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HYbrid FLying rollIng with-snakE-aRm robot for contact inSpection

HYFLIERS

D3.1

Lightweight hyper-redundant robotic arm for aerial inspection tasks

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Abstract:

This document is about the design and development of three different prototypes of robotic arms projected in order to obtain a visual and UT inspection on pipes. This document includes mechanical details, a brief kinematic model description, and an overview of the motion capabilities of robots. Will be shown a useful of redundancy to achieve a measure in a wide range of applications. They will be presented in an order sorted by ascending complexity and application range.

Keywords:

Deliverable, snake robot, hyper-redundant robotic arm, UT inspection, Visual inspection, UT probe, tube inspection, measure probes, elbow inspection, remote inspection, refinery, operations support, quarter measure tool, robotic arm, semi-circular measure tool.

Executive summary

This document describes the design of the robotic arm developed in the HYFLIERS project. Based on the initial specification and to achieve the set objectives, three unique prototypes following separate approaches will be designed with different levels of technology readiness (TRL):

- Fixed articulation with 180° probe (FAP180):
  - The arm is a 2 DoFs (degrees of freedom) kinematic composed by a revolute joint and a predefined path guide.
  - The arm is linked to an articulated rover adding the additional required DoFs to the system.
  - A semi-circular (180°) actuated probe with two opposite UT sensors is used to perform measures around the pipe circumference
  - The arm can perform measures along linear pipe segments, horizontal curves and vertical upward curves.
- Anthropomorphic Robotic Arm with 180°/90° Probe (ARAP180/ARAP90)
  - A 5/6 DoFs anthropomorphic arm is used
  - The arm can be linked to an articulated rover to perform continuous measurements (without flying near curves)
  - A semi-circular (180°) actuated probe with two opposite UT sensors is used to perform measures around the pipe circumference. Alternatively, a quarter-circular (90°) probe with only a UT sensor can be used in combination with a 6 DoFs arm to improve the dexterity
  - The arm can perform measurements along linear pipe segments, horizontal curves and vertical curves. Moreover, the prototype with the 90° probe can perform measurements also on the T-pipes.
- Snake Arm with Pan and Tilt Probe (SAP):
  - A snake Hyper-redundant, tendon-actuated, arm is adopted
  - The snake arm is mounted on a pan-tilt structure that contains all the motors
  - A single UT sensor mounted in a pan-tilt frame linked with the arm end-effector.
  - A custom designed tendon articulation is adopted to reduce the required number of actuators.
  - The novel snake-like arm structure provides high dexterity and possibility to implement advanced collision avoidance algorithms.
  - The arm can perform measurements along linear pipe segments, horizontal curves and vertical curves and T-pipes.

Abbreviations and symbols

The paragraphs for the list of acronyms use the style Abbreviations.

API	Advanced Program Interface
DoF	Degree of Freedom
DC	Direct Current
DH	Denavit - Hartenberg
EC	European Commission
HYFLIERS	HYbrid FLying rollIng with-snake-aRm robot for contact inSpection
HMR	Hybrid Mobile Robot
HRA	Hybrid Robot w/ Arm
ICT	Information and Communications Technology
IMU	Inertial Measurement Unit
MATLAB	MATrix LABoratory
MPC	Model Predictive Control
FAP180	Fixed Articulation with 180° Probe
ARAP180	Fixed Articulation with 180° Probe
ARAP90	Fixed Articulation with 90° Probe
PWM	Pulse Wide Modulation
SAP	Snake Arm with Pan and Tilt Probe
ROS	Robotic Operating System
TOF	Time Of Flight
TRL	Technology Readiness Level
V-REP	Virtual robot Experimentation Platform
UART	Universal Asynchronous Receiver-Transmitter
USB	Universal Serial Bus

UTUltrasonic Thickness

Table of Contents

List of figures

List of tables

1. Introduction

The objective of the WP3 is to design and develop the prototypes of versatile hybrid robot systems for contact inspection with application to pipe inspection in industrial plants. In details, the WP3 focus on the arm design. This document is about the design for each proposed solution with their different inspection devices and capabilities.

1.1. Design Approach

To maximise the fulfilment of the industrial requirements and to achieve the set objectives, three unique prototypes following separate approaches will be designed with different levels of TRL. The solutions will be presented with an increasing level of complexity that translates to an increasing level of dexterity. In this section, an overview of the different prototypes is reported focusing on the main differences.

Figure 1-1. Concepts of the HYFLIERS arms.

1.1.1. Approach 1: Fixed Articulation with 180° Probe (FAP180)

The FAP180 prototype has been designed to comply the following requirements:

- Reduced weight respect to the other solutions in order to maximise the flight time and, at the same time, reduce the drone dimensions.
- A simple folding solution of the sensorized end-effector allowing take-off and landing.
- Simple mechanics and control to reduce failure risks.
- Possibility to execute measurements along linear pipes but also horizontal and vertical upward curves.

