FINAL REPORT

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[1] Usually the contact person of the coordinator as specified in Art. 8.1. of the Grant Agreement .

[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

1 FINAL PUBLISHABLE SUMMARY REPORT

1.1 AN EXECUTIVE SUMMARY

The main objective of CableBOT project is the development of a new generation of modular and reconfigurable robotic devices that are capable to perform many different steps in the life-cycle stages of large-scale structures.

The CableBOT project deals with a novel methodology for designing, developing and evaluating cable robots customised for the automation in large-scale auxiliary processes. Parallel cable robots extend the payloads and workspace of conventional industrial robots by more than two orders of magnitude.

Three key technologies will be developed to enable the vision:

- Design of Cable Robot: Software tools to design the layout and geometry of cable robots. The ad-hoc connection of groups of winches to different end-effectors creates different setups for cable robots in order to achieve flexibility and reconfigurability.
- Industrial Process Planning: Simulation of cable robots to verify the operation of cable robots in environments with large-scale structures
- Control Algorithms and Systems: Distributed control and kinematic transformation to operate modular cable robots such as grids of cable robots under industrial requirements.

The combination of these technologies in an integrated robotic system results in a versatile system. CableBOT will demonstrate the potential of such automated systems for life-cycle maintenance and repairing of aircrafts and to introduce automation in life-cycle applications in the construction industry such as handling of beams. Both applications are characterized by the fact that the state-of-the-art automation can hardly be used due to manoeuvrability of heavy and large structures and risks associated. The results are feasible for many other fields including large-workspace movements of products, with impact in logistics, transport, and warehousing.

1.2 A SUMMARY DESCRIPTION OF PROJECT CONTEXT AND OBJECTIVES

In recent years, the application of robotics to automation of large-scale post-production (i.e. aircrafts, ships, construction) is having difficulties to carry out efficiently all life-cycle stages (i.e. repair, maintenance, replacement and handling) because the robotic systems designed for the majority of large scale products do not allow to design flexible automation solutions suitable for wide ranges of industrial processes. Furthermore, robotic or automated systems must compete with existing highly flexible manual labour-based solutions but with their corresponding low productivity, which contrast to the widespread use of robotics in the small-scale industries. Others limitations for robotics to be commonplace in large-scale post-production sites are the economic cost of investment and larger power needs than current solutions require.

Robotization of production is one of the main solutions to lower manufacturing costs in order to keep production in Europe. Due to some limitations such as the limited workspace of commercial robots, or the huge cost of the civilian engineering needed for large Gantry robots, manipulation over large workspaces is still done with traditional non automated cranes.

Cable-driven parallel robotics **aims** at providing smart automated solutions over large or very large workspaces, at a reasonable cost. Cable-driven parallel robotics intend to:

- Bring **flexiblility**
- **Improve** operational efficiency and functionality of the product
- **Reduce** the overall life-cycle costs
- Be used in **complex manipulation** tasks and in multiple industrial sectors

The **advantages** of the cable-driven parallel robots are:

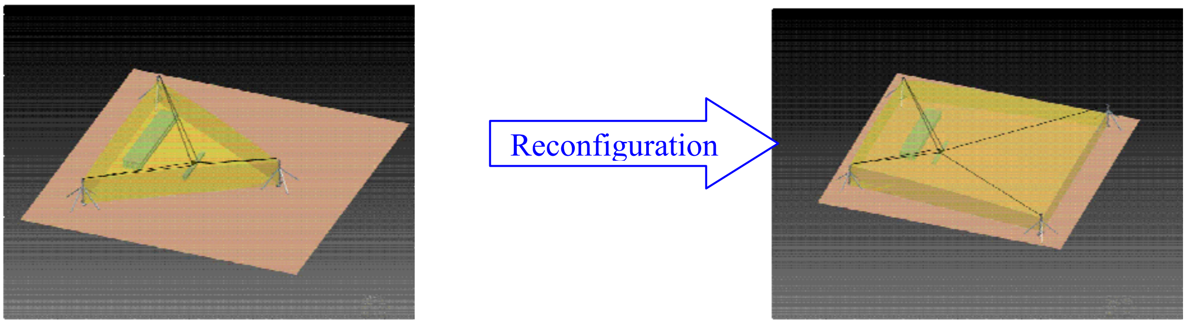
- Manipulation of heavy payloads over large workspaces
- Control of the 6 degrees of freedom of the manipulated part
- Automation of manipulation, assembly tasks, manufacturing operations, ...
- Manual control of the smart crane by means of a remote controller if required
- High ratio workspace/footprint, low visual impact
- Actuator placed outside the workspace (easy protection from radioactive, chemical or explosive environments,…)

The **challenges** of the cable-driven parallel robots to be tackled in CableBOT project are the followings:

- Cable interferences
- Cable only works with tensile stresses
- Redundancy
- Sagging, elongation
- Vibrations
- Cable breaking

The CableBOT project deals with a novel methodology for designing, developing and evaluating cable robots customised for the automation in large-scale auxiliary processes. Benefits obtained with the implementation of cable robotics include an increase of the post-production efficiency, a wider range of product target, light and reconfigurable structure mechanisms and adaptable and more flexible assistive systems.

Reconfiguration of kinematics of parallel cable robots allow to develop configurations for multiple applications and to cover more process workspace. Furthermore, the relative ease of reconfiguration of the cable robot kinematics causes an increase of the flexibility to achieve different life-cycle tasks over large-scale products. Most of the cases, a single robot or manipulator configuration is not able to cover all the process workspace. Therefore, the intrinsic flexibility of a wire robot decreases the cost of the maintenance massively. Hence, one of the challenges of CableBOT project will be the optimisation of reconfigurable cable robot architectures in order to maximize the workspace required in large-scale processes and minimize the number of possible kinematics configurations needed to cover all the workspace process.

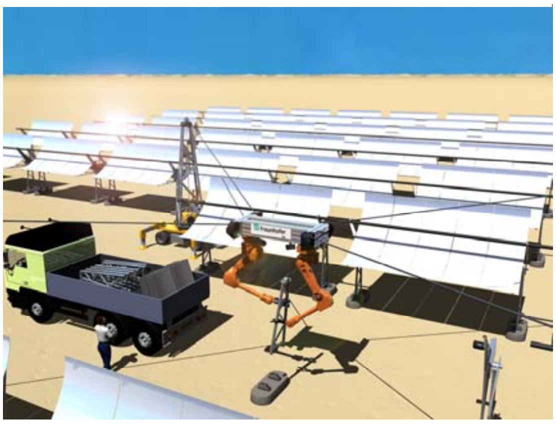
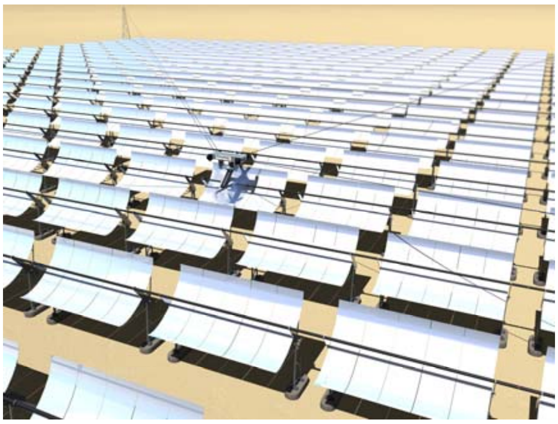


Flexibility by the use of reconfigurable cable robots

On the other hand, the optimum cable robot architectures in terms of process workspace covered may not be the best for all the process conditions (i.e. velocity and payload) which at the same time depend on the cable robot dynamics. Then a validation of the cable robot performance for large-scale post-production will be required because cable robots on multiple kinematics configurations show different payload lifting capacities. Thus, another challenge is to simulate the large-scale post-production process assisted by parallel cable robots in order to validate the kinematics fulfil the life-cycle stages. Furthermore, simulations will be carried out to validate the performance at industrial user scenarios.

Once the configurations of kinematics of parallel cable robot and the process conditions are validated, the feasibility of the controller must be considered. There are many challenges on the control of cable robots, e.g. many of the parallel control algorithms have to cope with force disturbances in open loop, the interaction with the productive environment makes the trajectory generation difficult. Finally, the development of an ergonomic and assistive interface with the human operator is an open topic.

The customisation of cable robots to be used in different large-scale processes is possible by using different types of end-effectors. These can be connected, interchanged and quickly released or fastened. End-effectors can be customised and task-targeted to perform specific life-cycle operations such as inspection, preparation, stripping, cleaning or painting. Moreover, mobile platforms can used to carry human workers to perform manual tasks. Another end-effector example is the use of a robot arm mounted on the mobile platform for complex manipulation tasks and larger workspaces covering. A unique ability to perform accurate, flexible, sensor-based manipulation and the ability to cover efficiently huge workspaces is thereby obtained with improved reachability in cluttered areas or over complex-shaped parts.

Automation and customisation provided by the use of reconfigurable cable robots

The **main objective** of CableBOT project is the development of a new generation of modular and reconfigurable robotic devices that are capable to perform many different steps in the life-cycle stages of large-scale structures.

Three key technologies have been **developed** to enable the vision:

- **Design of Cable Robot**: Software tools to design the layout and geometry of cable robots. The ad-hoc connection of groups of winches to different end-effectors creates different setups for cable robots in order to achieve flexibility and reconfigurability.
- **Industrial Process Planning**: Simulation of cable robots to verify the operation of cable robots in environments with large-scale structures
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The combination of these technologies in an integrated robotic system results in a versatile system. CableBOT will **demonstrate the potential of such automated systems for life-cycle maintenance and repairing of aircrafts and to introduce automation in life-cycle applications in the construction industry such as handling of beams.** Both applications are characterized by the fact that the state-of-the-art automation can hardly be used due to manoeuvrability of heavy and large structures and risks associated. The results are feasible for many other fields including large-workspace movements of products, with impact in logistics, transport, and warehousing.

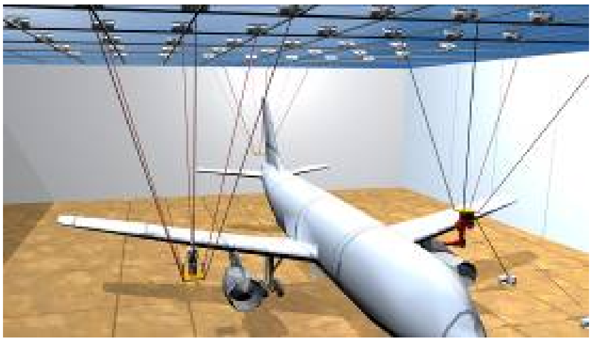
Within CableBOT two fields of application are targeted: Aircraft life-cycle maintenance in the aerospace industry and the construction beams post-production handling. Both applications are characterized by the fact that the state-of-the-art automation can hardly be used due to manoeuvrability of heavy and large structures and risks associated.

First Industrial Use Case: **Aircraft life-cycle maintenance in the aerospace industry.** Aircraft maintenance operations are performed in two levels: i) Regular inspections during exploitation: visual local checks, reparation when and if necessary and ii) Schedule maintenance visits, 4 to 5 times during exploitation phase: this is a complete visit to check the structural and external health of the aircraft. Operations currently performed manually and in hostile environment are as follows: Preparation, masking; Paint stripping (manual, chemical), removing sealant beads; Cleaning; Inspection, reparation; New sealant beads (orbital and longitudinal) application; Painting (primer, top coat application, clear coat and decoration).

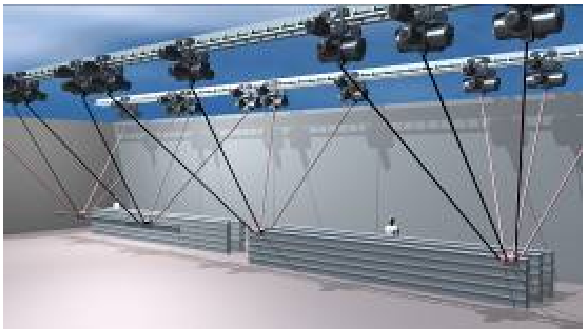
All these essential and necessary maintenance operations involve immobilisation of aircraft. Furthermore, actual maintenance operations involve several telescopic gantries or scaffoldings (dedicated to a hangar for one type of airplane) to allow simultaneous work on different surfaces of the same airplane. Thus, parallel cable robots reconfigurability will allow a more agile removing, painting and repairing work. Moreover, large scale cable robots can be used to perform parts of the maintenance operations procedure automatically and multi task phases of the maintenance (i.e. multi layers with different coatings and also with surface cleaning). Furthermore, mobile platforms will be design for other types of manual work to be performed such as surface decoration or for visual and quality inspection.

