols, and more. However, special events, namely "integration weeks" will be organised along the timeline of the project, to keep track and aid in the proper execution of this goal. During the integration weeks, those subsystems –either hardware and/or software– completed at each phase will undergo a partial integration procedure, where the respective WP leaders will be able to identify and resolve issues that arise in actual testing scenarios, also profiting from the live cooperation opportunities presented. The interfacing of the components and the WP teams will serve collaborative debugging and performance assessment purposes for the integrated subsystems' functions. Each integration week will be held in the institution of one partner, a choice determined by: a) operational necessities, such as non-movable equipment indispensable to the testing procedure, and b) the specialization of that partner with respect to the projected assessment trials.

The overall management and oversight functions of AEROWORKS are contained within WP1, with a single leader assigned to it and its respective Tasks. The setup of governance bodies and the functions of project internal communication, quality assurance, and economic management are responsibilities located in the context of this Work Package.

3.1.2 *Project Planning - GANTT Chart*



3.1.3 Detailed Work Description

Table 3.1a: Work package description

Work package number	**1**	**Start date or starting event:**		**M1-M36**						
Work package title	***Project Management & Coordination***									
Activity type[4]	MGT									
Participant number	1	2	3	4	5	6	7	8	9	10
Participant short name	LTU	ETHZ	KTH	UT	UEDIN	UPAT	ASC	SBX	AIR	SKL
Person-months per participant	30	0	0	0	0	0	0	0	0	0

Objectives

This work package will cover the overall legal, contractual, financial and administrative management of the project, while establishing a reliable contact with the EC throughout the Project duration. The overall co-ordination and control of the international collaborative work will be done by LTU as the coordinating partner, together with the Management Board. Moreover, this work package will ensure that the work is carried out in a timely and cost-effective manner and will supervise the preparation and the overall quality of the produced deliverables.

Description of work

Task 1.1 - Financial and administration management (LTU)

The main objective of this task is the overall project management concerning financial and administrative aspects, and the effective communication with the EC (e.g. cost statements collection and submission to the EC, establish contact with the Commission Financial Office, advanced payments coordination, final check of deliverables).

Task 1.2 - Co-ordination and project monitoring (LTU)

This task covers the overall project management concerning the coordination of the AEROWORKS consortium in collaboration with the WP leaders in order to cope with the problems of specifying, integrating, developing and evaluating the concepts, methodologies and technologies within AEROWORKS. These activities include not only communication within the consortium, but also with other related, existing or emerging projects and initiatives as well as international standardization activities.

Task 1.3 - Development of regular Progress Reports and Final Report (LTU)

This task is meant to develop the AEROWORKS Progress Reports (D1.1), which represents the assessment of the project results concerning the acquired concepts and methodologies and software development status. The produced report will be revised and will be considered as an on-going document with 6 months releases throughout the project duration.

The mid-term Progress Report (scheduled for the 18th month) mainly focuses on the evaluation of the project progress during its first part, and includes a detailed outlook for the second part of the project's duration.

The AEROWORKS Final Report (D1.2) will focus on representing the final results of the project and the evaluation of the results compared to its initially defined objectives and goals.

[4] Please indicate one activity (main or only activity) per work package:
RTD = Research and technological development; DEM = Demonstration; MGT = Management of the consortium.

Role of Partners: LTU will lead this WP as the coordinator of the AEROWORKS proposal.

Deliverables	
D1.1: AEROWORKS Progress Report releases (LTU)	M6,M12,M18,M24,M30,M36
This deliverable will be an ongoing document that embodies the evaluation and estimation of the project results concerning the developed concepts, methodologies and development status. The planned releases are:	
▪ D1.1a: First Progress Report ▪ D1.1b: End of Year 1 Progress Report ▪ D1.1c: Mid-term Progress Report ▪ D1.1d: End of Year 2 Progress Report ▪ D1.1e: Mid-term Progress Report ▪ D1.1f: End of Year 3 Progress Report	M6 M12 M18 M24 M30 M36
D1.2: AEROWORKS Final Report (LTU)	M36
This deliverable will present all the achievements of the project, the main contributions and the overall financial reporting, while it will also summarize the results and the impact of all AEROWORKS WPs.	

Work package number	**2**	**Start date or starting event:**	**M1-M24**							
Work package title	***Applications, Requirements and Benchmarks***									
Activity type[5]	RTD									
Participant number	1	2	3	4	5	6	7	8	9	10
Participant short name	LTU	ETHZ	KTH	UT	UEDIN	UPAT	ASC	SBX	AIR	SKL
Person-months per participant	6	5	3	3	4	3	6	6	10	11

Description of work

Task 2.1 - Application scenarios (**SKL,** AIR, All partners involved)

This task will be focused on achieving the utmost exploitation of the end-users participation within the AEROWORKS consortium, which incorporates the large-scale asset owner SKL, and service robotics company AIR. The initiating point will be the thorough analysis of reports and regulations on the state-of-the-art methodology currently applied in the fields of infrastructure inspection, repair and maintenance, with respect to their various application sectors. In one part, this will enable us to gain conclusive insight on the potential applications where the AEROWORKS team can have its maximum impact in the long run, but also to assess the most feasible realistic scenarios where it can be deployed within –or right after– the Project's lifetime. The second objective of this process is to identify the crucial parameters to such procedures, and derive their correspondences to the required specifications for our systems. This refers to: a) system mechatronic design aspects, b) system capability levels, such as perception fidelity and manipulation strength/precision, and c) specialized collaboration capabilities. The respective information will be acquired via technical questionnaires distributed to the partners, and teleconference meetings will be organized to allow for interactive discussion between the partners. The identified value chain presented in Section 2.1.6 will provide the guideline for structured information flow within these processes. Our application experts of the field will set the ground for investigation of the desired target sectors and respective specifications, and our robotics experts will correlate that information-basis with the so far mature developments and know-how, while our academic experts will be consulted where novel R&D challenges are identified, in order to determine the capacity to answer these through their expertise. The consortium management team will constitute a detailed common-basis for the required synergies among the partners, and indicate how, when, and within what timeframe each specific objective will be handled.

Based on the decomposition of the various application scenarios to our interest, a sketch of modular elementary behaviours, perception abilities, aerial manipulation primitives, co-manipulation requirements and multi-robot collaboration goals will be formulated.

Further direct insight into the challenging nature of various infrastructure inspection and maintenance activities will be pursued. To this purpose, visits to sites undergoing such processes will be organised, in order to: a) observe the current methodologies applied in inspection and repair operations, and b) conduct organized discussions with technical experts of the staff who may possess "secrets-of-the-trade". The results of this process will enhance our readiness-to-deal with real scenarios and their documentation will be an additional asset during the Project's dissemination activities (respecting any Confidentiality issues).

Task 2.2 - Benchmark specifications and related performance measures (**AIR,**SKL, All partners)

The requirements from *Task 2.1* will be correlated with the abstract target capabilities to determine the corresponding performance measures for each distinct system functionality level. A progressive strategy will be followed in order to evaluate the capabilities of each of the AEROWORKS subcomponents, ending with the final benchmark of the project as the most complete and most integrated benchmark.

- *Specifications for "Flying-qualities and fail-safe" requirements:* this benchmark will specify metrics on the flight response as well as required fail-safe options and properties. The desired flying qualities will have to hold in all cases, including the phases during which the manipulators of the ARWs have grasped objects not aligned with the center of mass of the system. Additionally, the ARWs should exhibit excellent robustness during unforeseen collisions of their bodies or of any manipulated/carried objects.

- *Specifications for "Single & collaborative perception capabilities":* here benchmarks regarding the environment reconstruction fidelity using one aerial robot will be specified, followed by test-beds in order to validate the efficiency of the collaborative perception algorithms in local and global level.
- *Specifications for "Aerial manipulation capabilities":* here, the required manipulator workspace as well as the desired maximum applicable forces in order to allow efficient work-task execution will be derived. Accordingly measures on flight robustness will be specified accompanied with metrics of the control performance against the forces and moments exerted during active physical interaction.
- *Specifications for "Aerial co-manipulation capabilities":* as AEROWORKS focuses on co-manipulation and aims to understand and address the problem of mutual physical interaction between multiple ARWs, benchmarks regarding the capabilities of the coupled system of at least two aerial robotic workers that co-manipulate the same object will be specified. These benchmarks will aim to evaluate the performance of the systems in terms of detecting the aiding or hindering role of the forces and moments applied from the other co-manipulating parties as well as the manipulator and flight control strategies efficiency.
- *Specifications for "Multi-robot collaboration capabilities":* within this subtask, benchmarks regarding the capabilities of multiple ARWs to coordinate their paths autonomously and collaborate towards inspection and repair operations will be specified. The degree of autonomy and mission execution efficiency compared to offline computed solutions will be the main concern of these benchmarks.
- *Specifications for "Final AEROWORKS benchmark":* the final benchmark of AEROWORKS will aim to evaluate the potential of the team of collaborative ARWs in terms of autonomous work-task execution towards the successful accomplishment of the application scenarios envisaged in Task 2.1. This will be the most integrated benchmark and will also be related with the project's final demonstration scenario.

Task 2.3 - Platform and overall system requirements (**ASC,** SBX, All partners involved)

The detailed specifications for the aerial robots, their sensory systems, their autonomous perception, mapping & navigation capabilities, their flying qualities, the manipulator workspace and maximum applicable forces, as well as specifications regarding the communication capabilities and the collaboration autonomy of the team of the aerial robotic workers will be the outcome of this task. Additional concern will be dedicated to the incorporation of requirements identified within Task 2.1, for intuitive ground-station interfaces available to technical experts, which will enable the human operator-guided semi-autonomous operation. All partners will be strongly involved with the definitions of their concern.

Task 2.4- Final validation scenario definition (**SKL,** All partners involved)

In this Task the specification of operational requirements for the final AEROWORKS benchmark will be established. Being the final benchmark, emphasis will be given to set up a realistic scenario that combines all the developed "primitives" validated in the previous benchmarks. The final benchmark will attempt to closely emulate a challenging realistic application, where the aerial robotic team will have to perform reliably, but also verify its advantages compared to human-based operations. A focus is thus given on the collaboration of multiple ARWs for both inspection and maintenance. The AEROWORKS team will be tested in relation with its capabilities to operate autonomously, perceive the environment, inspect the infrastructure and perform specific work-tasks on it that require manipulation and collaborative action.

Role of Partners:

SKL leads this work package due to its great experience on infrastructure assets needs for inspection and maintenance. AIR further contributes from a service robotics perspective while all partners contribute to the goals of the tasks of this work package.