Based on the requirements the FAP180 is composed by:

1. A novel kinematic composed by a revolute joint and a driving guide.
2. A measuring tool capable of rotating around the pipe axis about 180 degrees to move the instruments along its circumference.

The FAP180 must be mounted on an articulated mobile vehicle able to walk on pipes as shown in Section 2;

Technology specifications:

- Arm weight 200 g
- Tool weight 530 g
- Permitted tool rotation: 180 degrees
- Number of UT sensors: 2

Number of DoFs: 3

1.1.2. Approach 2: Anthropomorphic Robotic Arm with 180°/90° Probe (ARAP180/ARAP90)

The ARAP180 prototype has been designed to improve the FAP180 by enhancing the system flexibility. In details, the ARAP180 is composed of:

1. An anthropomorphic robotic ARM with 5 DOFs
2. A measuring tool able to rotate around the pipe axis about 180 degrees to move the instruments along the its circumference.

The FAP180 must be mounted on an articulated vehicle able to walk on pipes as shown in the following figures.

Technology specifications:

- Arm weight 750 g
- Tool weight 530 g
- Arm payload: 670 g
- Permitted tool rotation: 180 degrees
- Number of UT sensors: 2
- Number of DoFs: 5+1

The ARAP90 prototype differs from the ARAP180 due to the use of a quarter-circular probe (90° probe) instead of the 180° one. That choice allows to have a lighter probe with only one UT sensor. Moreover, the geometrical structure of the 90° probe allows also to made measures on the T-pipes (see section 5 for more details). However, an additional degree of freedom is required in the arm to move the 90° probe.

The technology specifications of the ARAP90 are:

- Arm weight 830 g
- Tool weight 300 g
- Arm payload: 670 g
- Permitted tool rotation: 90 degrees
- Number of UT sensors: 1
- Number of DoFs: 6+1

1.1.3. Approach 3: Snake Arm with Pan and Tilt Probe (SAP)

The SAP is the most complex solution we designed with a target TRL 3. In detail, this prototype has been designed to further improve the dexterity and flexibility of previous systems, i.e., to work in a wider range of scenarios. In particular, the SAP is composed of:

1. A pan and tilt motor box connecting the arm with the drone frame.
2. A hyper redundant robotic snake arm.
3. A pan and tilt probe with a single UT sensor.

Technology specifications:

- Arm weight 2400 g
- Tool weight 530 g
- Arm payload: 300 g

- Number of UT sensors: 1
- Number of actuated DoFs: 12
- Number of Joints: 21 (2 m.box, 1 pan-tilt, 18 snake)

1.1.4. Comparison of the capabilities of the FAP, ARAP and SAP prototypes

Table 1 shows a comparison of capabilities of each provided robot arm/tool version.

Table 1. Approaches

ID	Approach 1: FAP	Approach 2: ARAP	Approach3: SAP
Capabilities	Measure on rectilinear pipes, horizontal curves, vertical curves only upward	Measure on rectilinear pipes, horizontal curves, vertical curves. Measure on T pipe (only ARAP90)	Measure on rectilinear pipes, horizontal curves, vertical curves. Measure on T pipe
Precision in the spatial positioning of the UT sensors	High positioning accuracy in continuous measurement due to the tool structure	High positioning accuracy in continuous measurement due to the tool structure	Low positioning accuracy in continuous measurement due to the snake structure
Weight of the system	Low weight of the system due to the simple arm (830g)	High weight of the system due to the complex arm (ARAP180: 1280 g, ARAP90: 1130 g)	High weight of the system due to the complex arm (2930 g)
Complexity of the mechanics and control	Low complexity of the arm mechanics and low number of DoFs	High complexity of the arm mechanics and high number of DoFs	High complexity of the arm mechanics and high number of DoFs
Necessity to use additional systems	The arm needs to be mounted on an articulated vehicle to perform measures along horizontal curves	The arm can reach each position, but it is suggested to use an articulated vehicle to performs continuous measurements	The arm can reach each position, but it is suggested to use an articulated vehicle to performs continuous measurements

2. Fixed Articulation with 180° Probe (FAP180)

In this section, the first arm solution is presented. The FAP180 is the solution with the lower level of TRL, in which the design focused on reducing the global arm weight and complexity but maximizing the system capabilities.

2.1. Hardware Description of the articulated mechanism

The FAP arm is composed of a revolute vertical joint that rotates around the vertical axis and a novel custom shape guide. The guide has been designed to constrain the movement of a cart along a specified path. This path has been obtained based on the 6-inch pipe specifications allowing a correct probe motion along horizontal and vertical (upward) curves. The revolute joint is, in our prototype, actuated using an Actuonix servo linear motor in order to maintain a control homogeneity respect to the other two joints in the rover. On the other hand, the cart motion is actuated using a servo DC motor through a rack-gear transmission.

Figure 2-1. Rendering of the FAP180 arm.