Second Industrial Use Case: **Handling and Assembly of construction beams**. Handling of construction structures and, more specifically, of large civil structure components is described in the context of ACCIONA industrial activities. Two tasks are primarily targeted, namely, the displacement of large structure components and the positioning of such structure subparts for assembly.

Cable robots can be used in the construction industry to automatically handle large construction beams with weights of 10-15 tons and a length of some 10 meters. A cable robot can handle large beams by sharing the load between the cables. The cable robots can flexibly be partitioned into two or three smaller cable robots which can handle shorter beams at different stations within the same industrial setting. Furthermore, the cable robot allows changing the positions of the fixtures at the beams. Since cable robots are able to control the six degree-of-freedom motion of the beams, safety in immediate proximity can be increased since load swinging can be eliminated and positioning can be done in a smooth way. Complex manipulation tasks can be significantly improved since cable robots can move faster and safer to precisely reach a given target position. Collision detection and position control are supervised by the integrated control system.



Aircraft life-cycle maintenance in the aerospace industry



Handling and assembly of construction beams

1.3 A DESCRIPTION OF THE MAIN S&T RESULTS/FOREGROUNDS

The **main results achieved** in the Cable BOT project are listed next:

1. **Design of Cable Robot (developed in WP1)**:
    - Conceptual mechanical, electrical and control system design guidelines of cable driven robots
    - Software tools for the design and management of cable robot reconfigurations
    - Design validation

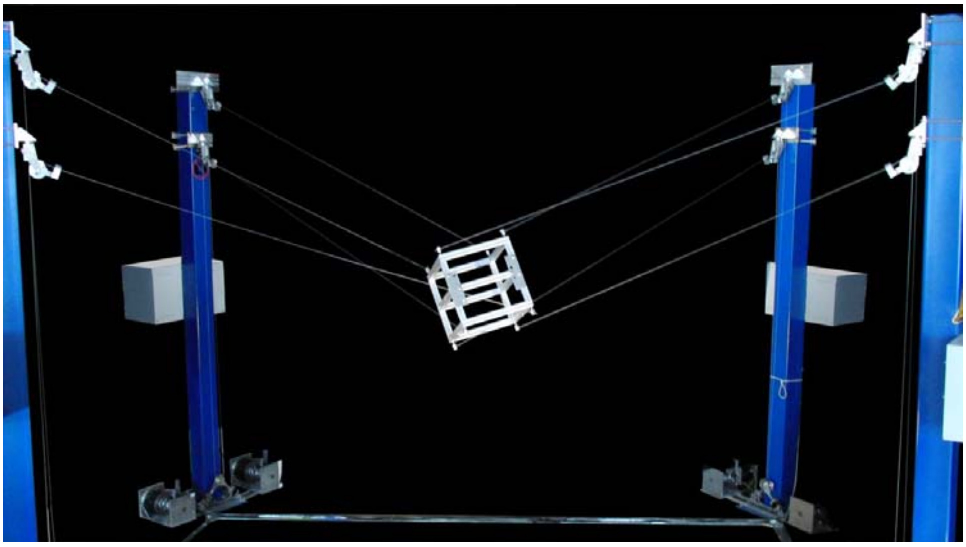
2. **Industrial Process Planning (developed in WP2)**:
    - Cable-driven robot simulation framework based on XDE which offers the user two main features: simulation and control of cable driven robot with XDE and MATLAB/Simulink. The simulation allows validation of the application process: simulation of the motions of the robot and execution of the tasks, validating workspace, detecting collisions, accessibility, maneuverability etc.

3. **Control Algorithms and Systems (developed in WP3)**:
    - Kinematics transformation: Real time kinematic codes to solve the forward and inverse kinematic transformation for different kind of cable robots
    - Force control strategies tested in simulation and in real prototype
    - Calibration strategies for reconfigurable robots
    - Use of Industrial controllers: Beckhoff controller (TwinCAT3 software) or B&R controller (Automation Studio software)
    - SEGESTA robot updated with reconfiguration capabilities
    - Human-Machine Interface. Automatic, manual, reconfiguration and calibration modes integrated in the controllers
    - Methods for reliable and safe operations: Safe motion planning with collision detection and singularity avoidance

4. **Prototypes validated in the two industrial applications (developed in WP4)**
    - IPANEMA robot to validate the feasibility of using cable robots in aircraft maintenance operations
    - COGIRO robot to validate the feasibility of using cable robots in handling and assembling of construction beams

Before explaining in detail the results achieved in the CableBOT project, a **description of the prototypes developed by the CableBOT RTD partners** is given. All these demonstrators have been used to achieve the listed results.

REELAX8 – TECNALIA & CNRS-LIRMM



Max. payload: 10kg
Max. platform velocity: 1.6m/s
Repeatability : 1mm (in ReelAx6 three-post suspended configuration)

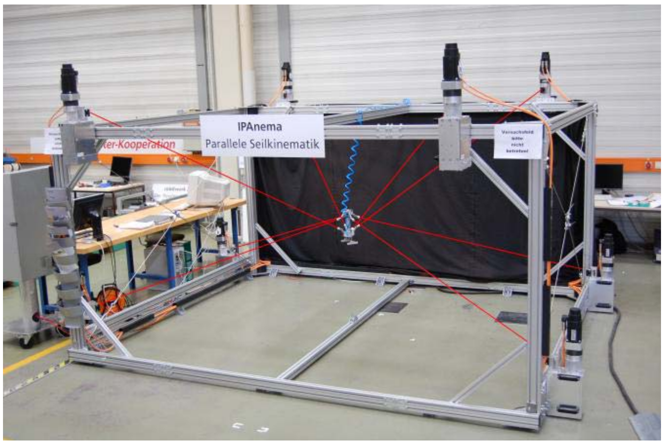
Dimensions: (length x width x height) 4m x 3m x 3m
Cables Material: Steel; Diameter: 1.2mm
Controller: dSpace-System

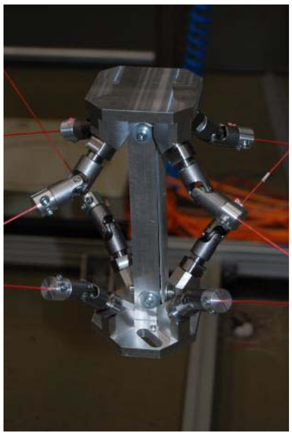
COGIRO – TECNALIA & CNRS-LIRMM

Max. payload: 500 kg
Max. platform acceleration:
linear acceleration: ≈ 6 m/s2
angular acceleration ("all direction"): ≈ 14 rad/s2
angular acceleration (about vertical axis only): ≈ 45 rad/s2
Max. platform reference point velocity: 3 m/s
Mean positioning accuracy: 50mm
Mean positioning repeatability: 3mm

Dimensions: (length x width x height): 15x11x6 m3
Workspace up to 80% of the footprint
Cables Material: Steel; Diameter: 4 mm
Industrial controller: B&R Automation

IPANEMA 1– Fraunhofer -IPA

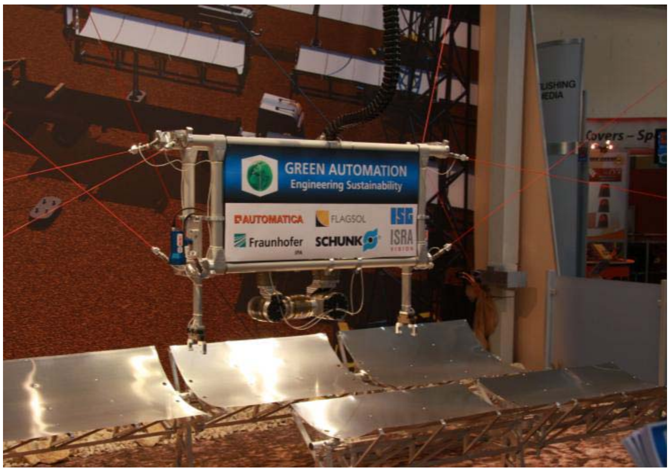




Max. platform acceleration: 100m/s2
Max. platform velocity: 10m/s
Position repeatability: 0,5 mm

Dimensions: 4x3x2m
Cables Material: Dyneema, Diameter: 2,5 mm
Industrial Controller: Beckhoff Twin-CAT3

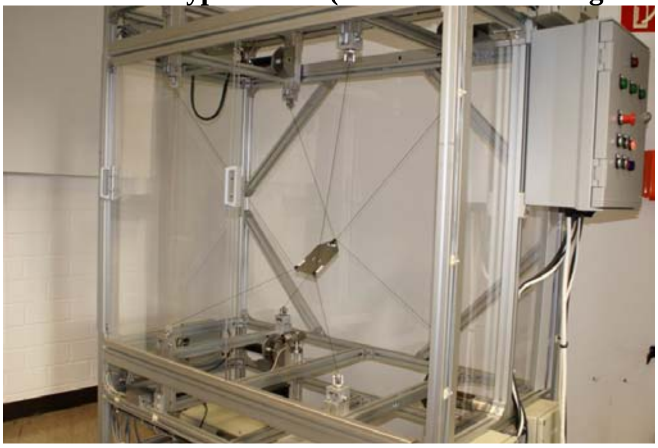
IPANEMA 2– Fraunhofer –IPA



Max. platform acceleration: 25m/s2
Max. platform velocity: 2.5m/s
Position repeatability: 0,5 mm

Dimensions: 9x7x5,5m
Cables Material: Dyneema, Diameter: 2,5 mm
Industrial Controller: Beckhoff Twin-CAT3

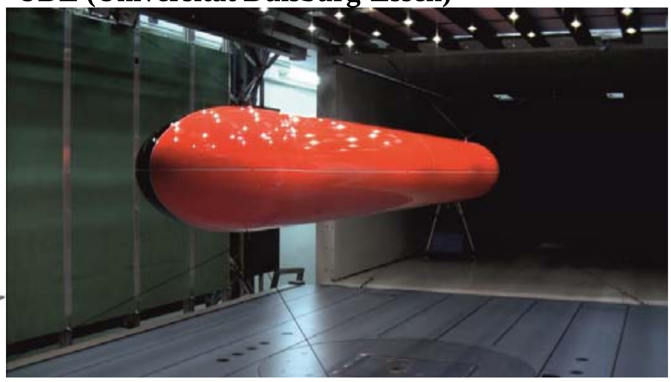
SEGESTA Prototype – UDE (Universität Duisburg-Essen)



Max. payload: 0,5 kg
Max. platform acceleration: 100 ms-2
Max. platform velocity: 8 ms-1
Absolute positioning accuracy: 1 mm

Dimensions: (length x width x height) 2 x 2,1 x 0,9 m
Cables: Material: Dyneema; Diameter: 1 mm
Industrial Controller: Beckhoff Twin-CAT3

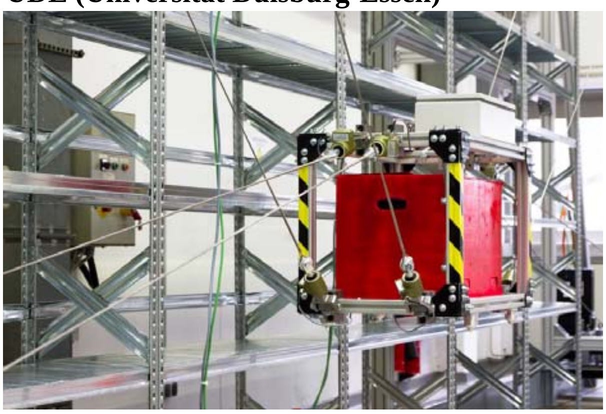
SHIP SIMULATOR – UDE (Universität Duisburg-Essen)



Max. payload: 100 kg
Max. platform acceleration: 150 rads-2
Max. platform velocity: 10 rads-1
Absolute positioning accuracy: 0,02 rad

Dimensions: (length x width x height) 5,3 x 3,8 x2,2 m
Cables Material: Dyneema, Diameter: 3 mm
Controller: dSpace-System

STORAGE SYSTEM - UDE (Universität Duisburg-Essen)



Max. payload: 20 kg
Max. platform acceleration: 5 ms-2
Max. platform velocity: 6 ms-1
Absolute positioning accuracy: 3 mm

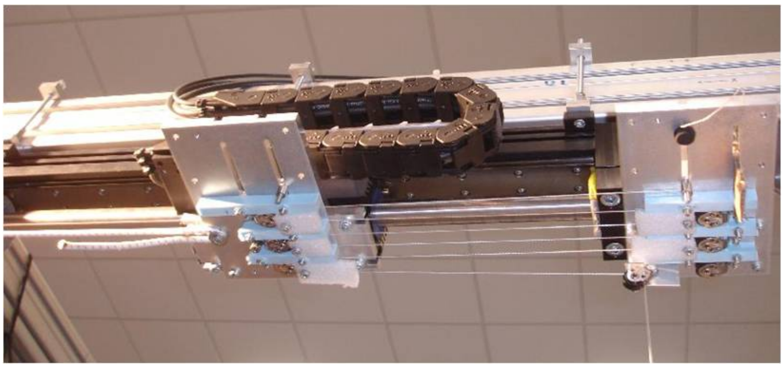
Dimensions: (length x width x height) 10 x 2 x 5 m
Cables Material: Dyneema, Diameter: 5 mm
Controller: dSpace-System

MARIONET FAMILY- INRIA

MARIONET-CRANE is a very large robot intended to be used, for example as a rescue crane for natural catastrophes. In such an application accuracy and speed are not at premium while lifting ability and easy deployment are.