Deliverables	
D2.1: Benchmark specifications and related performance measures (SKL)	M6
D2.2: Platform and overall operation specifications (ASC)	M6
D2.3: Report on application scenarios, end-user requirements, and regulations (AIR)	M8
D2.4: Final validation scenario definition (AIR)	M12

Work package number	**3**	**Start date or starting event:**		**M3-M32**						
Work package title	***Dexterous Aerial Manipulator***									
Activity type[6]	RTD									
Participant number	1	2	3	4	5	6	7	8	9	10
Participant short name	LTU	ETHZ	KTH	UT	UEDIN	UPAT	ASC	SBX	AIR	SKL
Person-months per participant	4	4	0	27	0	8	6	4	0	0

Objectives

This WP focuses on the mechatronic design and implementation of the ARW-maintainer. The development of such a platform is required to effectively develop a team of aerial robotic workers that are capable to perform physical interaction with the environment and with each other during a maintenance and repair task. Therefore the ARW-maintainer will be equipped with dexterous manipulators that will enable its manipulation abilities. The manipulators that will be developed will only minimally influence the stability of the aerial platform, both in free-flight and in interaction with the environment and other ARWs. Moreover they will make use of compliant mechanisms that modify the effector's physical properties. As a consequence, the ARW-maintainer will be characterized by high levels of mechanical configurability and adaptability. It will be able to perform safe physical interaction with the environment and with other ARWs by dealing with the risk of undesired collisions. Smart primitive behaviours that use the onboard sensors will be developed, in order to modify the physical interaction properties of the ARW. As a result, the ARW-maintainer will be characterized by a high level of dependability that will ensure the mechanical adaptation necessary to work in uncertain and dynamic real environments.

Within this WP the following objectives will be achieved:

- Design of manipulation systems that allow mechanical adaptation and safe interaction with the environment and other ARWs for collaborative maintenance and repair.
- Increased sensing capabilities for interaction control: the manipulator should be equipped with sensors to measure and predict the risk of undesired collisions. The result of the prediction and the risk measurement are necessary quantities to define the desired mechanical properties of the ARW manipulator performing the interaction.
- Intelligent grasping through adaptable mechanics and sensors: the use of adaptable mechanics and increased perception capabilities are motivated also by the task requirements. Since the type of tools the manipulator should handle can be various and not necessarily known a priori, the manipulation system should be capable to embed proper proprioceptive sensing capabilities and adaptable mechanics to perform autonomous grasping and manipulation.
- Disturbance prediction and reaction: the manipulator during its motion introduces dynamical effects on the floating base aerial vehicle, which increase the difficulties of autonomous object tracking. Methodologies to predict the effect of the disturbances and online adaptation of the motion primitives will be investigated, aimed at achieving performing aerial grasping.

Description of work

Task 3.1: Dexterous manipulation system design (**UT,**LTU,ETHZ,UPAT,SBX,ASC)

This task focuses on the mechanical design of the manipulation system of the ARW-maintainer. The main subtasks towards developing the AEROWORKS Aerial Dexterous Manipulator are:

- **Requirements analysis, specification and design:** task requirements and specifications from the aerial platform will be considered to define the design constraints of the manipulation system. Depending on the tasks both the single and collaborative aerial robotic worker is required to perform, a preliminary

6 Please indicate one activity (main or only activity) per work package:
RTD = Research and technological development; DEM = Demonstration; MGT = Management of the consortium.

definition of the morphology, structural requirements, placement, number of manipulators and payload will be derived. Compliant mechanisms to favour the adaptability to external uncertainties will be considered for possible implementation.

- **Hardware development and construction:** given the design of the dexterous manipulation system, the mechanics and electronics will be constructed, assembled and tested.
- **Sensors choice and design:** sensors and systems will be chosen or be custom designed and integrated to allow the manipulator to have a proper knowledge of the surrounding environment, get a representation of the state of the vehicle, and to have a map of the external disturbances introduced by tools handling and collaborative interaction.

Task 3.2: Interaction control of the single aerial robotic worker (**UT**,LTU,ETHZ,UPAT,ASC,SBX)
This task focuses on the definition of the control algorithms that will be exploited by the single ARW-maintainer in order to safely perform active physical interaction with the environment. The task is aimed at:

- **Introducing limited disturbances to the vehicle's dynamics**, as a consequence of the dynamics of the manipulator itself while moving. The manipulation system should be capable of performing aerial grasping and tool handling with a reduced influence on the dynamics and stability of the vehicle itself. The dynamical properties of the manipulation system will be investigated to generate a set of primitives to perform aerial grasping with limited impact on the vehicle's dynamics.
- **Predicting the risk of interaction**, in order to adjust the mechanical properties of the manipulators to safely physically interact with the environment and overcome the risk of failure that may arise from undesired unpredicted impacts in uncertain realistic environments. Vision systems and onboard localization sensors will mostly be considered by the prediction algorithm, but other technologies will also be taken into account during the design phase.
- **Actively manipulating tools on the environment**, in order to accomplish realistic maintenance and repair tasks. Active manipulation of tools is a necessary step towards the effective development of the team of collaborative aerial workers. Vision based cognitive algorithms will be utilized as driving methodologies to classify, recognize and estimate the tools and objects pose with respect to the ARW. The cognitive algorithms will estimate the relative configuration of the object with respect to the ARW, in order to properly finalize the grasping of the tool. The use of vision-based fusion algorithms to feedback the relative position of the tool to grasp will also improve the positioning accuracy of the AWR with respect to the object to be grasped. Moreover, the use of vision-based algorithms and the use of compliant manipulators that can adapt their mechanical properties to minimize the effects of undesired collisions of the manipulator with the environment, will guarantee an high level of dependability of the developed product. The grasping task will be in fact handled by the definition of both feedback and model predictive control algorithms aimed at improving the performances of underactuated floating base systems that actively interact with passive environments by means of known tools.

Task 3.3: Physical interaction control of multiple aerial robotic worker (**UT**,LTU,ETHZ,UPAT,ASC,SBX)
This task is aimed at proposing relevant control algorithms for the control of the physical interaction of multiple ARWs. This task can be seen as the extension of task 3.2 and focuses on understanding and controlling the dynamics of the group of AEROWORKS aerial workers that performs active operations on a common object. The task is of extreme relevance for the development of the team of collaborative aerial robots and represents a necessary condition to the effective development and application of the theories and algorithms that are expected to come out from the other work packages.

Role of Partners:

The activities of this WP will be led by UT. UT will be responsible for the design, implementation and functionalities of the dexterous arm with advanced physical interaction capabilities. LTU, ETHZ, UPAT, ASC and SBX will assist in the control design and physical interaction operations of the manipulator.

Deliverables	
D3.1: Analysis and design of the Hardware for collaboration (UT)	M12
D3.2: Version 1.0 of dexterous manipulator and sensor fusion (UT)	M22
D3.3: Version 2.0 of the collaborative robot and cognitive control implementation (UT)	M34

Work package number	**4**	**Start date or starting event:**		**M3-M32**						
Work package title	***Collaborative Perception, Mapping and Vision for Manipulation***									
Activity type[7]	RTD									
Participant number	1	2	3	4	5	6	7	8	9	10
Participant short name	LTU	ETHZ	KTH	UT	UEDIN	UPAT	ASC	SBX	AIR	SKL
Person-months per participant	8	34	0	13	64	0	3	18	0	0

Objectives

This work package will develop the modules that form the backbone of autonomy of the team of Aerial Robotic Workers (ARWs) and all of them are required for the majority of the other tasks in the AEROWORKS project. The main objective is the development of the onboard perception of the ARWs in order to perceive their motion and map their workspace to the precision necessary to perform the complex inspection and manipulation tasks dictated by the AEROWORKS paradigm. Towards this goal, this WP will explore suitable algorithms and sensor setups to develop the framework for Simultaneous Localization And Mapping (SLAM) onboard each ARW to permit autonomous navigation for each agent, which is later going to be used as a basis to enable dense scene reconstruction for the imagery captured by each ARW. Given the autonomous operation of each ARW in perceiving and mapping their environment, the presence of multiple ARW will be exploited in order to allow for more efficient and effective scene perception and mapping by employing collaborative approaches to these problems. Finally, with a common map and a unified frame of reference for the poses of each robotic worker, the team of ARWs will cooperate autonomously to accomplish complex missions that require co-manipulation and coordinated navigation. These perception capabilities will further assess the problem of vision for aerial single- or multi-robot co-manipulation.

Description of work

Task4.1 - Real-Time vision-based SLAM for each ARW (**ETHZ**,UEDIN,SBX,LTU,KTH,UT)

This task will develop the capabilities of ego-motion estimation and map-building of the workspace for each aerial robotic worker, which as a whole form the basis of the perception necessary onboard each individual agent, member of the AEROWORKS robot team. For true autonomy, the SLAM framework developed shall only use the sensing and computational capabilities onboard each platform, avoiding any unrealistic assumptions on reliable communication links with a ground station.

While SLAM is by now a well-studied problem, we are yet to see successful systems enabling fully autonomous navigation for agile robots such as UAVs. In a bid to enable autonomous operation outside the controlled laboratory environment, here we aim to build on our previous work [22] to address the challenges on visual-inertial SLAM for truly autonomous operation.

Vision-based approaches for SLAM have a very successful track record and as a result, they are now well-established in the Robotics community. Moreover, given the low weight and power consumption of cameras (e.g. with respect to laser range finders), makes vision sensors a great candidate for the sensor suite onboard each aerial robot. Visual cues, however, are usually insufficient to provide the robustness necessary for the estimation processes, so fusing information from heterogeneous sensors can be very beneficial as these can provide complementary information. Typically, rough motion and lack of visual features for a short period of time, is addressed by fusing estimates from an IMU when employing visual SLAM on a mobile robot. The rich representation of a scene captured in an image, together with the accurate short-term estimates by gyroscopes and accelerometers present in a typical IMU have long been acknowledged to complement each other, with great uses in navigation [23] [22]. Moreover, with the availability of both types of sensors in most

[7] Please indicate one activity (main or only activity) per work package:
RTD = Research and technological development; DEM = Demonstration; MGT = Management of the consortium.

smartphones, there is great interest and research activity in effective solutions to visual-inertial SLAM.

Following the long experience and expertise of UEDIN, ETHZ, and all partners involved in this field, here we will explore the application of different sensor setups and fusion strategies in order to address the new challenges entailed in the mission of each ARW. Namely, as they are rotorcraft, their high agility and the disturbance caused by the movement of the manipulator onboard imply high dynamics, which currently, are often fatal in state of the art systems. Moreover, the mission of aerial manipulation requires depth information even in close proximity (also necessary for autonomous take-off and landing) and limited aerial robot motion.

With the aforementioned challenges in mind, in this task we will develop a real-time SLAM framework fusing sensory data for robust performance. The sensory inputs will mainly be visual and inertial, while additional sensors will also be considered in order to improve robustness (e.g. additional cameras). With the complexity of the system growing vastly with each extra sensor, this study will take into account sensor synchronization, inter-sensor calibration and intelligent management of all the additional data that becomes available.

Task 4.2 – From vision-based SLAM to dense reconstruction (**UEDIN**, SBX, LTU, ETHZ, UT)
With SLAM comprising the first step towards the spatial awareness of a robot, it is well understood that for a robot to interact with its environment, the traditionally sparse feature-based SLAM methods are not sufficient. In the AEROWORKS paradigm, there is an increased level of 'scene understanding' necessary to permit interaction of the manipulator carried on an ARW with the environment. To this end, we aim to study powerful dense reconstruction methods [34] from the Computer Vision literature, with the aim of realising them within the context of the time-critical and computation- and power-limited robotic setup in this project. Driven by the need for CPU implementations especially within Robotics, relevant works have been emerging, albeit their operation in real-time is still a challenge and a hot research topic.