2.2. Hardware Description of probe

The core element of the FAP and the ARAP solutions is the semi-circular probe. We design the probe to accommodate two opposite UT sensors actuated using two Actuonix linear motors pushing on the pipe circumference. The probe can rotate around the pipe axis thanks to a novel cart design. The cart, linked to the arm end effector, is actuated by a DC servo motor and a rack-gear transmission.

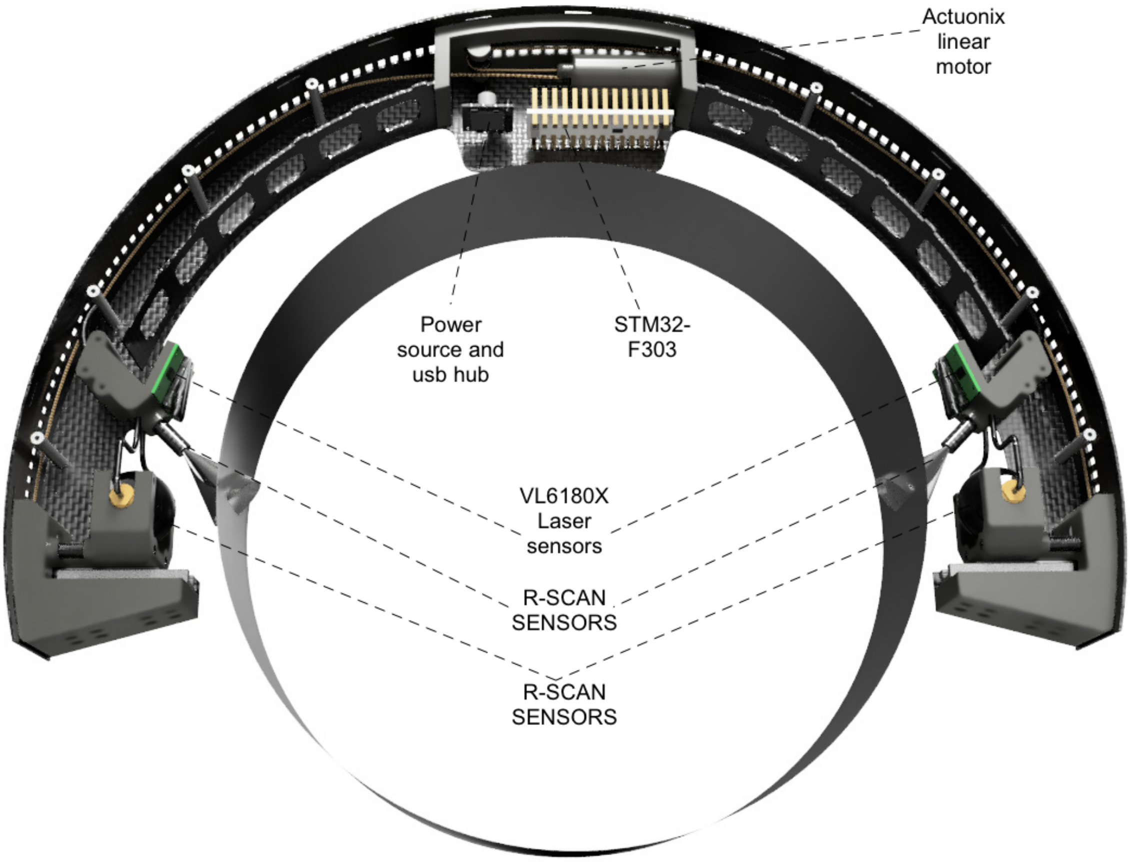

Figure 2-2. Design of the 180° tool with R-scan UT sensors.

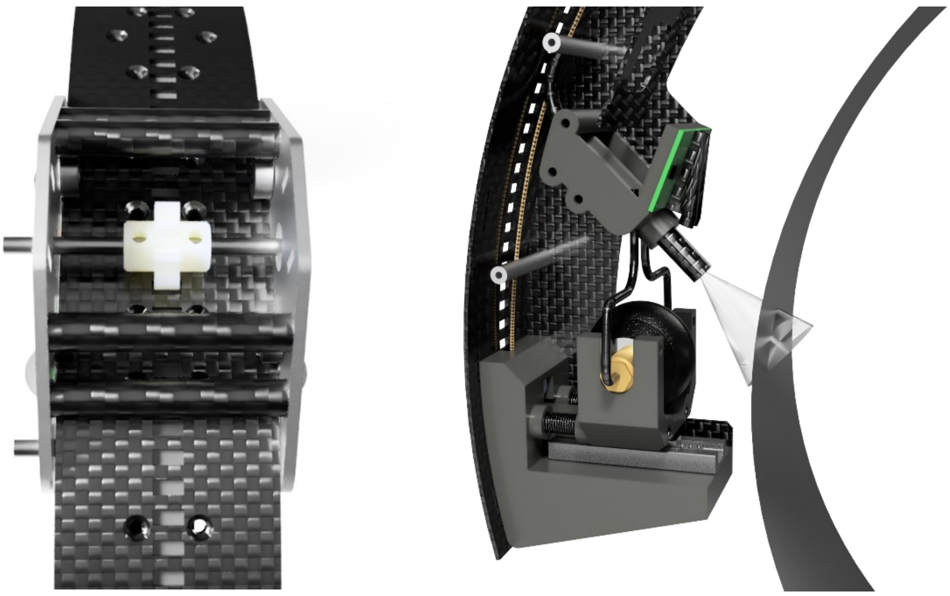

Figure 2-3. Details of the tool: geared rail (Left), internal components of one UT sensors.