MARIONET-ASSIST is a relatively large robot with a workspace of 4x4x3 meters intended to be used primarily for lifting elderly and handicapped people but also it should be accurate enough for manipulation (e.g. picking a fork in a drawer).

MARIONET-REHAB is a medium-sized robot with a workspace of 3x2x2.5 meters intended to be used for rehabilitation and ultra fast pick and place. For such tasks, accuracy, speed, reversibility are at premium while the amount of available force at the end-effector is less important.



MARIONET-VR is a large robot with a workspace of 12x6x3 meters intended to be used for rehabilitation, entertainment and task simulation in an immersive room. It uses linear actuators with a stroke of 2 meters that is amplified by a pulley system. The maximal speed of the actuator is 5m/s with a maximal force of 700N. Hence the robot is able to lift approximately 200 kg.

MARIONET-SCHOOL is a pedagogical robot which is intended to be used for dissemination purposes.

Next, the main results obtained in each WP are explained.

WP1. Definition of the architectures of cable robots for their application in industrial environments

The first work package (WP1) of CableBOT deals with the definition of the architecture of cable robots dedicated to post-production and other auxiliary processes targeted by the project. The two main industrial applications considered in CableBOT are the handling of large civil structures and the aircraft life-cycle maintenance. In such contexts, modular and reconfigurable parallel cable robots are expected to satisfy the need of flexible robotic solutions that can work with products having varying dimensions and characteristics.

The main objectives of WP1 have been fulfilled. Indeed, a requirement analysis for industrial applications of cable robots has been proposed in Task 1.1. More specifically, this requirement analysis deals with the two use cases considered in the framework of CableBOT, namely the handling of large civil/construction structure components and tasks of aircraft life-cycle maintenance. Then, in the framework of Tasks 1.2 and 1.4, effective conceptual and design solutions to build cable robots possibly including modularity/reconfigurability have been proposed. Finally, in Task 1.3, tools to design and handle (reconfiguration planning) the continuous or discrete sets of possible cable robot layouts made possible by modularity and reconfigurability have been proposed.

Work done in Task 1.1

On the one hand, the handling of construction structures and, more specifically, of large civil structure components was described in the context of ACCIONA industrial activities. Two tasks are primarily dealt with, namely, the displacement of large structure components and the positioning of such structure subparts for assembly. The main characteristics of four such structure elements were provided in D1.1 in order to illustrate the diversity of structure elements to be handled. A particular workshop, located in Madrid, Spain, was also briefly presented. It allowed the specification of dimensions and constraints related to an existing facility.

On the other hand, aircraft life-cycle maintenance was dealt with. Some of the corresponding tasks are expected to be possibly automated (at least partially) by means of cables robots. These tasks are chemical and manual stripping, cleaning, painting and drying of aircraft surface. Manual stripping, which is presently done with sanding machines, requires a direct contact with the airplane surface. It is thus especially delicate because of the higher probability of damages to the airplane. Other tasks involved in aircraft life-cycle maintenance, e.g. masking, are left aside. Indeed, the issues related to their automation by means of cable robots were considered to be too difficult to be dealt with in the framework of CableBOT. The replacement of currently used telescopic platforms by parallel cable mechanisms was also mentioned as a possible application of cable robot technology to aircraft maintenance.

For both use cases, preferred scenarios for modular/reconfigurable cable robot implementations were introduced in deliverable D1.1. These prospective scenarios are mainly conceptual, representing first ideas of how cable robots could be implemented to satisfy the need of flexible machines fulfilling the industrial application requirements detailed in this report. In D1.1, references to safety and regulation standard texts were also provided.

As a conclusion, the objectives of Task 1.1 have been achieved apart from some of the expected cable robot characteristics and performances, required to achieve the targeted industrial applications, whose specifications would need to be enhanced in the framework of the direct implementation of a cable robot in an industrial environment.

Work done in Task 1.2

In Task 1.2 the conceptual mechanical design of cable robots was dealt with. Its focus was directed toward the realization of industrial machines. The design of these machines should follow classifications and state of the art requirements defined in Standards. The main Standards considered were those of hoisting appliances such as cranes. Indeed, these machines use the same principal components as cable robots, namely, winches, cables and associated routing elements as well as means of cable connection directly to a load or to a holding or handling system. Moreover, this category of machines corresponds, or at least is directly related, to the appliances currently used in the two use cases considered in CableBOT. Accordingly, conceptual mechanical design guidelines to build modular and reconfigurable cable robots were proposed. Moreover, it was noted that, on the one hand, most of the various cable robot prototypes of the CableBOT consortium partners possess several, if not most, of the main characteristics required for industrial machines.

On the other hand, it was shown that components specific to cable robots should be designed and also that some conceptual design ideas and rules could have been applied to these prototypes. As an example, we mentioned cable reeving means to effectively achieve heavy payload capabilities.

General guidelines for the conceptual design of electrical connections and of the control system were also provided. The considerations were mainly of a general nature since more specific design considerations could only be formulated being given specific manufacturer hardware requirements and capabilities.

In the work done in Task 1.2, the Standards considered were pertaining to cranes and hosting appliances. Depending on the application at hand, other Standards may have to be followed. In the case of the handling of large civil or construction structure components, the Standards considered in Task 1.2 should be the most relevant ones. In the second use case considered in CableBOT, the aircraft life-cycle maintenance, if workers can embarked on the mobile platform to achieve manual aircraft maintenance operations, other standards shall also be considered.

From a general point of view, the conceptual design of a cable robot should also include the layout of the cable connections to the mobile platform or to the load in case the latter is directly handled. This fundamental topic was not discussed in the deliverable D1.2 since it is directly and intricately related to the way a cable robot is designed and/or reconfigured to meet the requirements of a given application or task. For non reconfigurable robots, tools allowing the choice of a cable layout were proposed in the current state of the art of cable-driven parallel robot academic research. Besides, the management of reconfigurations and of modularity is dealt with in Task 1.3 of WP1.

Finally, an issue identified in the framework of Task 1.3 is the determination of the Safe Working Load (SWL) of the main components of a cable robot, e.g. the winches. Being given the SWL of the cable robot, that is to say the rated capacity clearly indicated on the machine, the main issue is the determination of the SWL of the winches and other critical components of a cable robot such as the cables themselves as well as the cable routing elements and mechanisms. Indeed, these SWL being determined, it should then be possible to apply standard design requirements and rules based on the mechanism classification groups given in deliverable D1.2. These classification groups should be determined according to the application and context at hand. The issue of determining these components SWL is mostly critical in case of modular or reconfigurable cable robots for which the tools proposed in Task 1.3 can be used.

Work done in Task 1.3 (Deliverables D1.3 and D1.4)

The first goal of Task 1.3 was to describe the preferred robot implementations for the targeted industrial applications. It appears clearly that the preferred geometry, evidently task dependent, is however highly influenced by the available infrastructure. Hence, the second objective, the preliminary versions of the reconfiguration and modularity management planning tools, has to be extremely flexible in order to accommodate the very large variety of cases that may occur in practice. The background and initial implementations of these tools were described in D1.3 and it was shown that these tools may indeed manage a large variety of cases.

In more detail, in the preferred implementations for the two tasks retained in the CableBot project, handling of structure elements and aircraft maintenance, it appeared that two main possibilities can be considered:

- Having the winches on an overhead bridge crane is a good implementation (possibly with some constraints on the direction of motion).
- Having a grid of fixed winches on the ceiling and possibly on the ground.

The preliminary versions of the modularity planning software were also described. The purpose of this software is to determine what should be the geometry of the CableBot crane so that it is able to perform safely and with guaranteed performances a pre-defined task. Two approaches were proposed and described. One relies on optimization tools while the other one is mainly based on interval analysis. Both are able to deal with the preferred implementations but they differ in the way they manage the requirements, in the computation time and in the possibility of taking uncertainties into account. These two approaches are complementary and they are able to manage application problems in a very flexible way.

While the preferred robot implementations for the targeted industrial applications were described in D1.3, along with the preliminary works on the implementation of the reconfiguration and modularity management planning tools, deliverable D1.4 presented in detail the tools developed and the methods used in the implementations. It also contained examples of uses of these tools in a variety of cases, including the preferred robot implementation of the targeted industrial cases.

Two types of tools to find suitable architectures of cable robots emerged and coexist. In a first part of deliverable D1.4, a tool with two operating modes was presented. The first one aims to assess configurations while guaranteeing the suitability of the configuration to a given application, for an arbitrary precision and a given set of errors. The second operating mode finds out an extensive set of configurations for a given application, with the same guaranty than the first mode. In a second part of deliverable D1.4, we presented a set of tools which aims at finding optimal CDPR reconfigurations in regards of a given set of criteria, for a given application. Two approaches were proposed, either fast, gradient-based optimization tools for both offline and online (real-time) reconfiguration, or reliable, derivative-free algorithms for offline reconfiguration.

The main difference in the two types of proposed tools lies in their objective: Either a throughout analysis including performance criteria (errors) and accounting for uncertainties, or an optimization approach. This difference branches out in practical ones, such as computation time or the way requirements from the application are treated. These two approaches are mostly complementary enabling a very flexible approach for any given application. Indeed, as one provides certification of performances, the other one offers the end-users fast computation solutions and can be applied to both offline and online (real-time) reconfigurations. Depending on the need of specific applications, one can use either approach to find suitable design and planning solutions for the CDPR.

The development and implementation of tool sets enabling modular/reconfigurable cable robot operations remains a challenging tasks which is almost not discussed in published cable robot research studies. The two different tool sets described in deliverables D1.3 and D1.4 are functional and results are already available. However, they can still be improved in different ways, these improvements being still a work under progress. The future potential industrial uses would now require the validation of these tools, as well as the development of GUIs to facilitate their use.

Work done in Task 1.4

The conceptual design of a cable robot includes notably the cable number and layout, the reconfigurability and/or modularity type, the cable routing components and the nature of the transmission between the motor and the drum of each winch. Once a cable robot conceptual design is decided, the typical detailed design decisions that have be made are the component dimensions according to mechanical criteria (stress, life…), the selection of suitable cables, transmission components, actuators, etc.

On the one hand, these detailed choices are notably based on the required maximal tension each cable has to sustain (in static and dynamic conditions of use), that is the SWL of the cables. This maximal cable tension should be obtained by means of workspace and wrench-feasibility analyses as usual in the state of the art of cable robot research. In the case of modular/reconfigurable cable robots, these classic analyses may need to be completed by the tools developed in Task 1.3 (deliverable D1.4) because the actual maximum cable tension depends on the way modularity/reconfigurability is managed. Moreover, the maximal cable tension values should also be ascertained by means of simulations (WP2) or by using more advanced cable models (e.g. elastic catenary) if not used in the first place. In deliverable D1.5, it was assumed that the maximal cable tension was known.