Following the development of real-time vision-based SLAM for each ARW in T4.1, this task will address dense scene reconstruction, using the feature-based SLAM map as a basis. Unlike high-performing dense mapping alternatives, here the focus is on techniques that can realistically be applied on the envisioned scenario of a power- and computation-independent ARW. As a result, our study into denser mapping strategies will avoid power-hungry GPUs and rather aim for a methodology employable on CPUs. While the use of a more powerful ground station for post-processing of information will not be excluded, the aim here is to enable the acquisition of at least a first 'draft' of a dense map in real-time by each ARW.

Task 4.3 - Collaborative ARW Sensing and Mapping (**UEDIN,** ETHZ, LTU, KTH, UT, SBX)

This task aims at exploiting the presence of multiple agents (ARWs) in the AEROWORKS team, in order to create a unified representation of the environment in a more efficient and effective way. Given the ego-motion estimation of each aerial robot and the local map of its workspace developed in T4.1, the task here is to (a) recognize if a different ARW has been to the current place before (place recognition / loop-closure detection) and if this is the case, (b) stitch the relevant maps together, which will subsequently result to a common map, provided there is sufficient overlap in the trajectories of the robots. Emphasis will be put on the type of visual features used and the inherent representation of the world as a set of past observations (e.g. a graph of visual features/words). Finally, this task will explore possibilities of collaborative sensing of the environment from different ARWs, in order to aid the reduction of uncertainty within the estimation processes.

The longer the exploration sequence of each ARW, the more scenes will have to be checked against in case there is a loop-closure within the trajectory of each robot, but also with respect to the trajectories of the other robots. As a result, this task will explore efficient indexing strategies as well as suitable features to track in order to aid in place recognition. Typically, image features capturing a lot of information content provide great reliability in loop-closure detection, but are very computationally expensive. Attempts to use features on the cheaper end of the computational scale, suffer from false positive and negative detections, especially as the database of visited places increases. In order to achieve the reliability and efficiency required for this task, here we will employ a probabilistic framework in order to take any priors into account to resolve ambiguities that might arise during the search for matching scenes.

Once two local maps are identified as corresponding to the same real place, an optimisation strategy needs to be employed in order to correct for the accumulated error, such that the unified map is globally consistent.

Once an updated map is produced, the robots involved also need to be updated with corrected poses and local point clouds. With multiple robotic agents and frequent trajectory overlaps, this quickly becomes a cumbersome task. As a result, this task aims at minimising the exchange of information necessary amongst the robots and the ground station, while ensuring consistency of the maps and the poses of each robot.

In the case where two ARWs perceive and map the same scene simultaneously, they can take advantage of the presence of each other, by sensing their environment collaboratively in order to reduce uncertainties. For example, within the exploration phase of their workspace, the robots will typically fly at relatively high altitudes hence the perception of depth quickly becomes inaccurate: in monocular systems this is always the case necessitating the presence of sufficient parallax in camera frames before triangulation becomes accurate enough, while the perception of depth using stereo rigs is bound to the stereo baseline, essentially reducing the configuration to monocular at high altitudes. In such situations, scene-depth can be very hard to estimate from a single aerial robot. Our approach to deal with this problem will be to introduce the concept of the *"**collaborative virtual stereo rig**"* where the distance between the ARWs corresponds to the new stereo-baseline dimension of this virtual stereo rig. Adjusting this stereo-baseline not only we expect to perform better depth estimates, but also enable flights in formation. Moreover, the concept of the *collaborative virtual stereo rig* provides an additional degree of freedom to the multi-robot collaboration strategies (WP6) to actively control the stereo-baseline in order to match the requirements of a particular mission.

Task 4.4 - Vision for Aerial Manipulation (**UT**, SBX, LTU, ETHZ, UEDIN)

This task aims at utilizing the improved perception capabilities of the collaborative team of ARWs to influence and improve the manipulation and physical interaction capabilities of the aerial robotic workers, both as single and as cooperative robots manipulating objects. To achieve this task, the approach of *collaborative visual stereo rig* will be extended to improve the manipulation capabilities of the team of collaborative ARWs. Multiple ARWs can simultaneously detect a target and share their relative information in order to improve the estimate of the position and orientation of a target object in the environment. The visual information of multiple ARWs will therefore be fused to obtain common absolute information of the position of the target objects that are necessary requirements for the planning of the trajectories and the capability of the ARWs to manipulate an object. Moreover, the reduced uncertainties in the estimation of the object pose in the shared environment influences the control of the interaction of the single ARWs and increase the performances of the group of ARWs performing manipulation tasks. As proposed in Task 3.1, the manipulators will be constructed in a way that variable compliance will be implemented to perform safe interaction, by minimizing the effect of impacts with the end effectors. The way the equivalent end-effector stiffness is set depends on the uncertainties of the estimate of the object to interact with. The information about the uncertainty is dependent on the amount of ARWs collaborating in this estimate and will therefore influence the stiffness profile and the interaction performances of the single ARW operating in the environment. As a result, the use of collaborative object pose estimation will allow better control of the compliant behaviour of the single ARW, leading to improved interaction and manipulation skills.

Task 4.5 – Fail-safe Robust Estimation (**SBX**, UEDIN, ETHZ, LTU, ASC)

This task serves for purposes of robustification and robustness against estimation/sensor faults and failures. The framework will be extended to incorporate up to four monocular cameras, state estimation quality will be automatically assessed and failures will be detected and compensated. GPS carrier-phase measurements will also be integrated in the visual-inertial state estimation framework.

Role of Partners:

UEDIN with its extended experience in vision and sensor fusion excellence will lead this work package, in close collaboration with SBX and ETHZ which also leads Task 4.1. LTU and KTH will be involved in the task of combining the produced SLAM with the developed control algorithms for one and multiple agents, while UT will lead the task of vision for aerial manipulation.

Deliverables	
D4.1: Methodology & Results on real-time vision-based SLAM for each ARW (ETHZ)	M14
D4.2: Methodology & Results on real-time dense reconstruction from an ARW (UEDIN)	M26
D4.3: Methodology & Results on collaborative ARW Sensing and Mapping (UEDIN)	M32
D4.4: Report and publications list on vision-based perception for the team of collaborative aerial robotic workers as well as release of open-source software (UT)	M26

Work package number	5	Start date or starting event:	M3-M32							
Work package title	*Aerial Robotic Workers Development and Control*									
Activity type[8]	RTD									
Participant number	1	2	3	4	5	6	7	8	9	10
Participant short name	LTU	ETHZ	KTH	UT	UEDIN	UPAT	ASC	SBX	AIR	SKL
Person-months per participant	23	17	6	13	0	32	17	1	0	0

Objectives

The keypoint objective addressed within this work package is the development of highly dependable and configurable aerial robotic vehicles equipped with increased motion capabilities, which will act as excellent solutions for the complex requirements of a fully functional ARW. On each standalone aerial unit level, significant research challenges lie in the development of reliable and efficient model-based control strategies that innovatively exploit the combined potential of the aerial vehicle and the mechanically coupled manipulator, in order to maximize the effectiveness of the ARW in the execution of work-tasks that require high-range force/moment control and potential load-transfer functionality. On the ARW collaborative work-task execution level, in-depth investigation of the underlying dynamics in co-manipulation operations will yield novel dynamic motion capabilities, and expose the significant potential within the field of aerial robotic collaborative manipulation.

Description of work

Task 5.1 - Development of the Aerial Robots (**ASC**, LTU, ETHZ, UPAT, SBX)

The properly developed aerial vehicle system will provide the solid foundation in order to fully unfold the true potential of collaborative aerial work-task execution. The development process will incorporate the expert specifications of WP2, and import the best practices in system design-intensive industries to ensure assessable and certifiable functional dependability. Commercially-available component solutions with excellent performance will be preferred, in order to additionally increase the ARW's market impact. The consortium's established experience with multirotor platforms will guarantee the development of high-end reliable aerial systems with levels of failsafe dependability and increased motion capabilities, to act as the AEROWORKS baseline platform for early system testing and integration across the WPs. Additionally, significant research effort will be invested in identifying the advantages of work/task-tailored designs which innovatively exploit mechatronic reconfiguration in order to increase the ARW's safe manipulation envelope and exerted force/moment margins. These systems will be aimed for more demanding work-task execution.

The architecture of the ARW will consist of: a) the attitude/orientation sensors suite and attitude/trajectory tracking controller, b) the high-level controller, c) the communication systems, and will provide the necessary integration modules that adhere by the AEROWORKS architecture in order to accommodate: d) the Sensing and Processing Unit, e) the manipulator control and sensor feedback, and f) the intelligence-driven control synthesis. This architecture will maximize the configurability of the ARW (e.g. enabling the integration of multiple SPUs on an ARW for maximal sensing at start-up configuration).

Generalized interaction/manipulation tasks pose significant flight control challenges, due to: a) asymmetries and imbalances induced by the manipulator and its use in load carrying/load transfer operations, b) failed-to-predict impacts with the environment, and c) approaching environment surfaces and structures while airborne. Hence, in order to guarantee a dependable low-level control solution, the baseline attitude controller will be selected after employing established performance metrics to examine the effectiveness of excellent commercially available control structures, versus advanced custom controllers with the key benefits

[8] Please indicate one activity (main or only activity) per work package:
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of model-based prediction and robustness against uncertainty, which will also exploit estimates of the disturbing forces and moments introduced from the manipulator.

Task 5.2 - Modeling the coupled Aerial Robot-Manipulator dynamics (**UPAT**,LTU,ETHZ,UT,ASC)

This task deals with the modelling of the ARW system, placing particular emphasis on the coupled dynamics during generalized interaction/manipulation. The derived high-fidelity model will be the product of in-depth analysis and accurate modelling methodologies, accurately capturing: a) the rotor blade aerodynamics, b) the manipulator interaction effects and constraints, c) the collision dynamics, and d) the multi-body aerial vehicle-manipulator dynamics. Complementarily, a scalable simulating framework will be developed to accommodate the developed models, which will also comply with the AEROWORKS architecture in order to provide the capability for mixed Hardware and Software-in the loop simulations. The framework will act as a modular test-bench, to be used for isolated systems performance assessment within several operating key-scenarios, and for the initial simulated deployment of the task-driven multi-agent collaboration strategy.

The high-fidelity models and simulation framework will also enable the extraction of certain dominant characteristics of the ARW during challenging operational conditions, such as:

i) Take-off and landing, as well as approach/descent manoeuvres, where primary focus will be placed in capturing the influences of the ground-effect, the ground-resonance and the aerodynamic disturbances.

ii) Laden flight while performing manipulation, where the attitude stabilizing margin, the thrust margin, and the thrust dynamic range while under maximum-payload stress will be analysed.

iii) Object capturing phases, where special attention will be paid to the accurate capturing of the collision-induced dynamics, as well as the respective effects in various manipulator configurations.

The framework will have a significant role throughout the AEROWROKS lifespan, as it will provide reliable design and control guidelines for the ARW components. Several control strategy alternatives, (i.e. hybrid mode-switching or parameter adaptation schemes) addressing the aforementioned challenging operations will be seamlessly evaluated. Significant insight regarding the manipulator design parameters will be gained, by examining the coupled system motion range, the manipulator force/moment margins that ensure overall stability and attitude control decoupling, and the effects on compliant motion and manipulation efficiency.