In Figure 2-4 the probe degrees of freedom are shown: From the left to the right, the different phases to obtain the measure are reported (UT sensors in rest position – UT sensors are pushed on the pipe – UT sensors retracted); from the top to the bottom, the rotation motion used to move the UT sensors along the pipe circumference is shown.

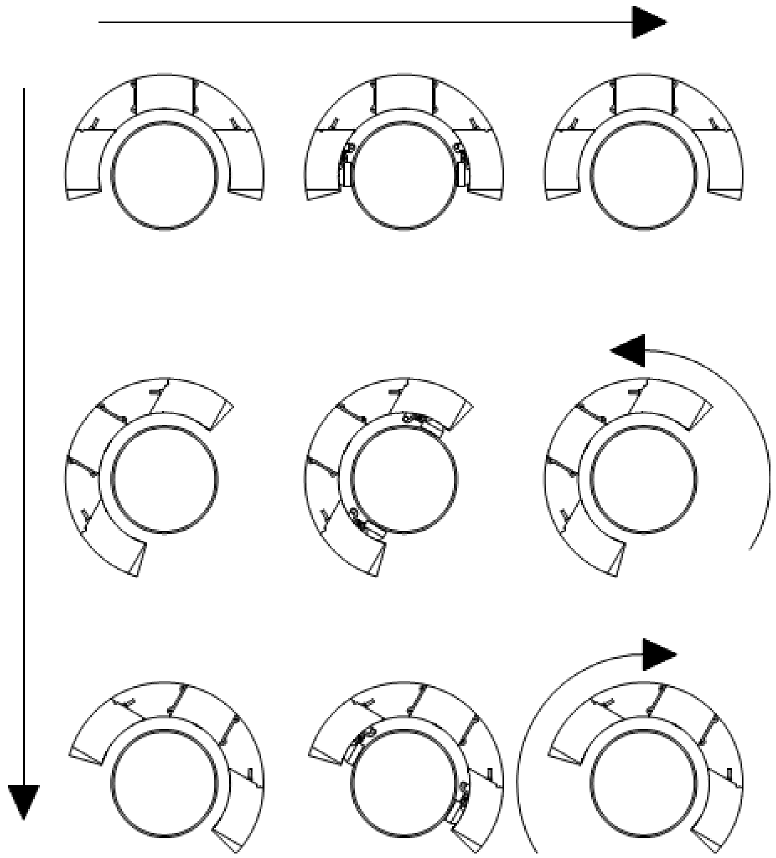

Figure 2-4. Working principle of the 180° tool.

2.3. Electronics and control

In Figure 2-5 the conceptual scheme of the FAP arm control architecture is reported. In detail, a single STM32-F303 microcontroller manages the arm and tool. The arm micro is commanded via UART by the main board included in the rover and communicates with:

1. Two Actuonix motors (see details in Section 7.2.3) one for the arm first joint rotation and one included in the tool to retract the UT sensors
2. Two Gear motors one to move the guided rail in the arm and one to rotate the tool around the pipe axis.
3. Four laser distance sensors inserted in the tool via I2C communication.