On the other hand, the detailed choices listed above are also based on the classifications of cable robots as hoisting appliances and of its winches and various elements as individual mechanisms and components, as it forms the basis to design cable robot according to standard requirements (Task 1.2, deliverable D1.2). Apart from the maximum loading, the classification of each component stems from load range, load cycles, hours of operation and risk. All of these factors are application dependent.

WP2. Detailed simulation of cable robots performance

The main goal of WP2 is to find a suitable methodology and the suitable software tools to simulate the different phases in the life-cycle of the cable driven robots. Those phases are:

- Conceptual design of the cable-driven robot application: from the application requirements, i) definition of the best candidate architecture, defined by number of cables, position of the anchor points, payload mass,…; ii) definition of the workspace and the hardware limits (data that limit the forces or the power in the robot); iii) trajectory simulation
- Design of the control system: virtual testing and optimization of the control laws, before their implementation in real robots.
- Validation of the application process: simulation of the motions of the robot and execution of the tasks, validating workspace, detecting collisions, accessibility, maneuverability etc..
- Safety in immediate proximity of robot platform and anywhere within the free space in which the cables of the robot move: evaluation of potential risks in case of failure of some elements of the robots (robots or cable for example).

Each of these phases imply different requirements to be simulated, and thus, can be achieved by different sets of simulation tools. Therefore, in the CableBOT project, the efforts dedicated to simulation will be focused to provide adequate simulation tools and methods for each of these phases. We will not develop a single huge simulator that would allow performing everything, but four sets of software tools and methods, potentially independent between them and dedicated to a given phase of the cable-robot application development lifecycle.

Work done in Tasks T2.1 and T2.2

In tasks T2.1 and T2.2 partners worked to define the suitable methodology and software tools to simulate the different phases in the life-cycle of the cable-driven robots.

One of the major differences between a traditional robotic system and cable-driven robot is the use of cables. Indeed, for traditional robotic systems, conceptual and detailed designs can be performed with CAD tools and their simulations with a robotic simulation environment that integrates a physics and graphical engine (such as ROS/GAZEBO or Blender for robotics). Most of the latter simulation tools are suitable for simulating rigid bodies. However, in the case of the cable-driven robots, the cable itself cannot be considered as a rigid body and alternative simulation tools are needed to be defined.

The *modelling and simulation of cable-driven robots is a challenging task***.** Although cable-driven parallel robots share a number of properties with classical robots (especially with parallel robots) the use of cables as transmission elements introduce a number of specific properties that are not respected in other simulation or modelling frameworks. Only few simulation software tools for kinematics and multi-body dynamics deal with cables as transmission elements and even fewer include robotic concepts such as workspace.

The capabilities and limitations of the tools currently used to design cable-driven robots were analysed. The selection of the tools for simulating cable-driven robots were done taking into the limitations of the design tools currently used.

A benchmarking of available software tools that could fit in one (or more) of the simulations required was performed and a pre-selection of potential simulation tools was done. The pre-selected potential simulation tools were evaluated and after the evaluation, CableBOT partners decided to go on working with XDE software tool, Dymola and Matlab/Simulink.

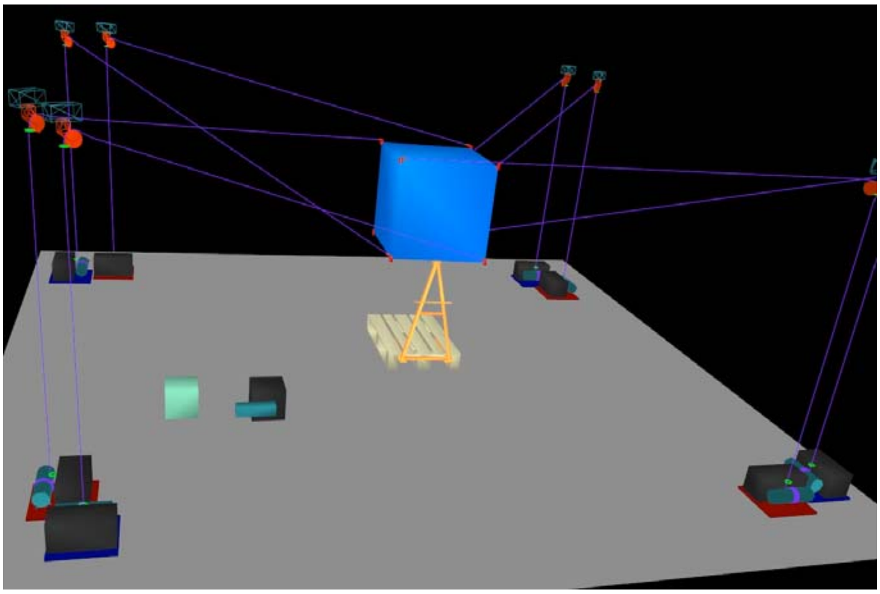
XDE is a physics simulation software environment fully developed by CEA LIST. It is the result of 10 years of software development in the Virtual Reality field. XDE is based upon a physics simulation kernel that handles rigid and deformable bodies, in particular cables, multibody systems with kinematic constraints and intermittent contacts and fluids: liquid, gas or smokes

Work done in Task 2.3

In Task 2.3, partners dealt with the simulation of the cable robots and aimed at obtaining a tool able to simulate concepts of cable robot by implementing these robots, the environment and the robot controller in a use case scenario.

The simulation has to compute the collision and interference between cables, objects and mechanical kinematic structures such as winches or pulleys. The dynamic of cable has to be taking into account by implementing the elasticity, the sagging, the winding with high load or high speed. The simulator has to be able to be used with a control device to test control strategies and study the system behaviour such as apparition of undesirable vibrations.

Partners have developped a XDE framework with C++ classes allowing to create a simulation of a cable robot composed of elementary component such as winches, pulleys, cable attach and mobile platform. We can create as much cables as needed and attach these cables to any object, this object can be a mobile platform or any object in the scene such as a piece to assemble with another one (Acciona use case). The winches are implemented in a such way that it’s possible to apply a torque on the rotating reel. The cable attaches allow the feedback of the cable tensions. The platform position, winches rotating position and speed are also available.



Complete CoGiRo robot scene in XDE

Partners have developped an interface between Matlab/Simulink and XDE simulator which allow to a Simulink control model to interact with the simulated robot. Sequence of motion, motion generation, inverse kinematics and PID control have been implemented to control the cartesian platform position. This combinaison of XDE simulation and Matlab/Simulink controler is able to simulate the CoGiRo robot displacing a palette.

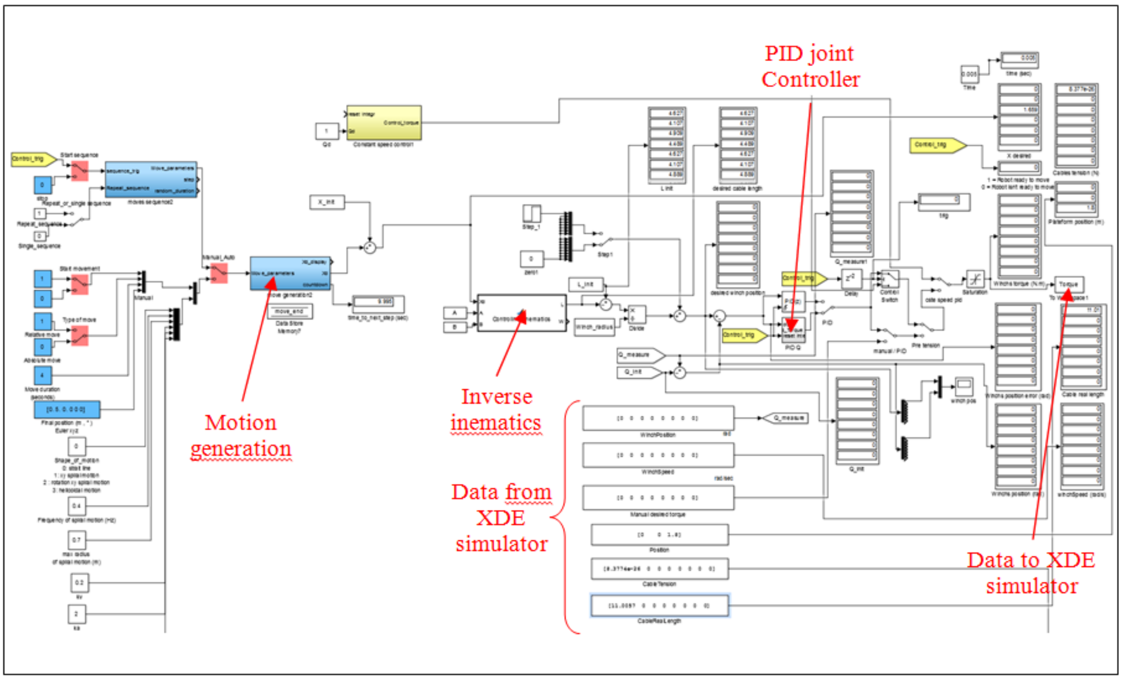


Figure: Simulink controller

The cable attach are able to be unweld from the platform, this allow to show the behaviour of the system in case of cable rupture.

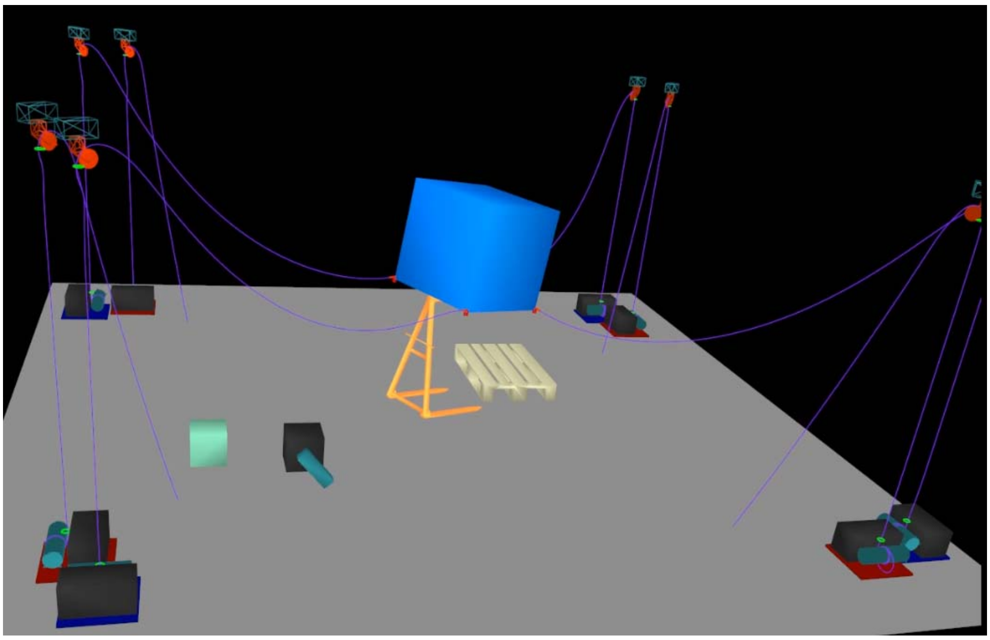


Figure: Simulation of cable failure on the CoGiRo robot.

The process simulation gives the chance to do rapid generation of kinematics, checking workspace, test auto-calibration procedures, do motion generation, control of the process, test user interaction with the robot.

Work done in T2.4.
In Task 2.4, partners identified the main risks associated to the operation of cable robots in industrial environments, collected the existing regulatory in this matter and defined a list of recommendations and requirements for a safety operation of the cable robots in the scenarios presented. The objective of Task T2.4 is to evaluate the safety of cable robots when operating in industrial environments such as the ones presented by EADS and ACCIONA during the project. Due to the complexity of the scenarios, the evaluation of the safety has been divided in the following sections:

- Risk analysis: The risks associated to the operation of cable robots in industrial scenarios can be divided depending on the source of the risk. If the risk is linked to the industrial installation itself they are identified as traditional risks, since when they are caused directly by the presence of the robots in the scenario can be classified as specified risks (e.g. collision, entrapment, projection…). An excel sheet to evaluate the hazards listed in EN 1050:1997 for CDPR has been prepared in collaboration with Task 2.5.