Task 5.3 -Control synthesis of the Aerial Robotic Worker (**ETHZ**,LTU,UPAT,UT,KTH,ASC)

The ARW unit is envisioned as a highly dependable aerial solution alternative to the human working hand. Airborne physical interaction (deliberate or unplanned), generalized object grasping/manipulation, and complex work-task execution routines are significantly challenging, and require excellent control capabilities. The system’s control scheme has to compensate for the ARW unstable dynamics, the presence of external or internal disturbances (e.g. due to manipulator reconfiguration in free-flight), and the requirement for work-task execution away from the center-of-mass while potentially remaining at hovering operation (non-rigidly docked). The ARW must dependably guarantee: a) stability during generalized interaction/manipulation, b) safe environment surface docking, c) robustness against rough manipulator –or manipulated load– collisions, d) increased capabilities for disturbance rejection. To this end, a high-bandwidth control synthesis will be developed, that fully exploits the platform’s increased motion authority, and that accounts for the hybrid/switching dynamics of the ARW. Potential high-efficiency solutions will be investigated from within –but not limited to– the fields of hybrid modelling and multi-parametric optimization. Finally, significant research will be invested in intelligently employing the manipulator’s force/moment feedback estimates during the environment interaction/manipulation control process. This will enable the synthesis of a high-level model-based strategy that will treat the manipulator and the aerial platform as a coupled system of increased functionality, benefitting from their combined potential in a similar sense that a human worker’s body aids their hands in performing complex work-tasks.

Strict safety considerations originating from the intended operation within industrial-grade environments will have to be guaranteed. A layer of basic decisional autonomy will allow the ARW to execute reactive-safety maneuvers in order to avoid collisions with humans or suddenly appearing structures. To this purpose, model-based strategies that account for the unit’s reachable manoeuvrability envelope, the interpreted environment knowledge and self-configuration awareness will be employed to ensure collision-free operation. Finally, the control layer will allow periods of direct tele-operated control, in order to enable supervised autonomy at lower levels. Smooth modal switching will be ensured, while the handling authority available to the operator will depend on user expectation (work-task expert/certified pilot).

Task 5.4 - Control of Mechanically Coupled Aerial Robotic Workers (**UPAT,**LTU,UT,ETHZ,KTH,UT,ASC)

This task focuses on a higher level of control and adds a context of intelligent natural interaction to the co-manipulation process, by optimizing aerial manipulation at the unit level. The case of co-manipulation is of special significance within the AEROWORKS concept, as it exposes the capability for active exploitation of the forces and moments induced by one ARW to the other via the commonly manipulated object. This concept is regarded not within the context of consensus-building collaboration, but as an analogue to the natural human-based co-manipulation paradigms found in tasks such as group table-carrying and double hand-saw tree-cutting. In order to similarly perform such tasks, each ARW unit must possess dynamic motion capabilities ensured at the control level, in order to sense the aiding-or-hindering role of an externally imposed force, and consequently exploit or reject it.

The envisioned coupled super-system that benefits from the multi-robot physical interaction process presents significant research challenges. Initially, based on the coupled multi-ARW co-manipulating dynamics, extensive investigation will be conducted to derive the global stability margins, the applicable force/moment margins and manipulator workspaces which ensure that each ARW's dependability is not compromised. The synthesized supervisory control structure will employ the modeled coupled motion dynamics and manipulator feedback in order to: a) maximize the co-manipulation efficiency via minimization of the combined control effort, b) innovatively exploit their flight envelope configurations and their manipulators, and c) handle tasks of increased complexity. Significant research effort will be invested in order to provide model-based and task-adaptation methodologies for these purposes. Finally, special focus will be put on ensuring dependability during coupling/decoupling while performing aerial co-manipulation. The ARW's possible: a) approaching manoeuvres, b) grasping trajectories, and c) releasing strategies, will be thoroughly investigated in order to ensure near-optimal performance with minimal destabilizing effects. The advanced potential contributed by this scheme will be exploited in the coordinated collaboration process of WP6.

Role of Partners:

ETHZ leads this work package in strong collaboration with ASC, LTU and UPAT as well as UT and SBX. UPAT is responsible for the Tasks 5.2 and 5.4 while naturally ASC handles Task 5.1.

Deliverables	
D5.1: Assembled and thoroughly tested ARWs (ASC)	M12
D5.2: Report on the Aerial Robotic Worker model and release of the open-source simulator (UPAT)	M14
D5.3: Report, Publications list and Videos on the control synthesis of the aerial robotic workers (ETHZ)	M28

Work package number	6	Start date or starting event:	M5-M34						
Work package title	***Collaborative Planning and Control for Inspection and Aerial Manipulation***								
Activity type[9]	RTD								
Participant number	1	2	3	4	5	6	7	8	9	10
Participant short name	LTU	ETHZ	KTH	UT	UEDIN	UPAT	ASC	SBX	AIR	SKL
Person-months per participant	15	18	41	7	6	11	0	2	0	0

Objectives

This work package focuses on the development of the collaborative path-planning and control algorithms that will provide the intelligence for the autonomous execution of infrastructure inspection and maintenance tasks by the ARWs team. Global as well as reactive approaches will be employed focusing on the decentralized collaboration of the members of the AEROWORKS robotic team while ensuring complete and time-efficient inspection and structural maintenance along with collision-free navigation in cluttered challenging environments. More specifically, the envisaged objectives may be summarized as follows:

- Single aerial robotic worker autonomous path-planning for inspection operations
- Collaborative aerial robotic workers team path-planning for autonomous inspection
- Development of methodologies for collaborative manipulation through multiple aerial workers
- Development of decentralized navigation and task assignment methodologies for multiple ARWs
- Development of reconfiguration strategies for the online adaptation of the multiple ARWs team

Consequently, the AEROWORKS robotic team will be characterized by increased *decisional autonomy* and *re-configurability* in all anticipated environments. As a series of public demonstration events are planned to show, such algorithms will robustly provide the capability of autonomous aerial robotic infrastructure inspection, a key technology for improved, cost-effective and increased quality maintenance cycles.

Description of work

Task 6.1 Single-ARW Autonomous Path-Planning for Inspection (**ETHZ**,LTU,KTH,UT,UEDIN,UPAT)
This task deals with the development of the AEROWORKS single ARW autonomous structural inspection path-planning algorithm. Going beyond the majority of the methods that assume a-priori perfect knowledge of the structure or separate the problem of finding the inspection points and consequently planning the path among them, the envisaged methods will focus on being able a) to tackle uncertainty, b) ensuring that full coverage solutions are computed in minimum time while further computations will allow approaching improved solutions, c) being "*anytime*" and d) incorporating reactive mechanisms to deal with static and dynamic obstacles, temporal losses or quality degradation of the onboard perception systems and algorithms.

Task 6.2 Collaborative Path-Planning and Coverage Control for Inspection (**KTH**,LTU,ETHZ, UEDIN,UPAT,SBX)
This task relates with the development of distributed collaborative path-planning algorithms for inspection operations. The path planner for each robot should be collaborative in the sense that it has to guarantee collision avoidance with other members of the team as well as stabilization to the desired configuration points in 3D. These have to be decided by an online 3D coverage algorithm that should take into account the inspection mission as well as the dynamics of the UAVs. As AEROWORKS aims to achieve increased autonomy as well as mission completeness, the proposed algorithms will go beyond fully decoupled task-assignments solely based on individual specification but will also incorporate environment and perception uncertainties as well as heterogeneity of the robotic systems into the optimization process, whose cost function will aim at maximizing the coverage of the inspected area in a collaborative manner. This task expands upon the path-planning algorithms to be developed within Task 6.1 and aims at enabling key system

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abilities such as robot to robot interaction and configurability.

Task 6.3 Collaborative Manipulation through multiple aerial robots (KTH,LTU,ETHZ,UT,UEDIN,UPAT**)**

While the previous task involves collaborative navigation and decentralized task assignment, the particular task of manipulation through multiple aerial robots equipped with a manipulator in a collaborative way requires a developmental effort on its own. Although pairwise manipulation is considered in Task 5.4, in this task we are interested in manipulation tasks involving more than two robots. A first issue that should be addressed is that of equilibrium adaptation due to neighboring information. A typical example involves a number of aerial robots aiming at grasping an object. If the contact point of one of them is not the expected one, the others should collaborate in order to adopt their contact points and re-grasp the object in an optimal manner. We are planning to use tools from collaborative optimal grasping and sliding mode control in order to achieve this task. Finally, an important issue that arises is the fact that robots should reach the object of interest within almost the same time interval, in order to apply the collaborative grasping tools in an efficient manner. This poses the problem of synchronization in decentralized navigation. Such temporal constraints have not been considered up-to-now in decentralized multi-robot systems and thus constitute yet another research issue in this task. Overall, this task focuses on enabling key system abilities including collaborative manipulation and multi-robot decisional autonomy towards achieving advanced manipulation dexterity.

Task 6.4 Decentralized Task Assignment (KTH, LTU, ETHZ,UT,UEDIN,UPAT**)**

This task involves a decision making mechanism that assigns a priori tasks to the ARWs in a decentralized manner. Starting from the global and generic mission tasks, i.e. infrastructure inspection, repair and maintenance, the robots should possess the capability to define their initial individual task, i.e., define a sequence of local subtasks that fulfill their partial knowledge of the global mission as much as possible . As this decentralized task assignment algorithm will focus on revealing the most of the powers of the AEROWORKS robotic team, dynamic solutions that would lead to subsets of the robot operating in inspection mode, and others conducting maintenance tasks are to be expected. The abilities of distributed re-configuration and task adaptation and distributed mission oriented autonomy will consequently characterize the envisaged aerial robotic team. The results of this task serve as input to the reconfiguration Task 6.5.

Task 6.5 Collaborative Reconfiguration through on line adaptation (**KTH**,LTU,ETHZ,UT,UEDIN,UPAT)

The assignment mechanism should be dynamic, in that it should be updated once new information is gathered from one or more robots. This information should then be fused to one hop neighbors that should also update their planners accordingly. The way to update the task planner as well as the underlying controllers and planning strategies is the exact objective of this task. An important issue is whether to conduct the update in the discrete or the continuous level of control. For example, when an agent meets an obstacle, would it be more suitable to change the discrete objective by choosing another goal point or update the continuous controller in order to avoid the obstacle while keeping the same target? Tools from hybrid control theory, sampling-based path-planning and distributed decision making in the form of discrete graph search methods may be utilized in this framework. This task contributes to enhancing the robotic team distributed re-configurability, decisional autonomy, distributed task adaptation and mission dependability.

Task 6.6 Heterogeneous Multiple Aerial Robotic Workers (**KTH**,LTU,ETHZ,UT,UEDIN,UPAT)

In this task we will consider the case that part of the aerial robotics group is replaced by a different aerial platform than the original nominal one. We are going to use the decentralized collaborative nature of the previous analysis in order to show that the group of agents still satisfies the desired goal even in the case of heterogeneity, ensures mission completeness satisfactory performance. The latter will be depicted both in the different dynamics as well as the different individual path-planning and control design levels. With this being the final task of the work package, identified key barriers such as complex decision making in uncertain environments, improved manipulation through multi-robot collaboration will be targeted and be overcome as validated experiments and benchmarked public demonstrations will show.

Role of Partners: KTH leads this work package. ETHZ contributes particularly in Task 6.1 while all academic partners are generally involved. SBX is especially involved in the Task 6.2 research aspects.