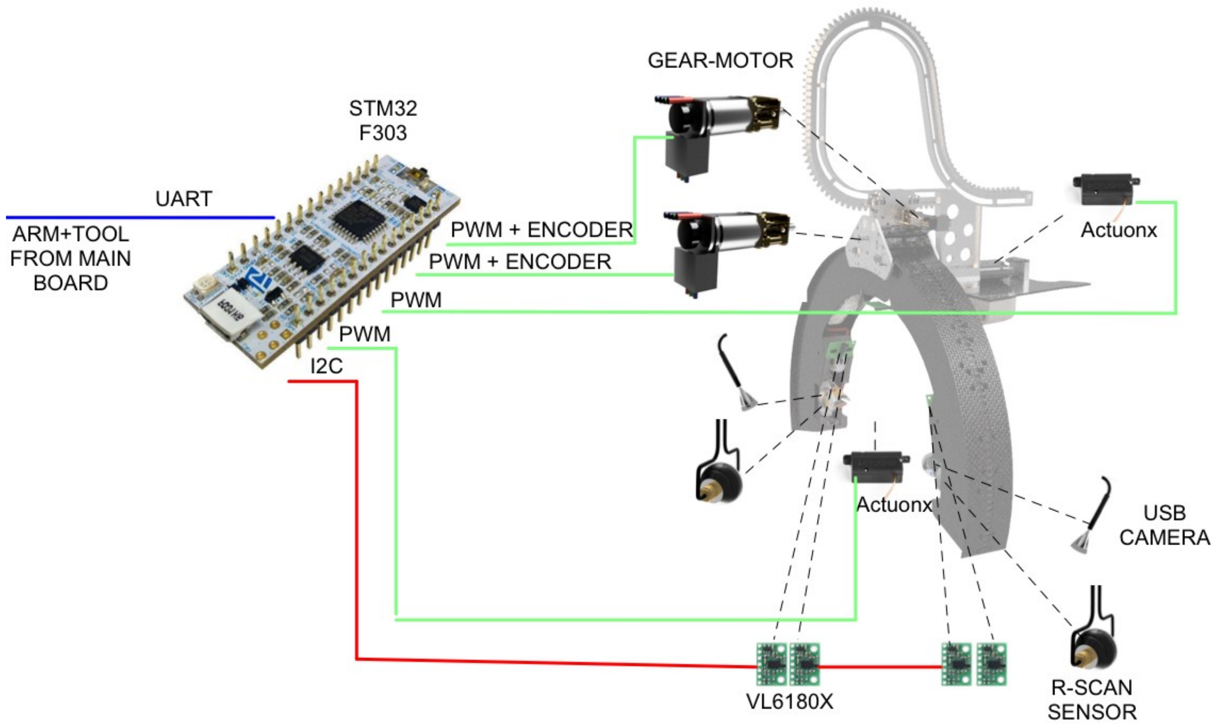

Figure 2-5. FAP180 electronics architecture.

2.4. Kinematic description

The FAP arm has been designed to reduce at minimum the number of actuators and consequently the arm weight.

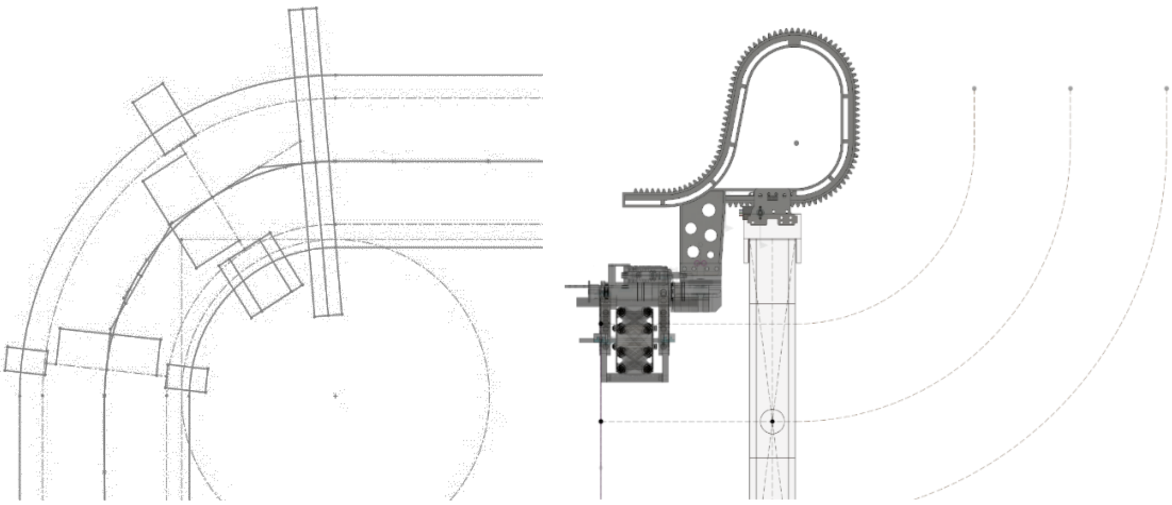

Figure 2-6. FAP180 guidelines to define the kinematics.

Hence, we have designed the FAP arm to work in cooperation with the articulated rover sharing some degree of freedom. In this way, the FAP arm can move following the pipe curvature as it is shown in Figure 2-7. Moreover, a novel rail-guide mechanism has been designed to move the probe following the upper pipe curve and to move the tool in the rest position (see Figure 2-7 and Figure 2-8). The guide must be modelled specifically for the diameters of different pipes.

2.5. Capabilities

As reported in the following figures the arm can perform measures along linear pipes, vertical (only upward) curves and horizontal (left and right) curves.