- Revision of the regulatory framework: The main objective in this section is to define the existing regulatory framework in terms of safety that the cable robots will have to deal with. The study includes an analysis of the existing regulatory framework focused on safety issues applied to robots in general, the specific for cable robots and also the regulatory framework applied to the industrial scenarios presented by the end users: EADS and ACCIONA.

- Evaluation of requirements for the cable robots: A set of recommendations and requirements for a safe operation of cable robots will be presented taking into account the list of risks identified and the aforementioned regulation.

During the task 2.4, the existing regulatory related to the application of robots in industrial environments, lifting and transport of loads and the normative applied internally by the end users in their operatives has been detailed. In addition, the potential risks for integrating robotic platforms (cable robots) in those scenarios have been classified and evaluated. Taking into account the regulatory framework and the hazards, a set of requirements and recommendations has been detailed for assuring a safe and successful application of cable robots in the industrial scenarios presented by the end users of the project.

This work has served as a base for designing the methods for a reliable and safe operation of cable robots in large scale environments.

Work done in T2.5.
In Task 2.5 partners have defined the validation criteria, validated the methodology, the simulation tools selected and the performance of the simulation for productive environments.

WP3. Development of control algorithms and strategies to command the cable robot

The main goal of WP3 is to develop the control algorithms and strategies to command the cable robots.

Work done in T3.1
The Task 3.1 deals with the requirement analysis of the control of cable robots with regards to the industrial application use cases defined in T1.1. The requirement analysis considers the software and hardware of the control as well as the robot hardware. Subjects like operational safety, usability and performance are covered.

The partners have provided a short overview of the technologies developed so far by them. They have specified the main parameters of the demonstrators and have given a summary of the used hardware and control components.

Secondly, they have shown the results from the requirement analysis and some promising concepts have been highlighted which agree with the requirements and may be used for the final robot system. Topics such as interfacing, usability, performance, and safety issues have been considered in the requirement analysis.

Then the control architecture for the cable-driven system has been outlined regarding the requirements and the use cases described in D1.1. The control architecture includes the numerical control and the communication infrastructure as well as the different operation modes and control algorithms. As a result of the requirement analysis and a subsequent system comparison, the TwinCAT 3 and B&R controls showed to be the best choices for the final industrial application.

Finally, the partners have given an overview over all parameters that are used to configure the control system. The structural relation of the parameters has been outlined and an xml-data format has been proposed which allows to store, load, and share the data among the partners in a standardized way. The xml specification regards the most fundamental parameters shared by all parallel cable-robots and can be extended easily as demanded by the application.

Work done in T3.2
The objective of the task T3.2 is to develop the algorithms modules for cable robots. The work done inside this task is:

- Kinematic transformations (simple, with pulleys, elasticity, catenary, extended platform geometries)
- Force control algorithms
- Calibration for reconfigurable cable robots (modelling, pose selection, parameter identification)
- Evaluation of control algorithms on Segesta, Cablar, and IPAnema
- Reconfiguration of cable robots
- Control of an embedded robot arm

The work done in the different subtasks is explained next:

T3.2.1 Kinematic Transformations

- Implementation of realtime capable code for inverse and forward kinematics
- The algorithms were implemented and tested on the control system selected in T3.1 (TwinCAT2/3)
- Current state: Real-time implementations of the inverse and forward kinematics algoithms are working on the TwinCAT3 system.
- Extended algorithms which include pulley geometry and elastic cables are implemented in Matlab and the simulation tool Wirecenter
- Extended tranformations dealing with cable sagging catenaries and non neglegible mass of cables were implemented

T3.2.2 Force control

- Designs to integrate force sensors between platform and cables as well as in the winch mechanics where realized
- Different algorithms to compute force distribution were implemented and tested
- (Barycentric mode, weighted average, close form , corner projection, ...)
- Approaches to cable-force control were developed and tested
- A first demonstration of admittance control for a sanding process was shown at IPA on the midterm meeting in Stuttgart
- Implemented force controllers:
    - Control of cable force in joint space and Cartesian space
    - Admittance control
    - Hand guided mode with huge damping factors which allows to position des platform at arbitrary locations by the user

T3.2.3 and T3.2.4 Calibration and reconfiguration

- Different approaches to robot calibration and pose identification were considered
- Direct measurement of geometrical parameters
- Direct measurement of platform position
- Measurement using system redundancy
- Additional sensors like accelerometers, gravity, and magnetic field sensors
- Additional cables for pose measurement
- Alternative: Real-time tracking of the platform during operation
- SEGESTA robot updated with reconfiguration capabilities

T3.2.5 Control of cable robots with embedded arm

- Cooperative position control of a cable robot with attached serial kinematic arm was tested
- Both, the cable robot and the 6 DOF robot arm were controlled by a Codesys PLC as one entity with 14 axes

The partners have started to analyse the characteristics/requirements from the control point of view to automate some tasks of the airplane maintenance such as masking, stripping, cleaning-inspection-reparation-new sealant beads and painting process.

Kinematic models for cable-driven robot are needed for robot control, simulation and system investigation. In order to operate the robot in an open loop position control mode it is necessary to compute the inverse and forward kinematics. The inverse kinematic model allows to obtain the necessary cable lengths and actuator set points for a demanded platform pose while the forward kinematic transformation allows to compute the platform pose for a given set of cable lengths. The inverse and forward kinematic algorithms are executed in the robot controller and have to be executed in real-time as specified in the requirement analysis D3.1. Different approaches to the solution of the complex forward kinematics problem such as local optimization, interval methods, and neuronal networks are investigated.

Kinematic models for different types of partially constrained, fully constrained, and overconstrained cable-driven robots are developed. Depending on the demanded accuracy and available computational power it is necessary to choose the appropriate kinematic solver for the specific problem. The software modules contain algorithms to solve the simplified inverse kinematics, extended inverse kinematics including pulleys, and an extended inverse kinematics considering the elasticity's in the cables. The correspondent algorithms for the forward kinematics can be executed in real-time for the simplified kinematic model as well as for the kinematic model regarding the pulleys. Moreover, in case of large dimension cable-driven robots for which the mass of the cables can hardly be neglected, inverse kinematics resolution based on the elastic catenary have been studied in the framework of a quasi-static analysis. Because of the nonlinear kinetostatic nature of the corresponding problem formulation, simplifications are desirable so as to ease the problem solving and lower the computation time. Therefore, simplified hefty cable inverse kinematics schemes have been proposed and tested in the trajectory planning module of the CoGiRo prototype control system software.

Prototypes of the algorithms are developed in Matlab and then reimplemented in C++ in order to improve the runtime performance. The kinematic modules are made available through a library which can be called by the robot control, but also can be used in standalone applications and simulation environments.

Beside performance tests regarding the convergency rate and robustness, the algorithms are integrated into a TwinCAT3 control system which is used to operate the IPAnema demonstrator.

Some use case scenarios as the sanding process during airplane maintenance demand a precisely determined process force at the tool center point which is oriented perpendicular to the airplane surface.

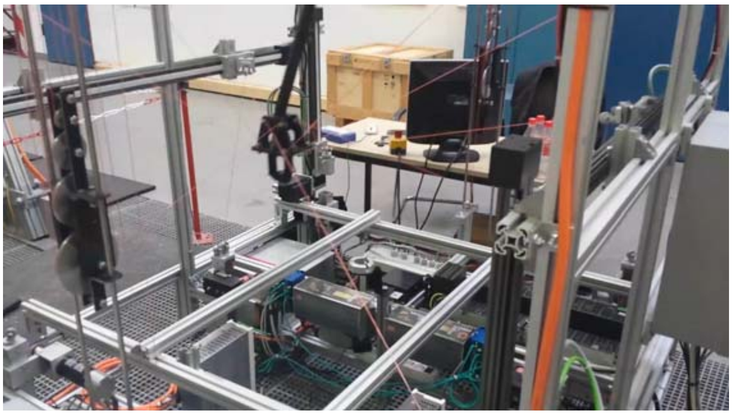
To cover the full range of possible structures (e.g. redundantly constrained cable driven parallel robots (CDPR)), force distribution algorithms have to be developed. Additionally a changing cable configuration during the application has to be considered. Two approaches can be identified: geometrical and optimizer-based approaches. Geometrical approaches operate commonly in the r-dimensional affine space of tension solutions of the working platform. In this context r defines the degree of actuation (DOA). One advantage of geometrical approaches is their known worst case computation time. For many applications, redundant CDPRs are driven by $m = n + 2$ cables where n denotes the number of the degrees of freedom (DOF) and m numbers the cables. Also in the current development stage we deal with the computation of the force distribution for redundantly actuated CDPR driven by $m = 8$ cables, leading to $r=2$. For this special case, solutions were developed in the consortium.

Within an automated application (e.g. painting process in the airplane maintenance application described in D1.1), the CDPR has to move automatically on a predetermined path. In the scope of the project, a universal control scheme will be developed and implemented on industrial control systems. Depending on the available sensors, two different kinds of position control strategies can be identified: Joint (JSC) and operational space control (OSC) approaches. JSC approaches require an inverse kinematic algorithm for the computation of the desired cable lengths. The movement of the working platform will be guaranteed by the regulation of the current cable length. Contrarily, OSC approaches require a forward kinematic algorithm for the computation of the pose of the working platform. Different algorithms were simulated and compared referring to a well-suited tracking behavior of the working platform. Accurate trajectory tracking must be guaranteed. To cancel non-linear effects and disturbances acting on the working platform, an inverse dynamic and a disturbance observer are integrated in the control strategies. The mentioned methods based upon the equations of motion of a cable driven robot.

It is desirable to regulate directly the interaction between the cables and the working platform to prevent vibrations in the cables. In the case of redundantly CDPR, the desired force distributions serve as set point values. A cascaded force control-loop is used to regulate the force set points. Within this approach, the velocities of the winches are used in the inner control loop. The cascade control takes a significant positive influence on the control performance. A major reason is the compensation of disturbances – e.g. in the form of friction forces - directly in the inner loop and therefore disturbances will not affect the desired cable forces to be regulated in the outer loop. The regulation of contact forces during an impact between a CDPR and the environmental is more complicated and must be considered separately.

Partners have also worked on the reconfiguration of a cable-driven parallel robot as capability characteristics of a CDPR depend strongly on the configuration. Reconfiguration of a CDPR can be used to improve its properties like: a) Parameter variability allows to flexibly adjusting the robot for a task; b) Characteristics can be actively distributed over the workspace (Payload and acceleration capabilities; Stiffness) and the workspace can be enlarged in this way.

UDE have implemented the reconfigurability concept in a lab-scale demonstrator. *They have updated their SEGESTA robot and have reached the first prototype which is capable to reconfigure itself depending on different criteria* like mechanical stiffness of the platform. In the next figure you can see that the output points of four cables are NOT in a fixed position as happen in other prototypes by mounted on linear motors.



SEGESTA prototype updated with reconfiguration capabilities

Finally, the coordinated control of a cable-driven parallel robot and a robot arm embedded into the platform of the former has been investigated. Two strategies are being considered. In the first one, the cable-driven robot is considered as a mobile base whose main role is to position the robot arm in an appropriate location to perform the task at hand. The cable-driven robot moves alone to position the robot arm. Then, the cable-driven robot is held in position (brakes) while the robot arm is performing its work. This first scenario has the advantage of circumventing the need of dealing with a relatively high redundancy resolution. Indeed, in the second considered strategy, the robot arm and the cable-driven move together to accomplish a task. Efficient control including redundancy resolution is then needed with the advantage of having a system offering flexibility and optimization (energy, performances, etc.) possibilities.