Deliverables	
D6.1: Report on Single-ARW Inspection Planning methods and performance analysis (EHTZ)	M12
D6.2: Report on Multi-ARW Inspection Planning and Manipulation Algorithms (KTH)	M30
D6.3: Report on Decentralized Task Assignment and collaborative reconfiguration methods (KTH)	M30
D6.4: Report on Heterogeneous multi-robot path-planning and control (KTH)	M33

Work package number	**7**	**Start date or starting event:**		**M5-M36**						
Work package title	***System Integration and Evaluation***									
Activity type[10]	RTD									
Participant number	1	2	3	4	5	6	7	8	9	10
Participant short name	LTU	ETHZ	KTH	UT	UEDIN	UPAT	ASC	SBX	AIR	SKL
Person-months per participant	13	20	7	4	4	4	15	11	6	6

Objectives

The objective of this work package is to ensure that tight and complete system integration of the different modules and algorithms developed within AEROWORKS takes place along with proper evaluation and demonstration of the technological capabilities achieved. System integration is conducted based on proper task assignment, utilization of common solutions, platforms and hardware as well as scheduled annual project integration weeks. The different modules such as the aerial vehicle, the dexterous manipulator, the sensing and processing unit and the corresponding perception and flight control algorithms the communication modules and the path-planning and collaboration strategies will be integrated into multiple fully functional ARWs and finally to the collaborative AEROWORKS robotic team. Thorough evaluation will take place in order to present the results of the project, improve the proposed systems and methods, demonstrate and benchmark the achieved capabilities within public events and eventually present some first real operational tests. An incremental procedure to increase the TRL of the proposed methods will be followed and all the proposed methods will be related with the identified critical system abilities and technology barriers by the global research community. The overall AEROWORKS-specific evaluation process will be based on the Application Requirements and Benchmarks as described in work package 2.

Description of work

Task 7.1 -Integration (**SBX,**ETHZ,ASC,AIR, LTU,UT,UEDIN,KTH,UPAT**)**

AEROWORKS aims at deploying autonomous aerial robotic infrastructure inspection and maintenance solutions characterized by advanced system abilities and increased technology readiness level. Consequently, subsequent integration cycles will take place, including efforts related with:

- Integration of the aerial manipulator hardware and device interface towards developing each single aerial robotic worker and deploying it with a modular control interface.
- Integration of the perception and advanced state estimation modules and algorithms to the aerial robotic workers. As all advanced estimation and perception algorithms take place in the AEROWORKS Sensing and Processing Unit, convenient and safe integration is envisaged.
- Integration and test-cases based evaluation of the autopilot functionalities that enable the active aerial dexterous (co-)manipulation by the ARWs team.
- Integration of the baseline teleoperated inspection and aerial manipulation control algorithms that enable the execution of infrastructure maintenance operations with a non-specifically trained human-in-the loop.
- Integration of the collaborative planning and control for structural inspection and maintenance operations. This integration task will also be followed by extensive evaluation in order to ensure that all the desired functionalities are successfully achieved and all hardware/software components are aligned.
- Development of the ***AEROWORKS intuitive-to-use Ground Control Center***

The AEROWORKS successful integration plan relies on the selection of unified hardware and software as well as the fact that it builds upon all the recent and most successful developments of the partners. Through proper task assignment, partner complementarities and well-scheduled integration weeks, the project will

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reach the level of mature and well integrated technological solutions, systems and prototypes.

Task 7.2 - Demonstration (**ETHZ,**AIR,SKL,SBX, LTU,UT,UEDIN,KTH,UPAT**)**
Achieving increased technology readiness levels, validated system abilities and deployment of successful robotic functions should be combined with public demonstration and evaluation events that can convince the public and all potential end users about the use and capabilities of robotic solutions and the potential they pose to provide advanced and cost-effective infrastructure inspection and maintenance solutions. Therefore, the ***AEROWORKS Benchmarking, Demonstration and Evaluation plan*** contains:

- Technology validation experiments in the laboratory environments of the AEROWORKS partners: all initial developments will be evaluated based on the benchmarks defined at WP2 and corresponding experiments at the AEROWORKS lab facilities. Such validation tests correspond to the lower-layer of the evaluation process and are related with a TRL equal to 4 (according to the MAR).
- Systems and Technology validation experiments in realistic mock-ups that serve as testing facilities that mimic the necessities of a real infrastructure inspection and maintenance scenario. These tests increase the presented TRL level of the project results to 5 and serve as a preparation phase for the partners in order to improve their integrated solutions before public demonstrations or real operational tests.
- Public systems and technology demonstrations will be conducted. These events challenge the AEROWORKS consortium to present the research and innovation results in a complete way that can convince the public and key public bodies and end-users about the potential of the envisaged robotic solutions. Such events increase the confidence on the potential of robotic systems and attract the industrial sector which is one of the fundamental goals of the project. Within these events the separate technologies as well as the integrated collaborative operation for inspection and maintenance will be presented and therefore a TRL equal to 6 will be targeted for all fundamental AEROWORKS technologies. SKL and AIR will be responsible to define the areas of public demonstration.
- Finally, operational tests will be conducted and the AEROWORKS robotic solutions will already present a subset of their capabilities in real infrastructure environments. The selection of the technologies to be employed within these operations will be done in collaboration with the end-users (SKL and AIR) of the consortium and will aim to show that the required methods and systems to integrate aerial robotic systems to the infrastructure inspection market are – at least up to a specific level – available. The relevant TRL is 7 and corresponds to the maximum aimed within the time frame of the project

The envisaged demonstration events will be publicly announced and will also serve as a way for disseminating the project results to the general public, the European and International societies.

Task 7.3 -Performance Assessment (**ETHZ,**AIR,SBX,LTU,UT,UEDIN,KTH,UPAT,AIR,SKL**)**
The performance of the proposed systems and methods will be evaluated regarding:

- Their technological capabilities, namely the mechanical robustness, flight-time, state estimation accuracy, environmental perception properties, 3D reconstruction fidelity, single and collaborative inspection completeness and time-efficiency, aerial manipulation capabilities and maximum applicable forces, co-manipulation dexterity and autonomy on multi-robot work-task execution.
- Their abilities as identified by the robotics society and its public bodies (IEEE-RAS, euRobotics, IEEE Aerial Robotics Technical Committee etc). This aims to clarify where AEROWORKS contributes to the cumulative effort to make aerial robots an integral part of our society and civil applications especially.
- Their capabilities regarding the requirements of civil infrastructure maintenance as identified by WP2.

The role of SKL and AIR as well as ASC, SBX is fundamental within this process in order to ensure that integrated, reliable, robust and ready systems that can have great market impact in short term are achieved.

Role of Partners:

SBX leads this work package as well as Task 7.1. The integration efforts are accomplished with the collaboration of all partners and particularly ETHZ ASC and AIR.

Deliverables	
D7.1: Manipulator and Interfacing electronics module (UT)	M34
D7.2: Aerial Robotic Worker integrated with AEROWORKS sensing and processing unit (ETHZ)	M34
D7.3: Single Autonomous ARW-Inspector (ETHZ)	M34
D7.4: Single Autonomous ARW-Maintainer (ETHZ)	M34
D7.5: Integrated software for collaborative ARWs for Inspection and Maintenance Operations (KTH)	M34
D7.6: Report/records on performance evaluation of the collaborative ARWs (LTU)	M36

Work package number	**8**	**Start date or starting event:**		**M1-M36**						
Work package title	***Dissemination, Promotion and Exploitation***									
Activity type[11]	RTD									
Participant number	1	2	3	4	5	6	7			
Participant short name	LTU	ETHZ	KTH	UT	UEDIN	UPAT	ASC	SBX	AIR	SKL
Person-months per participant	9	6	3	2	2	6	4	4	5	6

Objectives

This work package aims at collecting the knowledge and the results of the technical work packages in order to achieve their widest possible, well-focused, dissemination and enable effective exploitation. The goals of this work package are fundamental for the success of the project as targeted dissemination and promotion to stakeholders along with spreading the word about the potential of robotic solutions for civil applications to the general public are considered critical for the sustainability and the impact of the envisaged contributions. Similarly, exploitation of the project results and targeting of specific applications and market directions is important for the further success of the project idea and the integration of aerial robotic solutions for civil applications. Moreover, the consortium will focus to exploit the project results in areas and directions that go also beyond the main project idea such as environmental monitoring, emergency services or mine inspection.

Description of work

Task 8.1 - Public Visibility (LTU, ETHZ, UPAT)

Within the framework of this task all the activities that aim to increase the public visibility of the AEROWORKS project will be scheduled, organized and accomplished. The activities within this contain the dissemination material of the scientific results as well as non-strictly scientific actions and aim to raise awareness, inform, promote the project results and pave the way for further opportunities. More specifically, the following two subtasks will constitute this task:

<u>*Dissemination Profile and Material:*</u> The aim of this task is to produce a project coordinated image and dissemination materials, which will be distributed to specific target groups and the general public. The goal is to increase awareness across the world and the community about what robotics can achieve and how AEROWORKS contributes scientifically and towards aerial infrastructure inspection and maintenance solutions. These goals will be achieved through

- Publications in top-notch Scientific Conferences and Journals [*Task 8.2*]
- Participation in Industrial Conferences and Workshops, Robotics Forums and Exhibitions [*Task 8.3*]
- Preparation of general-public dissemination materials in printed and digital form

As well as the organization of:

- Public demonstration events to show the AEROWORKS robotic team capabilities in operation [*Work Package 8*]
- Press conferences in the association with some of the main events of the project (kick-off meeting, experimental validation periods, final dissemination workshop)

<u>*Online material:*</u> The aim of this task is to create and manage a website for public dissemination of results as

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well as establish other methods of communication. It will consist of six areas, namely:

- Project introduction section, where the partners, their profile, the main objectives as well as a technical analysis of the concepts to be addressed by the project will be presented.
- A web-management tool for quick online management of internal partner information.
- Project update section, where the project current status, main achievements and results will be reported in the form of a timeline slideshow accompanied with links to further dissemination material (publications, videos, articles or presentations in the media).
- Public calendar, so that anyone can track the progress and the main events of the project.
- An open source section, where all the software code and hardware schematics developed from the academic partners during the project will be published and fully documented based on the highest standards of the open-source community.
- A set of tutorial-like presentations that aim to provide an easier way of understanding the main contributions and relations with the bases of control, computer vision, mechatronics and multi-agent mathematical foundations. Through the utilization of a special series of video presentations – online lectures (2 per year of the project), slides and short accompanying documents and code-examples, the aim is to provide the means to help students to strengthen their understanding on challenging problems and attract people in robotics.

Understanding that the use of internet has changed over the last few years through the introduction of social media, special attention will be paid to use this channel of public dissemination. In that sense a) a *youtube* video channel will be maintained and b) Facebook/Twitter accounts will be linked automatically with the website updates.