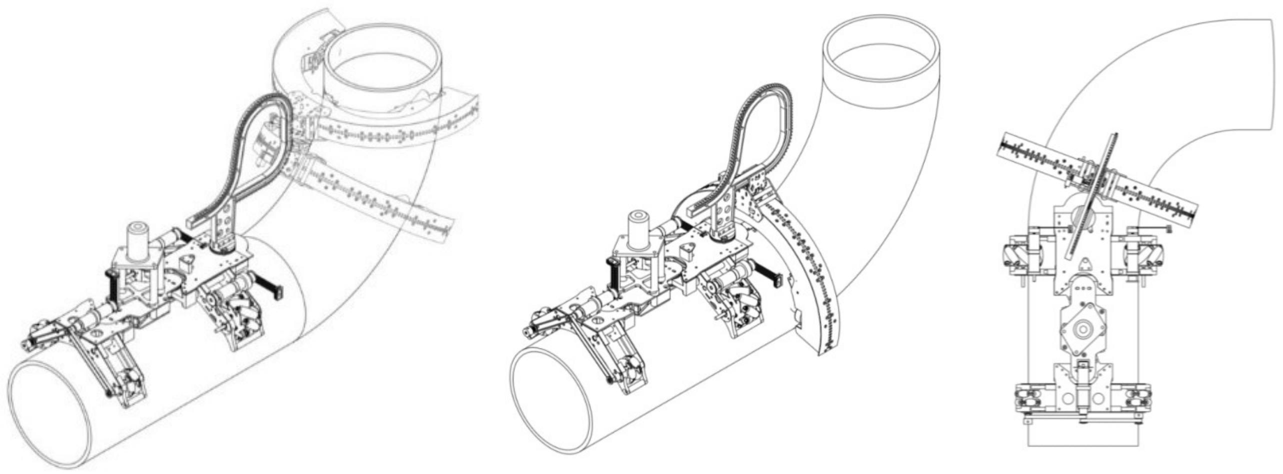

Figure 2-7. FAP180 capabilities of the system.

In the following figure the arm in the folded configuration is reported. In this configuration the interferences during the flight are minimized.

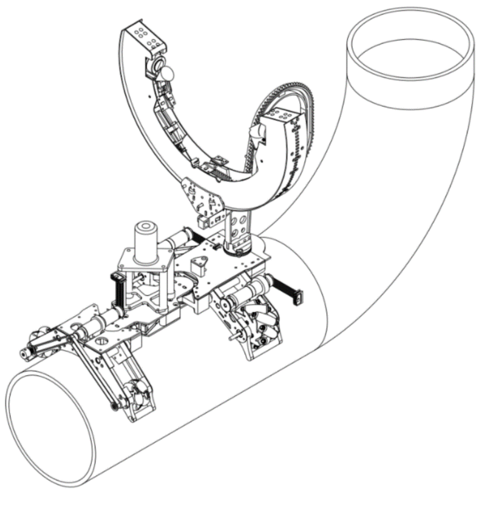

Figure 2-8. FAP180 arm rest position

2.6. First prototype

We developed a prototype of the probe using carbon fiber plates and 3D printed plastic elements. The prototype contains two UT sensors, two Actuonix linear motors, two miniaturized cameras to enable the visualization of the measuring point and six laser distance sensors used to control the arm along the pipe curves.

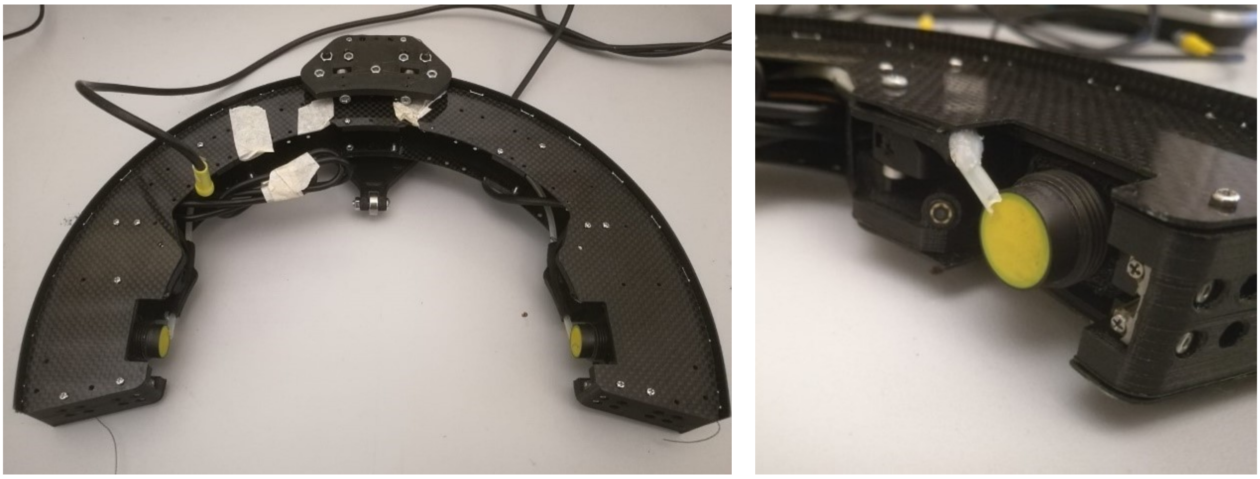

Figure 2-9. First prototype of the 6-inch tool with tritex UT sensors and gel dispenser.