Work done in T3.3

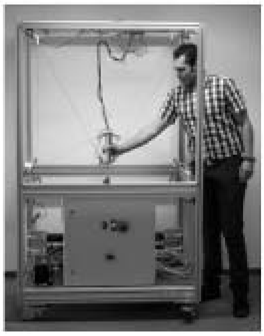
The objective of the task T3.3 is to develop the human machine interface (HMI) and the different control modes needed for cable robots aiming at industrial applications and general usability. The topics that have been tackled inside this task are:

- Implementation of different operation modes:
    - Programming mode: TwinCAT NC used; on-line and off-line modes tackled
    - Automatic mode: execution of programs defined in programming mode; open loop and close loop sensor supported mode (with force controlled modes and with vision supported mode)
    - Manual mode: remote control in Cartesian space, in joint space, assisted mode with haptic feedback.
    - Reconfiguration mode
    - Visually guided mode and visual interface
- Human-Machine-Interface HMI

The main requirements for the HMI are: a) easy access for experts as well as for instructed operators, b) Configuration Mode, c) Different operation modes and d) Clear and well-arranged user-interface.

The Human-Machine-Interface realized for cable robots can be designed similar to interfaces used for industrial robotics, since the abstraction layer implemented in the controller hides details of the specific properties of cable robots from the user. Beside standard interfaces as control terminals, joysticks, and touchscreens it is also possible to use more intuitive concepts such as haptic interfaces. For this the robot platform itself is used as input device to control the motion according to the applied force of the user.

The control of a haptic system can be realized either by impedance or admittance control. Both of them allow to control the movement of an actuator according to the interaction between the user and the actuator. They have developed both control strategies and have validated the algoritms in the IPAnema prototype; a small cable robot as haptic interface for larger systems can be used. They have taken into account that interactive handling of heavy payloads requires safety systems.



Also computer vision can be used to realize more comfortable and robust interfaces for different application tasks. Manual interaction with the robot mainly is done in the configuration or interactive mode to setup the system, teach specified procedures, or to execute human supervised tasks. For automatic operation modes, the programming can be done by industrial programming languages such as G-Code, or more expressive and complex languages such as C depending on the use case.

Work done in T3.4

The objective of Task T3.4 is to define and explain the different algorithms and methods developed during the project for ensuring a safety operation of the cable robots when operating in industrial environments.

Regarding Safety Operation, ACCIONA and CEMVISA have described the main safety aspects to be addressed by the cable robots when operating in large scale industrial scenarios. They have made a list of requirements for safe operation of the robots in those scenarios based on the risks associated to the industrial scenarios described in Deliverable D2.4: "Written report of the evaluation safety of cable robots". Then, they have defined the methodology for the implementation of the cable robots in the industry.

They have listed the Normative and Risks associated to the use of cable robots in aircraft maintenance operations and in lifting, transport and assembly of loads. They have described the modifications to be done in the industrial environments to fit the cable robots in them. Several alternatives have been considered, both intrusive and non-intrusive to the infrastructure of the workplaces.

They have also described the Personal Protective Equipment that workers must be equipped with to perform each tack. European Directive 89/686/EEC designed to ensure that the equipment meets common quality and safety requirements established by the market has been followed.

Finally, they have collected the methods and algorithms for increasing a safe operation of the robot that have been defined during CableBOT project by technical partners. Those algorithms are the following:

- Methods and Algorithms for controlling the collisions in the workspace (between cables, between cables and the mobile platform or the environment and between the mobile platform and the environment)
- Methods and algorithms for enabling motion planning of the cables
- Methods and algorithms for providing means for recovering from errors.

WP4. Prototyping of industrial scenarios

WP4 of CableBOT has three main objectives. The first one is to test the software tools developed in WP1 and WP2 for design and simulation of cable robots. The second objective is to prove the effectiveness of the control algorithms and trajectory generation strategies proposed in WP3. The third objective is to validate the feasibility of using cable robots in large scale tasks. These three objectives have been tested in the framework of the two targeted industrial applications which are aircraft life-cycle maintenance operations and the handling of large civil structure elements.

Work done in T4.1

The main goal of WP4 Task 4.1 is to define the requirements for the demonstrations of the principal objectives of WP4: test the developed software and validate the industrial use of cable robots. The list of requirements of the two main applications considered in CableBOT has been distinguished.

Work done in T4.2 & T4.3

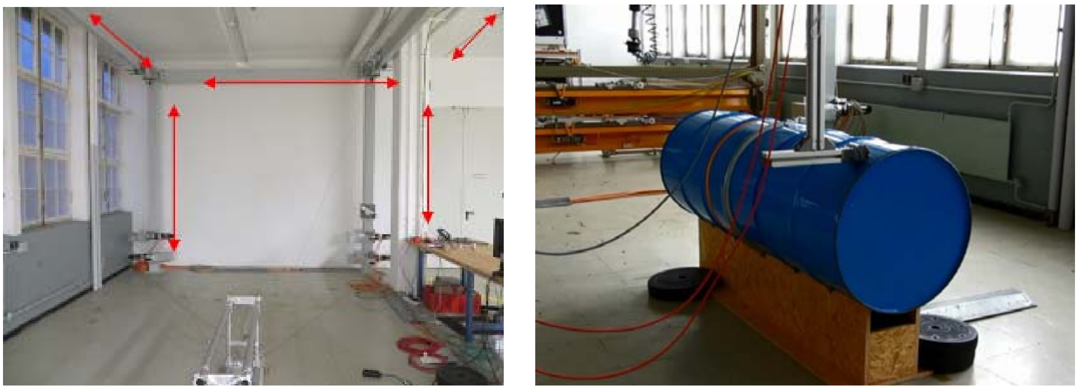
The objective of Task 4.2 is the re-design of the prototypes according to the requirement and use cases analysis done in Task 4.1 and to integrate the control algorithms developed in WP3 to be able to validate the use of cable driven robots in the two scenarios analysed during the CableBOT project. Whereas the objective of Task 4.3 is to validate the feasibility of using cable driven prototypes in the two user scenarios of the project.

First Use Case: Aircraft Life-cycle Maintenance Operations leaded by EADS, IPA and UDE.

Fraunhofer-IPA have worked in the redesign of the IPANEMA prototype for evaluating the use of cable driven parallel robots in aircraft life-cycle maintenance operations. In particular, they have updated the following components:

- Sensors: they have analysed and selected several sensors for safe operation, position control and force control that can be integrated in the IPANEMA prototype
- Robot and winch redesign:
  - A new optimized winch generation was developed to extend the maximum feasible cable length greatly, as well as the maximum cable forces. The new optimized winch generation integrates an omnidirectional guidance pulley.
  - Movable pulley unit: the robot geometry can be changed using eight pulley units which can be moved to nearly arbitrary positions along the frame. The cables do not have to be removed from the platform or the winches while adjusting the configuration.
- Optimized System Architecture for Industrial Applications. To increase performance and shorten the development cycles while keeping the focus on industrial hardware, a TwinCAT3 control was used to replace the Codesys-RTX setup. With TwinCAT3 powerful toolchains and direct Matlab/Simulink integration with automatic code generation become available.

Fraunhofer-IPA have prepared an scenario to validate the feasibility of using cable robots in aircraft maintenance operations. The IPANEMA robot used for the demonstration is 7x4x3 m size, payload of 60 kg and integrates flexible winch and pulley system to allow designing and comparing different robot configurations.

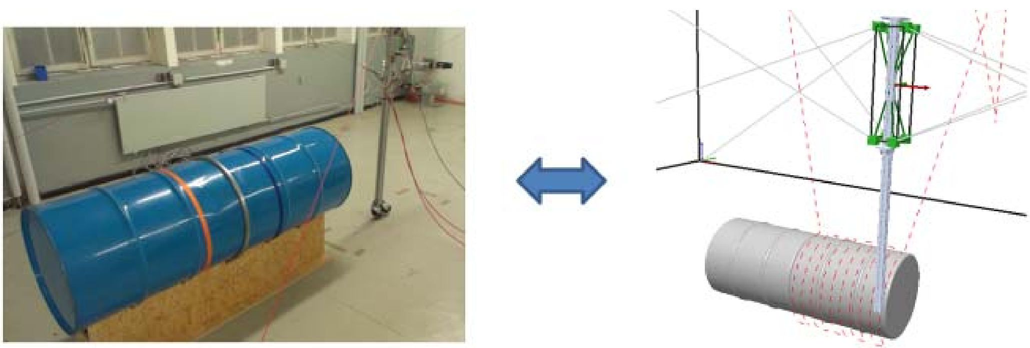


Eight different tasks have to be executed for the maintenance of aircrafts. To establish a set of requirements for the demonstration of this use case, these eight different tasks have been analyzed in more detail to specify the technical background and in order to define controller strategies for each of the tasks.

The most important tasks that have to be executed in the airplane maintenance use case can be covered by three different operation modes: the manual mode, the automatic position controlled mode and the force controlled operation mode (just for the sanding process). The demonstrations related to these operation modes have been realized with the Fraunhofer IPA cable-driven parallel robot IPAnema.

In the **manual operation mode**, it is possible to move the platform to arbitrary positions in the workspace using a hand-operated controller. Since the demonstrator is scaled down by approximately 1:10 with respect to the real application, the operator cannot be located on the platform but has to control the platform remotely. Standard industrial devices as well as a new haptic feedback controller were developed and tested with the IPAnema prototype. To emulate the control behavior on the smaller model system, maximum velocity and acceleration were scaled down.

The **automatic mode** includes trajectory planning and control under the given constrains such as total process time, max. velocity and max. acceleration. The platform was moved along a curved surface with a certain distance and accuracy to check the performance of the demonstrator regarding the process requirements. To increase process stability and robustness against disturbance, a camera system was used to allow for local corrections utilizing visual servoing. The automatic positions control expects a trajectory which is planned by a path generation tool. With focus on industrial applications the path for the test scenario was created using CAD data from SolidWorks and the simulation and design tool WireCenter to compute and simulate the respective trajectories



Sanding processes demands a **force controlled tool** which is moved along the airplane surface. The force control can be realized at the level of the winches, or directly at the tool. In the scenario tested on the IPAnema prototype, the wrench was measured and reconstructed using cable force sensors while moving a tool along the predefined trajectory on a curved surface and applying a certain force in the normal direction of the surface.

During the experimental tests it was shown that it is possible to follow a surface along a predefined trajectory while applying a predefined process force in the normal direction of the surface. While the results are very promising in the sense that implementation of cable robots for airplane maintenance is technically possible, it is necessary to do more investigations which proof the cost effectiveness of such a system with regards to alternative solutions, such as serial kinematic robots, and telescopic systems.

Second Use Case: Handling and Assembling of large civil structure elements leaded by ACCIONA; CNRS-LIRMM, TECNALIA, CEMVISA

The requirement analysis of this use case can be found in deliverable D1.1 of WP1. From the DOW, the goals of the demonstrations are:

1. Provide sufficient control to allow even a novice operator to position a load without sway within a few millimeters in x, y, and z.
2. Control orientation without oscillation in roll, pitch, and yaw.
3. Control forces and torques on a load due to disturbances.
4. Maneuver composite or steel beams in hazardous environment without human intervention.

In order to fully achieve points 1 to 3, a modified version the CoGiRo robot has been used. CoGiRo is a 6-DOF robot actuated by 8 motors so that it can control the motion in all 6 degrees of freedom (with the help of gravity to keep the cable tensed) and balance forces and torques in all directions (within some limited ranges of values). The corresponding modifications have been carried out by CNRS-LIRMM and TECNALIA and are the following:

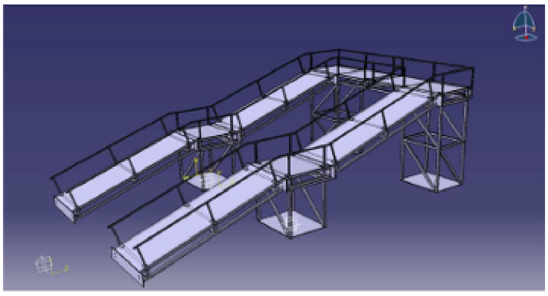
- Improvement of the robot calibration (required to achieve as high accuracy as possible) and replacement of "cable output points" by output pulleys.
- Modification of the payload (mobile platform) fastening means.
- Choice of a joystick for the manual operation mode and interfacing with the robot current control system.
- Improvements of the CoGiRo robot control system to enable:
  - Manual operation mode
  - Direct manipulation of the cables by an operator ("manual manipulation" when the cable is not attached to a payload)
  - Implementation and tuning of another (basic) control scheme to accommodate uncertainties in the payload characteristics
  - Determination of the cable attachment positions: needed when the payload (structure element) to which the cables are connected is changed
  - Cable tensioning procedure: required after having attached the cables to a new payload.