Task 8.2 - Dissemination of Scientific results and conclusions (KTH,LTU,ETHZ,UT,UEDIN,UPAT**)**

The main focus here is related with the scientific publications in **Conferences** (such as IEEE International Conference on Robotics and Automation (ICRA), IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), IEEE Conference on Decision and Control (CDC), European Control Conference (ECC), American Control Conference (ACC), Robotics: Science and Systems (RSS), International Symposium of Robotics Research, CVPR IEEE Conference on Computer Vision and Pattern Recognition, ICCV International Conference on Computer Vision, ECCV European Conference on Computer Vision, ACM SIGGRAPH, ACM Virtual Reality, UAV International Symposium on Unmanned Aerial Vehicles, International Unmanned Air Vehicle Systems (UAVS) Conference, American Helicopter Society Annual Forum and Technology Display, AIAA Modeling and Simulation Technologies Conference) and **Journals** (such as IEEE Transactions on Robotics, IEEE Control Systems Magazine, Journal of Field Robotics, Autonomous Robots, Control Engineering Practice, Robotics and Autonomous Systems, Unmanned Systems, AIAA Journal of Aircraft, IJCV International Journal of Computer Vision, IET Control Theory and Applications, Journal of Vision, Perception, wiJournal of Intelligent Robots and Systems). A special workshop will be organized in one of the aforementioned conferences with the aim to attract all scientists working in similar fields.

Task 8.3 – Strategic Market-based Dissemination (AIR, LTU, ETHZ, UPAT, ASC, SBX, SKL)

This task builds upon the results of Task 8.1 and focuses on the dissemination activities required to spread the technical results of the project to a wide subset of the potential end-users and stakeholders that are active in the area of civil infrastructure inspection and maintenance. The technical results will be combined with market analysis for specific application and test-cases. To aid successful dissemination, key public authorities and private enterprises relevant with the field will be invited to attend the AEROWORKS public demonstration events. Furthermore, members of the consortium will represent the project into conferences, workshops and exhibitions that the infrastructure business community is gathered. Additionally, the direct channels of SKL and AIR will utilized to raise interest to end-users while ASC and SBX will aid in order to increase the visibility of the project results in the industrial/commercial robotics sector. Among other ways, the consortium will focus on participating in technological exhibitions. A special role will be played by the Advisory Board. Overall, the consortium will prioritize paving the way for increasing interest from the European and worldwide investment communities.

Task 8.4 - Training Activities (LTU, ETHZ, UPAT)

Special attention will be paid on organizing training activities and particularly:

- A "*Summer School*" on topics relative to the project results and objectives for postgraduate and PhD students. The summer school represents the main training event of AEROWORKS.
- A "*Final Workshop*" that will aim in the presentation of the final results and scientific contributions achieved within the project as well as live experimental demonstrations. The workshop will equally focus on academic institutions and industrial end-users.
- A "*Maintenance Operators Training Event*", within which personnel that works on infrastructure inspection but is unfamiliar with robotic technology will be openly invited to join the AEROWORKS team in a demonstration event where they will be able to get a hands on experience on teleoperating the aerial robotic workers and designing example autonomous inspection and maintenance operations.

Task 8.5: Harmonization with other EU and Global Projects (**LTU**, ETHZ, UPAT, ASC, SBX)

This task involves efforts on harmonizing and integrating AEROWORKS with other relevant research projects relevant that took place or are currently taking place within the European research area as well as all the main international research efforts. This will be achieved via collaborative organization of workshops, participation in common events, round-table meetings to exchange ideas and directions as well as through the role of the AEROWORKS advisory board and by releasing open software and hardware contributions. An extensive list of relevant projects will be available at the AEROWORKS website.

T8.6 Data Management Plan (**LTU**, UPAT)

As AEROWORKS has been selected to participate in the limited action on open access to research data in H2020, a Data Management Plan (DMP) will be developed describing the data management life cycle for all data sets that will be collected. More details the DMP will specify what data the project will generate, whether and how it will be exploited or made accessible for verification and re-use, and how it will be curated and preserved.

Task 8.7: - Exploitation, management of knowledge (ASC,LTU,ETHZ,UPAT,SBX,AIR,SKL)

The objective of this task is to ensure the further exploitation of the project outcome. This will be achieved via the identification and assessment of the knowledge and technological contributions generated in the different WPs. This analysis will be related with studies on the potential market success in short- and mid-term in order to conduct focused actions that will raise awareness and attract interest. The consortium will focus on both exploiting the results on the specific area of infrastructure inspection and maintenance as well as on the individual technologies and subsystems that can have an impact in the wider area of civil and commercial applications. The goal is to increase the role of European enterprises in the worldwide robotics market while also forming collaboration with international enterprises.

Role of Partners:

LTU will lead this WP as also the specific tasks 8.1, 8.4, 8.5, 8.6 while is leading Task 8.3 and ASC leads Task 8. Overall, most partners participate in the several tasks of this work package.

Deliverables	
D8.1: Project identity and dissemination material schedule (LTU)	M1
D8.2: Project website and overall online presence (LTU)	M1
D8.3: Data Management Plan (LTU)	M6
D8.4: Summary Report on Live Demos and Videos with results (KTH)	M36
D8.5: Summer School (ETHZ)	M30
D8.6: Maintenance Operators Training Event (AIR)	M32
D8.7: Final Dissemination workshop in major Conference (KTH)	M35

Table 3.1b: List of work packages

No.	Work Package Title	Leader No.	Leader \Name	PMs	Start Month	End month
1	Project Management & Coordination	1	LTU	30	M1	M36
2	Applications, Requirements and Benchmarks	10	SKL	57	M1	M24
3	Dexterous Aerial Manipulator	4	UT	53	M3	M32
4	Collaborative Perception, Mapping and Vision for Manipulation	5	UEDIN	140	M3	M32
5	Aerial Robotic Workers Development and Control	2	ETHZ	109	M3	M32
6	Collaborative Planning and Control for Inspection and Aerial Manipulation	3	KTH	100	M5	M34
7	System Integration and Evaluation	9	SBX	90	M5	M36
8	Dissemination, Promotion and Exploitation	1	LTU	47	M1	M36
				626		

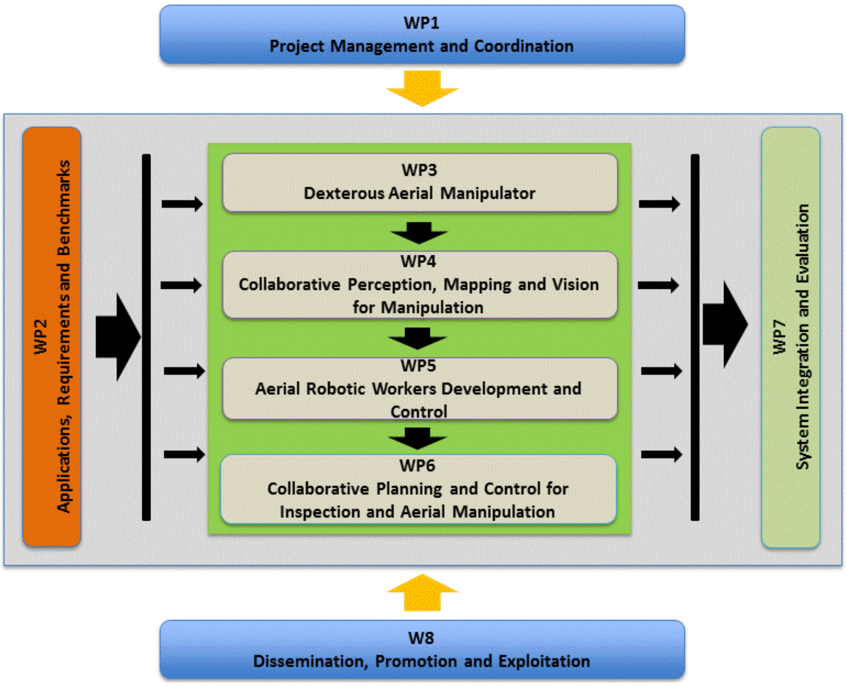
Table 3.1c: List of Deliverables[12]

No.	Deliverable name	WP number	Leader	Type	Diss. level	Date
D1.1	AEROWORKS Progress Report releases	1	LTU	R	PU	M6,M12,M18,M24,M30,M36
D1.2	AEROWORKS Final Report	1	LTU	R	PU	M36
D2.1	Benchmark specifications and related performance measures	2	SKL	R	PU	M6
D2.2	Platform and overall operation specifications	2	ASC	R	PU	M6
D2.3	Report on application scenarios, end-user requirements, and regulations	2	AIR	R	PU	M8
D2.4	Final validation scenario definition	2	AIR	R	PU	M12
D3.1	Analysis and design of the Hardware for collaboration	3	UT	R	PU	M12
D3.2	Version 1.0 of dexterous manipulator and sensor fusion	3	UT	R	PU	M22
D3.3	Version 2.0 of the collaborative robot and cognitive control implementation	3	UT	R	PU	M34

D4.1	Methodology & Results on real-time vision-based SLAM for each ARW	4	ETHZ	R	PU	M14
D4.2	Methodology & Results on real-time dense reconstruction from an ARW	4	UEDIN	R	PU	M22
D4.3	Methodology & Results on collaborative ARW Sensing and Mapping	4	UEDIN	R	PU	M36
D4.4	Report and publications list on vision-based perception for the team of collaborative aerial robotic workers as well as release of open-source software	4	UT	R	PU	M26
D5.1	Assembled and thoroughly tested ARWs	5	ASC	OTHER	PU	M12
D5.2	Report on the Aerial Robotic Worker model and release of the open-source simulator	5	UPAT	R	PU	M14
D5.3	Report and Publications list on the control synthesis of the aerial robotic workers	5	ETHZ	R	PU	M28
D6.1	Report on Single-ARW Inspection Planning methods and performance analysis	6	ETHZ	R	PU	M12
D6.2	Report on Multi-ARW Inspection Planning and Manipulation Algorithms	6	KTH	R	PU	M30
D6.3	Report on Decentralized Task Assignment and collaborative reconfiguration methods	6	KTH	R	PU	M30
D6.4	Report on Heterogeneous multi-robot path-planning and control	6	KTH	R	PU	M33
D7.1	Manipulator and Interfacing electronics module	7	UT	OTHER	PU	M34
D7.2	Aerial Robotic Worker integrated with AEROWORKS sensing and processing unit	7	ETHZ	OTHER	PU	M34
D7.3	Single Autonomous ARW-Inspector	7	ETHZ	OTHER	PU	M34
D7.4	Single Autonomous ARW-Maintainer	7	ETHZ	OTHER	PU	M34
D7.5	Integrated Software for collaborative ARWs for Inspection and Maintenance Operations	7	KTH	OTHER	PU	M34
D7.6	Report/records on performance evaluation of the collaborative ARWs	7	LTU	R	PU	M36
D8.1	Project identity and dissemination material schedule	8	LTU	DEC	PU	M1

D8.2	Project website and overall online presence	8	LTU	DEC	PU	M1
D8.3	Data Management Plan	8	LTU	R	PU	M6
D8.4	Summary Report on Live Demos and Videos with results	8	KTH	DEM	PU	M36
D8.5	Summer School	8	ETHZ	DEC	PU	M30
D8.6	Maintenance Operators Training Event	8	AIR	DEC	PU	M32
D8.7	Final Dissemination workshop in major Conference	8	KTH	DEC	PU	M35

3.1.4 *Pert Diagram*



3.2 *Management structure and procedures*

Management and co-ordination tasks are of great importance within the AEROWORKS project in order to succeed its objectives. The described targeted objectives of the project require a high cooperation and integration level in order to be accomplished. Thus, the management structure has been carefully defined and structured, both from a technical and an administrative point of view. The AEROWORKS project management deals with the overall management structure and the implementation of the management: the decision rules, conflict resolutions, meetings, internal communication flow and reporting progress.