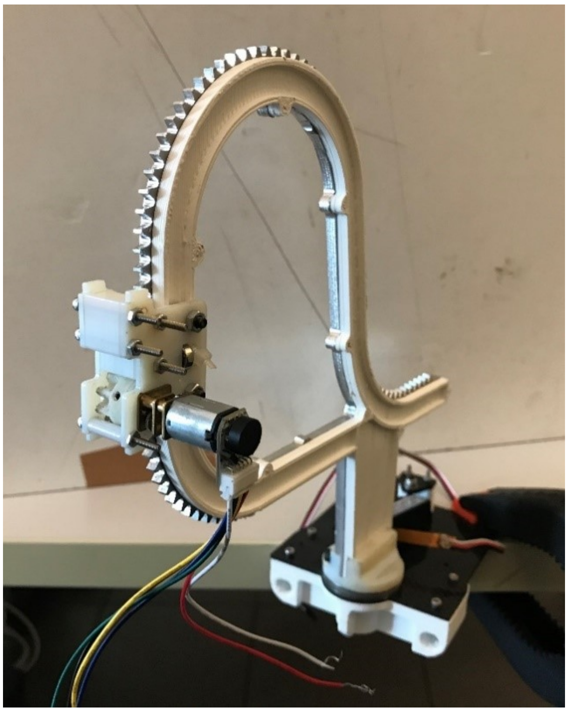

Figure 2-10. First prototype of the FAP180 arm.

3. Anthropomorphic Robotic Arm (ARAP)

In this section, the second arm solution is presented. We design the ARAP to maximise the system dexterity and capability but reducing the kinematic complexity with respect to the more complex SAP solution which will be presented in Section 4. Two different versions of the ARAP have been developed in HYFLIERS

- The ARAP180 uses a 5 DoFs Anthropomorphic robotic arm with a 180° probe equal to the probe used in the FAP solution.
- The ARAP90 uses a 6 DoFs Anthropomorphic robotic arm with a 90° probe with a single UT sensor. In this case, the reduced dexterity of the probe is compensated by adding an additional DoF in the arm. On the other hand, this solution enables also the possibility to measure T-Pipe thanks to the probe design.

3.1. ARAP180: Hardware Description of the anthropomorphic arm

A 5 DoFs anthropomorphic arm is used for the ARAP180. In our prototype, the arm has been linked to the articulated rover to improve the system capabilities. However, the arm can be used also stand-alone linked to the different add-ons of the HRA presented in the D2.1. In our prototype, the first revolute joint allows the rotation around the vertical axis. The other four joints are revolute and describe an anthropomorphic kinematic with a non-spherical wrist. Each joint is actuated using Dynamixel servo motors. The third joint is actuated with a parallelogram mechanism by a Dynamixel motor positioned near the second joint. This choice allows us to reduce retract the arm barycentre. Moreover, springs have been used in the second and fourth joints to compensate the arm gravity and reduce the effort on the actuators.

Figure 3-1. 3D rendering of the ARAP180 arm mounted on the system.