Once the modifications defined have been implemented in the CoGiRo prototype, ACCIONA and CEMVISA have defined two demonstration scenarios. These scenarios allow to test the capabilities of CoGiRo to realize points 1 to 3, especially the second one.

- **First demonstration** that consists on the displacement and assembly of simple elements designed and manufactured by ACCIONA.

Total weight	176 kg	Total weight	146 kg	Total weight	95 kg

- **Second demonstration** that consists on the assembly of a scaled footbridge designed and manufactured by ACCIONA.

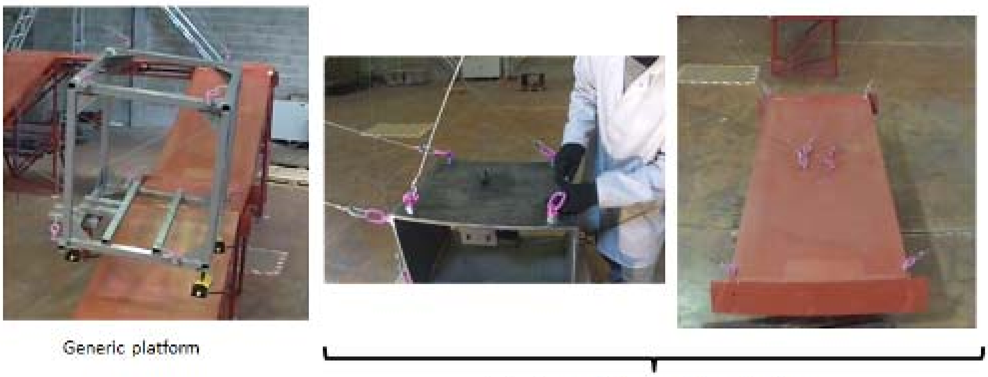


Dimensions:

- Length: 6 m
- Width: 4 m
- Height: 2.5 m

ACCIONA and CEMVISA defined the key parameters for the evaluation of the experimental tests.

Two different methods have been used to assemble the Acciona structures with CoGiRo cable robot prototype. The first one consists in using the "generic" CoGiRo platform. The second method consists in connecting the cable directly to the structure elements and uses those structures itself as platform.



Generic platform

Direct connection of cable on structure

First Demonstration: Displacement and Assembly of Simple Elements

To test the validity of cable tensioning, initialization and handling procedures simple Acciona elements have been used. After having hooked the cable to a first element, the tensioning procedure is launched. Once all cables are in tension, the controller compute the actual pose of the element and then the robot can start the displacement of it. The displacements are remotely control by the operator via a joystick. The first element is displaced to the mounting area and the cables are disconnected to be relocated on the second element. The tensioning, initialization and handling procedure can be run once more time to place the second element next to the first one on the mounting area. After the assembly of the two elements, the cables are reconfigured on the whole assembly which can be handled to a new area.

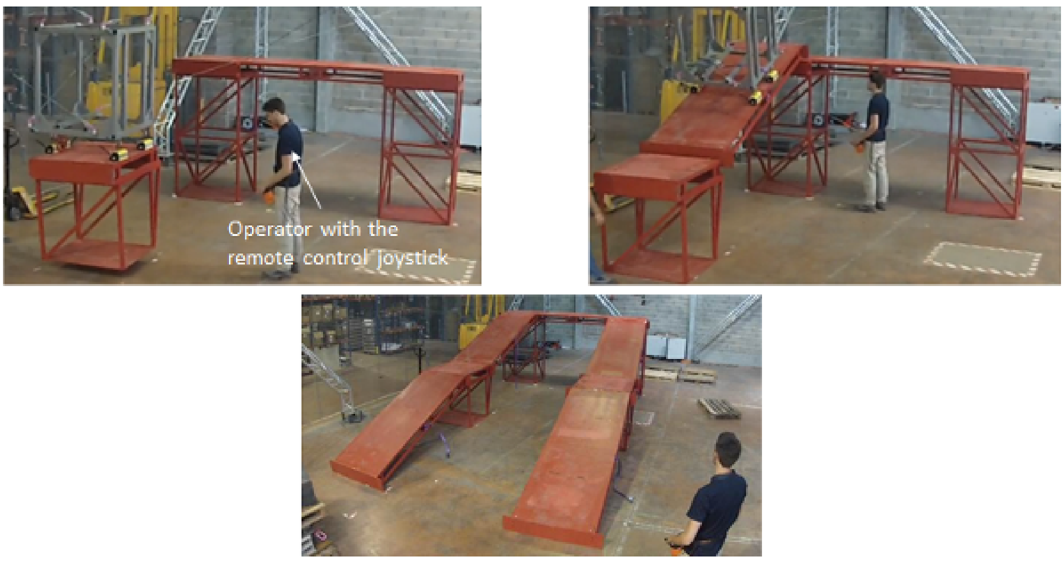
Beam assembly

Second demonstration: Assembly of a scaled footbridge with the generic platform

The Acciona structure elements are steel made and the use of magnets as interface between these structures and the platform is an efficient way to link temporarily the structure elements to the platform. The magnets are activated thanks to a lever manipulated by the operator when the structure element to handle is in contact with magnets. The use of remote control joystick allows easy and intuitive displacements of the platform. The displacements can be done relative to the robot base frame or to the platform frame. With this generic platform and the use of magnets the assembly duration of the footbridge is 39 minutes.

Accuracy of positioning of structures for assembly using manual mode in horizontal or sloping surface is 2 mm. The maximum accuracy obtained when placing together pieces with zero orientation in manual mode.

Footbridge assembly with generic platform



Second demonstration: Assembly of a scaled footbridge by direct connection of cables

The structure elements of the footbridge have been equipped with anchor holes allowing connecting cables directly on it. This method allows increasing the payload versus the use of generic platform. The footbridge assembly began from the initial position of structure elements. A first floor is displaced to its support to be mounted on it and the assembly of the two elements is displaced to the mounting position. The cables are disconnected from the assembly and connected to a second floor. The procedure is repeated for the four floors. Then the ramps are mounted to obtain the final footbridge. The assembly duration was 1 h 1 5 min. An improvement of the cable connection devices would probably allow decreasing the assembly duration below 1 hour.

Accuracy of positioning of structures for assembly using manual mode in horizontal or sloping surface is 2 mm. The maximum accuracy obtained when placing together pieces with zero orientation in manual mode.

Handling and assembly of a ramp

Final footbridge

The use case of handling of large civil structure elements has been successfully completed by using the CoGiRo cable robot prototype. Two different structures have been handled and assembled, a first simple small size beam composed of cubic elements and a large size and heavy footbridge. Those use cases have allowed to validate the methods developed to reach the goals and validate the concept of cable robot for large civil structure assembly either by using of a generic platform or by direct connection of cables on the structure to handle.

A video with all the demos performed with CoGiRo prototype can be found in youtube http://youtu.be/An_i8xoMXDc

1.4 The Potential Impact and the main Dissemination Activities and Exploitation of Results

Potential Impact

The **main potential impacts** of the Cable BOT project are:

1. Use of robots in complex manipulation tasks and in multiple industrial sectors

Kinematics, payload and reachable workspace can respond to any requirement just by changing the location, power of the winches, and the configuration of the cable robot. Therefore there are many high life-cycle cost processes where cable robots can be applied. In order to allow the application of cable robots to such sectors, design and simulation tools are required to validate any particular robot configuration.

2. Cost effective and flexible automated solutions

The ratio of the mass that the robot can move and the cost of robot, is an order of magnitude bigger than any other service robot. The ratio of the reachable workspace and the cost of the robot, is two orders of magnitude bigger as well. Therefore, cable robots are really cost effective, and in order to be flexible at the same time, specialized control algorithms are needed

3. Stronger penetration of advanced automation into small or medium-scale industrial sectors, specially through the introduction of new assistive automation and robot systems

Technical objectives of the CableBOT project provide design and simulation software tools that allow the implementation of cable robots by automation engineers of SME instead robotics researchers.

4. Extend the service life and/or improve the operational efficiency and functionality of the product, while at the same time reducing the overall life-cycle costs

CableBot project will impact by introducing of new agile automation solutions based in adaptable and reconfigurable Cable driven robots that will make possible efficient life-cycle tasks and associated post-production services.

Economical impacts

a. Impact on Next-Users

The software tool for the design of cable robots will have an impact on the research institution because it will allow them to collaborate with engineering and automation companies to develop applications with cable robots. The cost of a cable robot application is over-loaded by the need to work in height, skilled people, special griping components available only to specialized companies, while the high mathematical background of the cable robot discourages engineering companies to face the project alone. This software tool will shorten the gap between engineering companies and RTD and increment of 10% on the number of robotics projects will be possible.

The software tool for the simulation of the process allows to optimize the scheduling of the maintenance operations by means avoiding human intensive operations that impose severe constrains to fulfil with labour conditions of the workers. The quality of the robotic tasks and the required time are deterministic and they allow further optimisations. Consequently, EADS and ACCIONA will increase their productivity by the use of cable robots on their maintenance and logistics operations.

The control algorithms supply the flexibility to use the cable robots with different payloads, different configurations and different workspaces in plug and play operations. The control algorithms have a technological impact as an improvement to the state of the art but it involves the rise of the research activity of IPA and Tecnalia.

The prototype of a cable robot impacts the application performed by cranes and big gantry manipulators. Compared to a crane a cable robot is more precise and avoids swivelling of the load, this extra performance has an impact on tasks that involve high precision and put the load, the environment or the people into risks. For less precise or less constrained applications the use of cable robot means extra expenses because it uses more cables. For Vicinay CEMVISA cable robots can give higher market share as it can compete in the high end crane sectors.

b. Impact on End-Users

Aeronautic maintenance

EADS will use CableBOT technology in its factories for aircraft painting operations. After their validation in this project, EADS will extend this technology in different manufacturing application scenarios through the EADS group (the commercial aircraft manufacturer Airbus, the helicopter supplier Eurocopter and the space company Astrium).

As can be seen in the following figures, the maintenance operations require human intensive activities in hazardous environments


Sanding


Cleaning


Painting

Decorating

Some manual operations including sanding, cleaning, painting and decorating, involve the manipulation of chemical products or small particles thus requiring the use of protective outfits marks or complete clean air breathing devices and air removal systems.

While some tasks are and will remain manual (in particular docking and undocking, masking and customer inspection), cable robots can be used to position with 3 to 6 degrees of freedom automated tools, therefore releasing humans of these non-ergonomic and potentially unhealthy manual tasks. As a consequence, labour will shift towards higher value tasks like the programming, reconfiguration and maintenance of the cable robots. At the same time, the development and exploitation of such automated and flexible tools will favour the expansion of aircraft painting activities in Europe and similar activities, like aircraft paint stripping or inspection could benefit from this technology.

Given that cable robot has up to 6 degrees of freedom (real platforms over rails systems do not have so many) and they have a smoother movement, it could be possible to get more precision in assembly operations which would involve increase the quality of the product restricting dramatically the number of rejections. That is an important point because structural elements made of concrete have no residual value and it is impossible to valorise this kind of waste. Furthermore, the automatic movement administrator avoids crashes reducing fabrication mistakes. On the other hand, the growing of productivity in that kind of processes would mean a reducing consumptions and minimizing the visual impact of these activities.

Construction scenario

ACCIONA will use cable robots in an industrialisation of the construction scenario. Nowadays more and more parts of buildings and other infrastructures (bridges, …) are manufactured in workshops using the same manufacturing technologies used in the production of other manufactured products. In this scenario, most of the parts are heavy; the production change very fast from one to another product and Acciona is interested in hiring temporary workshops next to the building areas. In order to make it feasibly this scenario, these temporary factories should avoid expensive and inflexible infrastructure. Cable driven robots are a perfect infrastructure for the workshops of companies like Acciona interested in the industrialisation of the construction. These robots will replace traditional cranes used in factories, with the advantage of being flexible, reconfigurable, light and easy to move from one workshop to another.