3.2.1 *Management capability of the coordinator*

The leading partner of this Research and Innovation action will be the Control Engineering Group (CEG) in Luleå University Technology (LTU) and ***Assoc. Prof. Dr. George Nikolakopoulos*** will act as the coordinator of AEROWORKS. CEG conducts high value research and has significant experience in undertaking industrial R&D projects. CEG has been involved in large European and National projects with Volvo, LKAB, SAAB, Vidsel, and many more industrial partners and has published more than 400 articles in Journals and Conferences. Its specialization lies in control systems, optimization, robotics and mechatronics.

Prof. Nikolakopoulos is leading the Robotics and Autonomous System Group at LTU and has a significantly large experience in Managing European (STEPs and IPs) as well as National Projects. In the past he has been project manager in Several R&D projects funded from the EU, ESA, Swedish and the Greek National Ministry of Research, with some examples such as: a) EU funded projects: FLEXA (IP), C@R (IP),

NANOMA (STREP), SYMBIOSIS-EU (STREP), CONFIDENCE (STREP), PROMOVEO (STREP), CommRob (STREP), b) Swedish funded projects: Mine Patrolling Rovers and EQoREF.

In year 2003, Prof. Nikolakopoulos received the Information Societies Technologies (IST) Prize Award for the best paper that promotes the scopes of the European IST (currently known as ICT). His published scientific work includes more than 150 published International Journals and Conferences in the fields of his interest. Moreover he served as IPC member and Technical Track Chair for multiple conferences, such as ICIT'11, CoDIT'13, CASE'2010, ETFA'2010, ECC'09, MED'09, MIC'09, and MIC'10 international conferences, and has been Associate Editor and Reviewer of Several International Journals and conferences. From 2006-2012, he is a member of the IASTED Control Technical Committee.

3.2.2 Management structure and decision-making structure

The AEROWORKS project's management structure is described in the Figure 3.1. At the top of the structure, there is a **Steering Committee**, which is the decision-making and arbitration body of AEROWORKS concerned with policy and strategy. The **Scientific Committee** forms the second level of the management structure. It has powers delegated to it by the Steering Committee to implement policy and strategy decisions. It is composed of the work package leaders who are responsible for the day-to-day management of the individual work packages. The Scientific Committee is the supervisory body for the project execution and shall report and be accountable to the Steering Committee. The **Project Coordinator** will provide a strong central coordination, performing functions such as the technical coordination, financial administration and internal and external communications, to ensure that AEROWORKS will operate in a truly integrated manner. Moreover, the **Management Support Team** will assist the Coordinator.

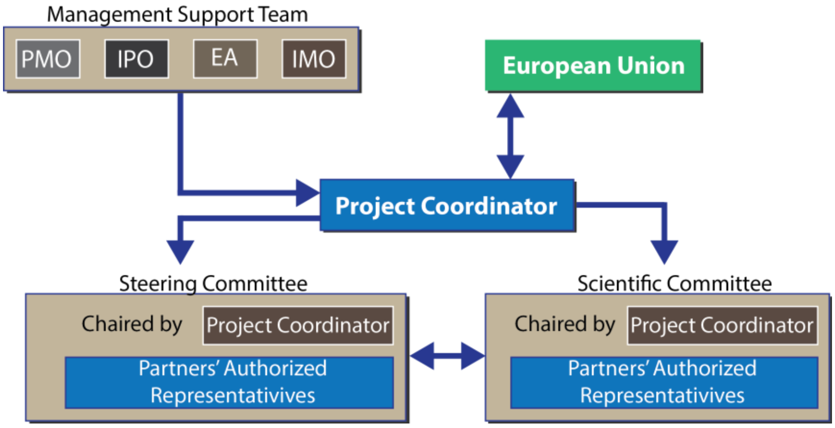


Figure 3.1: Management structure of AEROWORKS

<u>Steering Committee:</u>

Chairman: Project Coordinator.
Members: One representative of each partner that must have the legal authority.
Responsibilities:

- The overall supervision of the political and strategic orientation of the project and programme activities
- The management of changes and resolution of conflicts with respect to the programme of activities.
- The execution of deliverables and milestones, the follow-up of the performance indicators and the coordination of the progress reports.
- The approval of deliverables as well as financial statements.
- The agreement to any changes to the technical content.
- The supervision of all dissemination activities, including deciding on protection and access rights to knowledge based upon the Heads of Agreement.
- Management and preparation of the contract with the funding agencies.
- The preparation of the budget and financial allocation to each partner.

<u>Scientific Committee:</u>

Chairman: Project Coordinator.
Members: One representative per partner participating in the relevant WPs.
Responsibilities:

- Monitoring the progress of work packages against the implementation plan.
- Ensuring the coordination of the project activities.
- Implementing the decisions taken by the Steering Committee.
- Reviewing Intellectual Property issues and reports proposed by the Intellectual Property Officer.

- The preparation of progress reports, within each work package.

Project Coordination:

LTU as the **Coordinator** will assume responsibility for the management of the project, which will be carried out by **Assoc. Prof. Dr. Georgios Nikolakopoulos**. The Coordinator is responsible for:

- Administrative coordination and financial management.
- Communication between the Steering Committee, the Scientific Committee and all the partners.
- Acting as spokesperson of AEROWORKS towards the EC.
- Proposing agenda for consortium meetings.
- The collection, collation and forwarding of progress reports.
- Central document administration.
- Setting up a web-site, with internal and external faces, enabling easy transfer of large data files and documents with the appropriate degree of security, whilst also allowing a summary of the project and its achievements to be viewed by external parties.
- The transfer of all deliverables to the Commission.
- Monitoring of the Intellectual Property Plan.

Management Support Team:
The coordinator, Assoc. Prof. Georgios Nikolakopoulos, will be assisted by the **Management Support Team** so as to accomplish all these responsibilities:

Project Management Office (PMO) The PMO is in charge to compare in real time what is actually done to what is due by contract with regard to costs, time schedule and delivery. The PMO report any deviation, ask for proper decisions to be made in case of any deviation, and push the Consortium to update contractual framework toward the Commission (keep in line with the contract or amend it) and toward one another (IPR issues, budget share…) if the project does not evolves exactly as anticipated in the proposal (i.e. the usual scenario). The PMO shall also ensure the quality of work within the project.

Innovation Management Office (PMO) The IMO will be in charge of a series of activities ensuring that the highest innovative potential of the Consortium is realized throughout the entire project duration. With this goal, the IMO will create an innovation strategy to transfer the generated knowledge in the Consortium partners, to the European infrastructure services industry and the robotics developers and finally to the overall market. Furthermore, it will establish a consulting panel and provide on-going training on technical business development to managers and researchers within the consortium, support the decision-making process and secure the quality and progress of commercialization of the AEROWORKS outcomes. Finally, IMO will be closely working with other Management Support Teams to ensure the collaborative and integral innovation approach in the Consortium as a whole. ***Dr. E. Zwicker (AIR)*** will lead the IMO.

Dr. K. Alexis (ETHZ), Prof. D. Dimarogonas (KTH) will support the Coordinator. Dr. Alexis will lead the PMO, while all have a long experience coordinating projects and significant technological background.

Intellectual Property Officer (IPO) Dr. M. Chli (UEDIN) will act as the IPR manager and will support the coordinator in dealing with legal and IPR issues. This person will be responsible for the identification of pre-existing partners' know-how to be protected, will prepare and regularly update the Consortium Agreement according to the project evolution and will advise partners about knowledge protection.

Ethical Advisor (EA) Prof. A. Tzes from UPAT will be the Ethical Advisor and will advise the Scientific Committee on all matters relating to the Ethics of the project.

Advisory Board: Furthermore, an Advisory Board is already formed and consists of relevant International Stakeholders and high calibre scientists not directly involved in the AEROWORKS consortium. AEROWORKS will foster discussions with the advisory board members and will use this additional channel to form new collaborations, get further feedback and disseminate its results better. No financial contribution is foreseen for the members of the advisory board.

Organization		Country	Person
1.	Kavraki Lab, RICE University	USA	Prof. Dr. Lydia E. Kavraki
2.	The Robotics Institute, Carnegie Mellon (CMU)	USA	Prof. Dr. Sanjiv Singh
3.	Queensland University of Technology	AU	Prof. Dr. Peter Corke
4.	The University of Queensland	AU	Prof. Dr. Paul Pounds
5.	PIX4D SA	CH	Company representative

6.	ETH Zurich	CH	Prof. Dr. Raffaello D' Andrea
7.	Hellenic Electricity Distribution Network Operator	GR	Dr. Emmanouel Thalassinakis
8.	Det Norske Veritas (DNV) R&I, Greece	GR	Dr. Nikolaos Kakalis, Head
9.	CASY-DEI University of Bologna	IT	Prof. Dr. Lorenzo Marconi

3.2.3 Implementation of the management

DECISION RULES: The voting rules for the AEROWORKS project will be the following:

- Each partner (that is not a defaulting partner) will have one vote *(applies to all partners)*
- Decisions in the Steering Committee (minimum quorum 2/3) will be taken upon 2/3 of the votes with some exceptions
- Decisions in the Scientific Committee (minimum quorum 60%) will be taken on a unanimous basis of its members

An intention to publish or patent of results emanating from the project must be declared to the Steering Committee, the principles governing the Steering Committee's decisions being stipulated by the Grant Agreement. The decision-making and conflict resolution processes will be further explained in the Consortium Agreement. Nevertheless, the existence of collaborative ties among the partners and the cohesiveness of the Consortium do not pose the threats of major conflict.

Conflict Resolution: Conflicts will be solved at the lowest level possible, and preferably amicably. In the event that Consortium Partners have been unable to amicably resolve any dispute arising out of the work (disagreements, strategic divergence, conflicts of interest etc.), the following steps should be carried out:

- Any member of the Consortium may bring up a major problem. A written statement is required which declares the problem as a major problem and clarifies and identifies it properly.
- The Coordinator tries to solve the problem with the concerned member. If the conflict cannot be solved, the following steps apply.
- The Coordinator raises the issue at the next regular Steering Committee meeting, or calls for a special meeting to solve the problem,
- During that meeting, the different solutions of the problem have to be worked out clearly. The problem can be solved at this level if an agreement is found between the partners.
- If not, a formal vote takes place according to Steering Committee's normal procedure.

Quality Assurance: The project will apply the following reviewing procedure to guarantee the quality of its results:

- All deliverables shall require the approval of the Project Coordinator and PMO prior to transmission to the Project Officer.
- The Work Package Leader shall give his/her initial approval to the draft. Initial drafts of deliverables may be sent to the PMO for initial comments if wished.
- When a final draft is ready, it should be sent by the Work Package Leader to both the Project Coordinator and PMO in parallel for approval.
- The Project Coordinator will be responsible for the technical content of the deliverable and the PMO will be responsible for its compliance with project standards.
- Important deliverables will additionally be subject to a peer review by an expert external to the project.
- The PMO will be responsible for uploading an approved deliverable to the project management web site. The Project Coordinator will take this version forward to the Project Officer.

For each step of the procedure explained above, corrections will be made to the deliverable until the approval of the reviewers is get.