Movement and assembly of great volume structural elements operations are made using platforms over rails so this means to have enormous unutilised work areas. Furthermore, when the assembly is completed it is difficult to change them to other position because the internal rails network cannot allow it. Consequently, the inclusion of that new technology could allow unexpected stops.

Platforms over rails

Researching in that technological environment will benefit the next work areas:

- Reduction in associated costs, saving area and decreasing the facility visual impact.
- Improve of control systems in order to allow unexpected stops and getting simultaneous processes which will grow up the productivity.
- Increase in safety of the process, simplifying the control operations and consequently, reducing the accidents.
- Increase the precision of the processes which in turns it would increase the quality of the product assembled.

Through the use of cable robots it is expected to achieve a significant reduction of the initial investment costs. Indeed, the roof mounted independent XY railing systems could be replaced by either a static grid of winches or a hybrid solution of a single rail and movable winches. In both cases, fast reconfiguration of the robots by detaching and attaching the nacelle to other cables is possible in order to achieve the required workspace while avoiding cable interferences. The vertical telescopic mechanisms are replaced by simple vertical cable length variations.

Exploitations costs should also proof significant savings, since cable robots are expected to be 5 to 10 times lighter and therefore perform faster while consuming 4 times less energy. Finally, cable redundancy can be used to increase the system availability as well as the overall safety and maintenance costs should be significantly lower for a winch and cable system than for the telescopic gantries currently in use.

The manufacture of beams is made in facilities near the construction. These facilities are hired and the dimensions of these are important because they must be able to house all the machinery needed. To move the beam and the different parts and assemblies made, it is necessary crane and other tools, which are bulky items that occupy a great space. It is necessary to deliver this machinery to the place where this work.

Crane installed on civil works

Installations and cable system takes up less space. In turn this system is more lightweight and portable so that it will dramatically reduce costs in transportation, it will not be necessary to use special transport, or carry heavy equipment. And with this system the weight is distributed in different parts of fixturing so that you can place the weight smoothly, without jerks, even with heavy loads. This increases safety and minimizes wear. It is also easier synchronization of certain movements. The position control is faster and safer, as the path that robot is controlled in position, the collision detection tools could be combined more effectively with the command of the movements. The load stops smoothly and without balancing load just before it reaches its end of travel positions, both forward and backward or sideways. As a result of the above, the load can be moved more quickly and safely to the positions of end of career, which saves time and process economy.

Social and environmental impacts

Aeronautic maintenance

Aircraft maintenance operations are currently performed manually and special outfits are needed to prevent the operators of breathing the polluted air. Given that the painting process requires wet on wet application and involves immobilisation of finished aircraft, several telescopic gantries are used to allow simultaneous work on different airplane locations.

Manual Painting

Gantries for Manual Painting

These results in a heavy investment on special gantries and equipment that needs to comply with explosive environment regulations and demanding human health conditions.

At the same time, to paint operations for example, in order to decrease the emission of VOC (Volatile Organic Compounds) and the associated environmental impact, new products with heavier solvents are more and more adopted. However, the application gestures of some painters remain unchanged, leading to non-homogeneous thicknesses and increased plane weight. Depending on the complexity of the airplane decoration, the complete process spans between 15 shifts for an unornamented plane and 75 shifts for a highly elaborated airplane. Drying time represents an important part of the complete time.

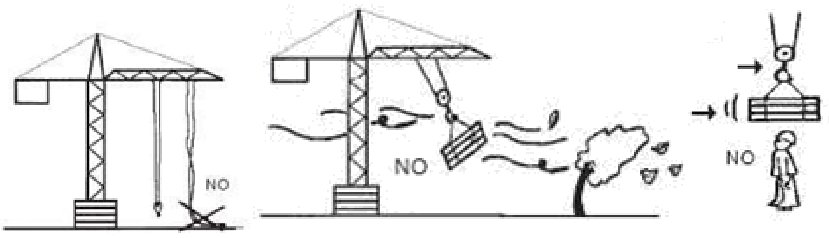
The main motors on the exploration of cable robots are therefore, whatever the size of the airplanes:

- reduction of initial investment
- reduction of unhealthy working condition
- homogenization of product application
- reduction of cycle time and recurrent costs
- increased positional accuracy and reorientation potential
- increased modularity and flexibility

In order to maximise impact, work will be performed on both the analysis of different cable robot solutions and the introduction of automated painting process adapted on the new cable robots.

Construction scenario

Safety and control are essential factors in all applications of cranes. The use of cranes involves accuracy and there is no margin of error. Starts and stops can cause dangerous shakes and false movements, unexpected oscillations and risk of entanglement as well as an accidental fall of the load.



Risk factors about use of cranes

By means of using of robot cable, the fall of the load will be avoided; apart from having control over the points of load, it will have both speed and torque direct control which will react extremely fast to load variations protecting the process and the operator. Furthermore, the use of control systems more and more intuitive reduces the stress that the workers are put under. By the other side, electronic controllers would manage the movements avoiding the accidents.

In order to perform successful safety ancillary processes, cable robots should be provided with safety equipment that guaranty presence of humans to be free from adverse and unsafe working conditions. Furthermore, due to the characteristics of cable robots, themselves can also create dangerous conditions and threaten human safety. Therefore, it is essential that cable robots users and manufactures recognize the potential hazards and implement safety actions to eliminate any hazard in life-cycle applications. In either case, CableBOT offers safety solutions for the automation of postproduction and ancillary tasks with regards to ensure human safety.

On the other hand, the introduction of heavier solvents results in a reduction of VOC (Volatile Organic Components) emission inline with European directives. However, the manual application of the new preparations produced significant variations on the product quantities applied by different operators, since new gestures needed to be apprehended.

Cable robots can be designed for 3 or 6 degrees of freedom. In both cases, through the addition of painting nozzles similar to the ones developed for the automotive industry, the automation of some tasks will be explored. Successful results will allow a better homogeneity of the applied layers and therefore a reduction of the used chemicals and the associated VOC emission. At the same time the reduction of planes weight will bring a fuel consumption decrease. Together with the energy consumption reduction expected from light, parallel cable robots this adds towards a durable development.

Dissemination and Exploitation of the Results

The **main dissemination activities** performed in the CableBOT project are the following:

- Promotion and dissemination through the project website www.cablebot.eu
- A new leaflet of CABLEBOT project prepared for marking purposes
- 32 papers submitted to Conferences
- 4 papers submitted to scientific journals
- Dissemination within the members of related European Technology Platforms (ETP) MANUFUTURE, EURON and EUROP
    - INNOROBOT 2012: Organisation of a workshop on cable-driven parallel robot at the European Robotics Forum
    - INNOROBOT 2013: Organization of the session “Control and Application of Cable-Driven Parallel Robots” at the European Robotics Forum
    - INNOROBOT 2014: Attendance to European Robotics Forum
- Organization of Conferences
    - CABLECON 2012: First International Conference on Cable-Driven Parallel Robots; IPA – September 2012
    - CABLECON 2014: Second International Conference on Cable-Driven Parallel Robots; UDE – August 2014

Participants of the Second International Conference on Cable-Driven Parallel Robots. University Düisburg-Essen facilites

- Participation in events organised by the FOF-NMP programme
    - Workshop on the Impact of the Factories of the Future PPP – Belgium, March 2012
    - Workshop on the Impact of the Factories of the Future PPP – Belgium, March 2013
    - MANUFUTURE 2013 conference "ManuFuture View on Horizon 2020: sustainable re-industrialisation of Europe", Vilnius, October 2013
    - Workshop on the Impact of the Factories of the Future PPP –Cablebot Project was selected as successful project and was presented in the session on "FoF Success Stories – Projects with high impact and outcome". - Belgium, March 2014

- Participation in 2 forums
    - Participation to the summer school Models and Methods in Kinematics and Robotics 2012, Technical University of Cluj-Napoca, Romania, July 2012
    - IGM-Seminar "Kinematik, Dynamik und Mechatronik in der Bewegungstechnik", Institut für Getriebetechnik und Maschinendynamik, Aachen, Germany, July 2012

- Participation in 7 international fairs at Bilbao, Hannover, Munich, Nice
    - Spanish Machine Tool Fair – BIEMH 2012, Bilbao (Spain) June 2012
    - BAUMA Fair 2013, Munich, April 2013
    - Ferroforma Fair, The International Hardware, DIY and Industrial Supplies Fair, Bilbo, May 2013
    - National Robotics Expertise Center fair, Nice, January 2013
    - Hannover Fair, Hannover, April 2014
    - CEMAT Fair - Materials handling and Intralogistics – Hannover, May 2014
    - AUTOMATICA Fair - International trade fair for robotics and mechatronics – Munich, June 2014
    - Spanish Machine Tool Fair – BIEMH 2014, Bilbao (Spain) June 2014

Tobias Bruckman (UDE), Cedric Baradat and Mariola Rodríguez (TECNALIA) at BAUMA fair 2013

José Ignacio Olmos (CEMVISA) and Mariola Rodríguez (TECNALIA) at BAUMA fair 2013

- Visits to potential customers
  - Several visits to potential customers have been carried out
  - INRIA has organized a large number of visit (around 300 visitors per year among which a representative of the French government, representatives of Toyota Europe) at its facility in Sophia-Antipolis where a cable-driven parallel robots is in permanent exhibition.

- Other dissemination activities
  - CableBOT project included in the second Brochure prepared by EFFRA
  - Summary of CableBOT project in CORDIS – “Result in brief“ http://cordis.europa.eu/result/rcn/58602_en.html
  - The story on *CableBOT* project has been published on Horizon 2020 website, in the Projects stories section at https://ec.europa.eu/programmes/horizon2020/en/news/robotic-answer-safe-automated-industrial-maintenance
  - Manufacturing of Low-cost pedagogic wire-driven robots to be shown in fairs
  - Dissemination of the CableBOT project in the Newsletter of VICINAY CEMVISA that it is disseminated to more than 3000 contacts
  - Dissemination of the CableBOT project in the webpages of Cablebot Partners
- Cluster Activities
  - Participation in the First workshop on the FoF cluster "Robots for Automation of Post-Production and other Auxiliary Processes“ - (RAPPAP)

Regarding to activities of **exploitation of results**, partners have written the **Plan for the Use and Dissemination of Foreground – PUDF** which contains information on:

- Dissemination of foreground
- List of Exploitation results
- Exploitable foreground and its use
- Notes and recommendations given by Peter Moran in the Exploitation Seminar organised on 21st May 2013
- Plan of contingency defined to mitigate the major risks of the project and progress of the actions defined
- A proposal of Commercialization Route

The **critical Key Exploitable Result** of the project is to combine all the partners' results into a working Cable Robot prototype that can then be developed into a commercial product – i.e. all results being exploited jointly. This project really is a case where the sum is far greater than the parts.

Next points in the PUDF must be highlighted:

- IPR and Exploitation Claim table included
- Once the Priority Map and the Risk Analysis have been done, a Plan of Contingency has been defined
- Actions defined in the Plan of Contingency are on progress
- A proposal for the commercialization route has been done. It includes the following points:
    - Carefully defined the market entry, work on understanding the selected market and develop a business plan based on the chosen application(s). Clearly articulated benefits vs existing solutions: Advantages of cable driven robots vs existing solutions for the selected application needed to be made clear in marketing documentation
    - Select the commercialization drives: Who is going to push what
    - Work towards setting up a commercial vehicle
    - Work on getting some patents filed
    - Get Industry Partner (end-customer) to endorse the product (very important for investors and licensors), or provide input on what would be needed (i.e. what must be achieved) in order for them to endorse the product. One useful way is to agree product specifications with them and try to get a statement from them saying if the product meets these specs we will buy it (or as close to that as possible)
    - Start to aggressively interact with additional potential end-customers to get validation and feedback. Keep knocking on the doors of potential customers in order to find real applications for cable robots. Focus on applications that cannot be solved with traditional methods.

It is important to highlight the big effort that CABLEBOT partners have done in dissemination and exploitation issues.

1.5 ADDRESS OF THE PROJECT WEBSITE AND RELEVANT CONTACT DETAILS

CableBOT data

Acronym: CableBOT
Call Identifier: FP7-2011- NMP-ICT-FoF
Project no NMP2-SL-2011-285404
Starting date: 1st November 2011
Ending date: 31st October 2014
Budget:4,4 M Euros
EC Funding: 3 M Euros

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