Meetings: An important part of the communication protocol will be the face-to-face meetings or videoconferences. Various meetings have been already planned according to the following basis:

- Kick-off meeting, as soon as the project starts.
- Every six-months a consortium meeting will take place.
- Annual meetings with the EU commission.
- Steering Committee meetings will be held at least once per year
- The Scientific Committee will meet at least every six months.
- WP meetings will be held at least once a month.
- Meetings between the academic participants, the robotic SMEs and end-users every 6-months

An important effort will be made for a confluence of some of these meetings in order to save costs.

Internal Communication Flow: A fluent communication among partners is essential to ensure the correct progress of the project. The communication flow will be bottom-up and top-down through the typical communication methods (such as: e-mail, phone, fax, etc.) and more advanced ICT services (videoconferences and/or teleconferences, net meetings etc.). Besides, an email address group will be created to facilitate the communication with the AEROWORKS's website will include a private section that will also help with the communication between consortium members. Passwords will be facilitated to all partners as well as to the European Commission. All participants will be able upload and download information regarding their concrete task according to their role and responsibilities. Besides, project documents (Grant Agreement, Technical Annex, Consortium Agreement, as well as deliverables and working papers) will be available. Another section will be for meetings, events, seminar, etc. Summary information about the project and public reports will be made available for everybody on the Internet as a means to effectively communicate with parties outside the consortium, such as other European projects or potential users.

Reporting Progress: The Project Coordinator will be responsible for monitoring the progress of the project, achieving the necessary cooperation and maintaining budgetary control. In addition, the Project Coordinator will be responsible for preparing and distributing all the reports required by the Commission at due time. In order to achieve these objectives, all consortium members will actively participate. The WP participants will report (technical progress, results obtained…) to their respective WP leaders. The WP leaders will write an extended report of the activities in their WP according to the milestones and deliverables tables.

- **GANTT charts** will be used to monitor WP/ tasks progress from a timing point of view. This tool will track delays or advances in the R&D work and help ensure that the project objectives are achieved.
- **Milestones and Deliverables tables** will be used to evaluate the progress. Deliverables refer to the results of each WP. These deliverables will be used as evaluation criteria for assessing the status of the WP and its level of success. This evaluation will be made during the Milestones reviews.
- **Annual report:** The Project Coordinator will collect the different reports sent by WP leaders and will be responsible for preparing a formal report to the EC every year. This report will describe the achievements of the project, critically assess its operation and recommend, further actions.

Consortium Agreement (CA): A Heads of Agreement has been drawn up that will form the basis of a *Grant Agreement* which will define regulations and procedures of the work as well as the exploitation of results, ownership of intellectual property, rights and duties of the partners. The partners are committed to sign the CA before the date on which the contract with the Commission enters into force. This agreement will cover: a) the list of participants, b) the management structure, composition, quorum requirements, responsibilities and role, c) specific arrangements concerning intellectual and industrial property rights to be applied among the participants and their affiliates, d) provisional list of pre-existing know-how used, e) major principles and dissemination issues, f) arrangements for the liabilities of the work-share

Promotion of Gender Equality in the Project: The co-ordinator in collaboration with the Ethical Advisor will be responsible for promoting and overseeing the gender equality plan, assisted by the WP leaders. The promotion of gender equity will be done through the following actions: a) inclusion of women in the efforts of the different WPs and tasks of the project (a 30% of women participation is aimed/expected), while b) gender free language is going to be used in the project reports and all other communications.

3.2.4 Milestones

Table 3.2a: List of milestones

No.	Milestone name	Related WPs	Date	Means of verification
1	Acceptance of Performance Evaluation Strategy and Targeted Impact Goals	WP1	M06	Clear and measurable performance indexes and Impact goals are completed and agreed between the industrial partners and EU officer
2	Demonstration of the Aerial 3D Reconstruction Capabilities	WP4,WP5 WP7	M20	Through the collaborative research and development efforts of the AEROWORKS partners within WP4, WP5 and WP7
3	Demonstration of the Aerial Manipulation Capabilities for Maintenance	WP3,WP4 WP5, WP7	M26	Through the collaborative research and development efforts of the AEROWORKS partners within WP3, WP4, WP5 and WP7
4	Demonstration of the	WP3,WP4	M28	Through the collaborative research and

	Autonomous Inspecting and Maintaining single ARW	WP5,WP6 WP7		development efforts of the AEROWORKS partners within WP3, WP4, WP5, WP6 and WP7
5	Demonstration and successful evaluation of the complete AERWORORKS collaborative ARWs team	WP3,WP4 WP5,WP6 , WP7	M35	Through the collaborative research and development efforts of the AEROWORKS partners within WP3, WP4, WP5, WP6 and WP7

3.2.5 Critical Risks and Associated Risk-Mitigation measures

No.	Risk	Impact	Prob. to occur	Contingency plan
WP1.1	Unrealistic Time Scheduling	High	Low	*Common approval of the time schedule and constant tracking will retain delivery times, predict delays and propose alternatives.*
WP2.1	Misleading benchmarks	Medium	Low	*Adoption of approved benchmarks, commonly utilized in other EU projects, as well as our end-user experience will secure the proper project evaluation*
WP3.1	Low manipulation dexterity	High	Low	*Different approaches for dexterous manipulation including different degrees of freedom designs and alternative control laws based on UT expertise will be investigated until high dexterity is achieved.*
WP4.1	Low collaborative mapping accuracy	High	Medium	*ETHZ is already conducting work on that field and several alternatives in terms of utilized hardware, as well as different solutions to the direction of the "virtual stereo rig" will be investigated.*
WP4.2	Vision occlusions during manipulation	Medium	Medium	*Based on ETHZ approach for tight IMU-Vision integration, the system will be alternatively able to rely for significant time on its inertial sensors.*
WP5.2	Low control robustness during co-manipulation	Medium	Medium	*This challenge will be addressed both with respect to the manipulator, as well as the aerial vehicle control, based on the collaborative expertise of our partners in energy-based and hybrid control laws.*
WP6.1	Increased computational complexity of the algorithms	Medium	Low	*This problem will be addressed by considering realistic system requirements, decentralized approaches and based on the advanced onboard hardware of modern aerial robots.*
WP6.2	Low decentralized collaboration performance	Medium	Low	*KTH expertise on multi-robot collaboration and task allocation will lead to the minimization of the performance degradation during decentralized operation.*
WP7.1	Inconsistencies in partners schedule delay integration	High	Low	*The constant supervision of the time schedule, the complementarities among the partners and the involvement of the private partners with experience in out of the box solutions will tackle such issues.*
WP8.1	Low Dissemination/ Publications level	High	Low	*The involved partners contain world-class research leaders. High impact Journal and Conference publications as well as open-source code and dataset releases are among our top priorities.*

3.3 Consortium as a whole

The goal of this project proposal is the successful achievement of the research and innovation actions that will: a) address the theoretical challenges posed from the problem of the collaborative aerial robotic infrastructure inspection and maintenance, b) provide the necessary implementations, algorithms and designs that will enable the realization of the autonomous team of collaborative ARWs, c) validate the potential of such a robotic team with benchmarks, experiments and demonstrations very relevant to the real operation requirements and even with real-life tests. This challenging task requires novel and focused contributions in the fields of multi-robot collaboration, path-planning, perception and estimation, dense reconstruction, control theory, manipulation as well as a demanding integration effort. In order to successfully conduct this endeavour while also addressing the several financial, market-related and societal aspects, we collected leading research groups from the academia, innovative robotic technology developing SMEs and End-Users with different characteristics. The AEROWORKS consortium encompasses the required expertise per partner along with the necessary complementarities as well as a plan to formulate an appropriate value chain. More specifically, the AEROWORKS asset owner (SKL) and our service robotics enterprise (AIR) bring all the expertise, strategic planning, application understanding and capability of proper evaluation of the AEROWORKS robotic solutions. Noteworthy, SKL corresponds to one of the most significant power supply and management industries in Europe, while AIR is a highly innovative joint venture of ALSTOM with years of experience in service robotics. The infrastructure business-oriented background on SKL and AIR is combined with the robotics manufacturing, developing and market experts of ASC and SBX. ASC is among the world leaders on commercial high-performance multi-rotor systems, while SBX is a successful example of technology transfer from a very active research lab (ETHZ-ASL) to the market while they now provide one of the worldwide-first integrated and 'plug-n-play' solutions for sensing and computation with tight IMU-Vision integration. Finally, the research and innovation activities of AEROWORKS built upon the great expertise and planned efforts of our top notch academic partners. Their expertise covers all the spectrum of required research contributions while the existing complementarities ensure that all the knowledge interfaces are well understood. It is also important to highlight that the AEOWORKS partners had (*in several subsets and ways*) previous collaboration experiences with great success. This is for us an important feature since we always target sustainable, but also expanding, collaborations. Overall, the integration of the academic/private-sector AEROWORKS partners will lead to a substantial synergy effect and will provide innovative solutions to the problem of collaborative ARWs for infrastructure inspection and maintenance.

	Manipulation	UAV Design	Control	Estimation	Perception	Path-Planning	Multi-Robot Col-laboration	Teleoperation	Wireless Coms.	Sensors Development	Robots Development	Service Robotics Market share	Infrastructure Management	Infrastructure Services
LTU	✓		✓			✓	✓		✓	✓				
ETHZ		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			
KTH			✓			✓	✓							
UT	✓		✓	✓				✓			✓			
UEDIN				✓	✓	✓								
UPAT		✓	✓				✓				✓			
ASC		✓	✓	✓					✓	✓	✓	✓		
SBX		✓	✓	✓	✓			✓		✓				
AIR											✓	✓		✓
SKL													✓	✓

Table 3.3.1: AEROWORKS' partners expertise

3.4 Resources to be committed

The AEROWORKS consortium has a clear vision of its objectives and therefore is committed to the right allocation of the financial resources at its disposal. The close nature of cooperation in the project is evident by the coherent program that has a joint focus, while distributing tasks among the different partners that have complementary expertise and resources. The clear combination among the Academic partners, the SMEs in the form of technology and service providers as well as the asset owner provides guarantee for a proper combination of resources and strong impact and innovation character of the AEROWORKS project outcome. All the academic partners contribute to the project with their lab facilities, all the SMEs with their production and service facilities, while SKL and AIR will provide the real life infrastructure for a full demonstration of AEROWORKS. The partners are in agreement, ready and capable of providing the self-financing and additional in kind contribution to the project if needed to undertake the extra cost implementation of the project objectives over the three-year duration of the project. The CH partners have a zero funding request from EU. Table 3.4a presents the person-month (PM) dedication per partner for the entire project.

Table 3.4a: Summary of staff effort.

	WP1	WP2	WP3	WP4	WP5	WP6	WP7	WP8	Total PMs
1. LTU	30	6	4	8	23	15	13	9	**108**
2. ETHZ	0	5	4	34	17	18	20	6	**104**
3. KTH	0	3	0	0	6	41	7	3	**60**
4. UT	0	3	27	13	13	7	4	2	**69**
5. UEDIN	0	4	0	64	0	6	4	2	**80**
6. UPAT	0	3	8	0	32	11	4	6	**64**
7. ASC	0	6	6	3	17	0	15	4	**51**
8. SBX	0	6	4	18	1	2	11	4	**46**
9. AIR	0	10	0	0	0	0	6	5	**21**
10. SKL	0	11	0	0	0	0	6	6	**23**
Total PMs	**30**	**57**	**53**	**140**	**109**	**100**	**90**	**47**	**626**

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