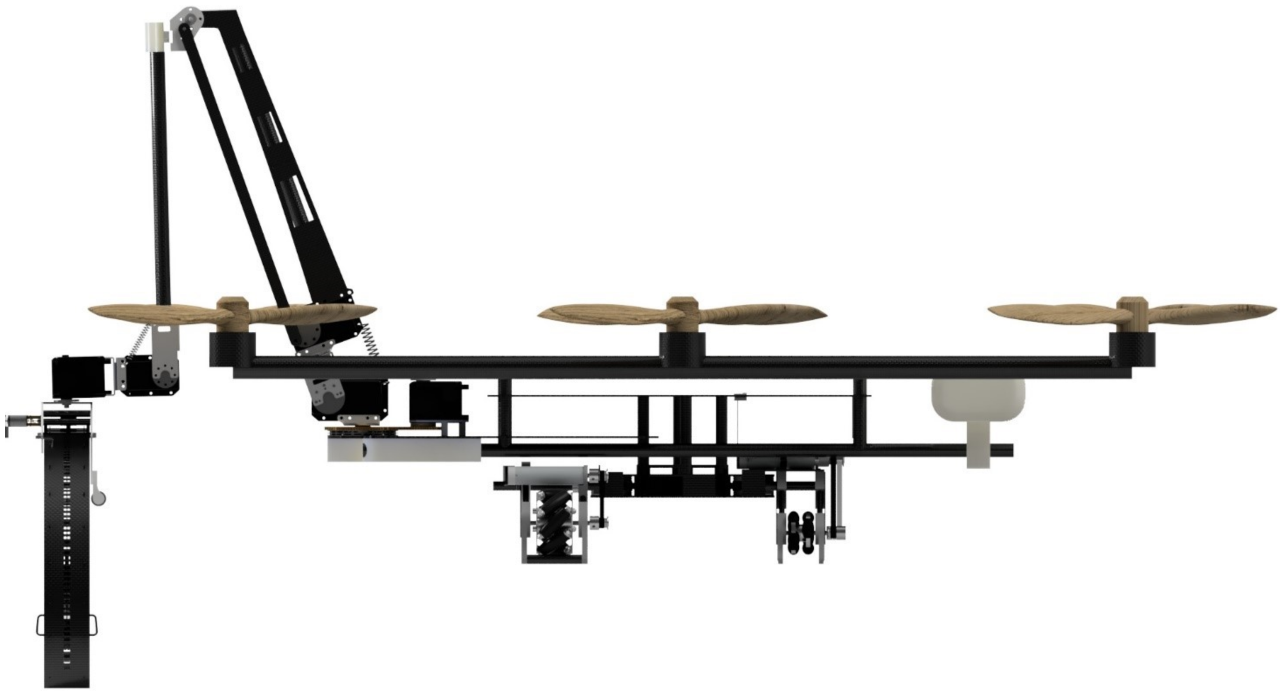

Figure 3-2. Lateral view of the system.

Figure 3-3. Detailed rendering of the ARAP180 arm (Left) and of the tool (Center). ARAP arm in a possible folded configuration (Right).

3.2. ARAP180: Kinematic description

The kinematics of the ARAP180 arm is reported in the following figures.

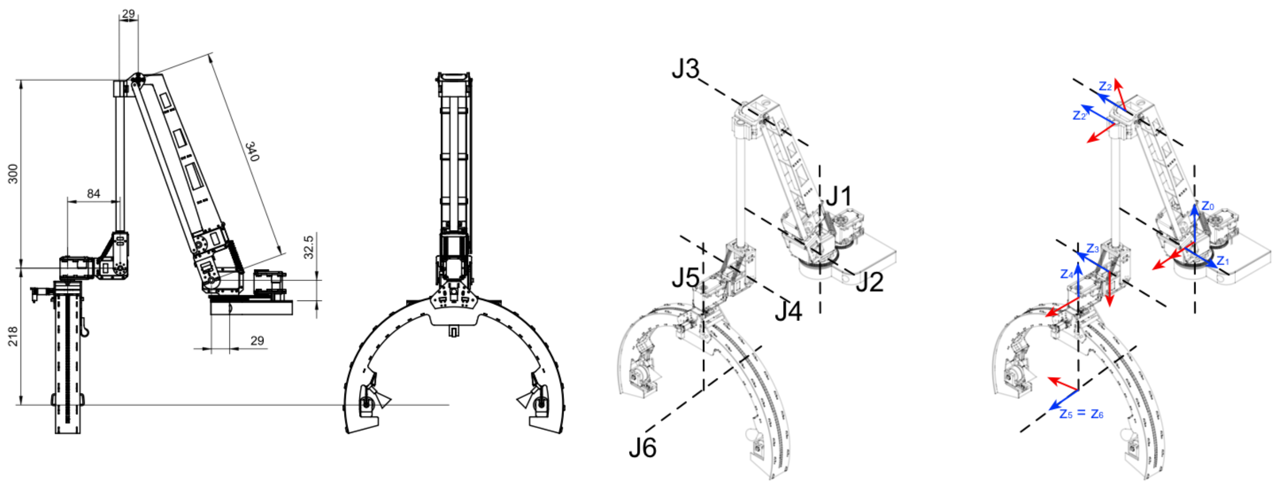

Figure 3-4. Dimensions, joints and frames of the ARAP180 arm.

The ARAP arm kinematic has been modelled with the Denavit-Hartemberg convention as reported in Table 2 and considering frames reported in Figure 3-4.

Table 2. DH parameters

Link	a [m]	Alpha [deg]	D	Theta	offset
1	0.029	-90	0	0	0
2	0.340	180	0	0	-90
3	0.029	0	0	0	-90
3' (fixed)	0.3	0	0	-90	0
4	0.084	-90	0	0	90
5	0	-90	-0.218	0	-90
6	0	0	0	0	0

The complete dynamic model of the arm has been obtained using the Newton Euler formulation. We calculated the torque requested to the actuators in different operative conditions. In Table 3 we reported the requested actuator torques in the worst case: arm full elongated with the 180° probe and considering an acceleration for each joint about $0.2 rad/s^2$. Furthermore, we include two springs in the joints 2, 3 and 4. The springs have been designed to apply a torque to compensate partially the gravity by maintaining a good bandwidth of the robot. The estimated torque values, the torques applied by the springs and the torque requested to the actuators have been reported in Table 3.

Table 3. Joint torques

Joint	1	2	3	4	5	6
Torque max estimated [Nm]	-0.07	4.3	-2.5	-0.34	-0.002	0.005
Spring torque [Nm]	0	-2	1	0.2	0	0
Torque requested to the actuators in the worst case [Nm]	-0.07	2.3	-1.5	-0.14	0.002	0.005

Considering these parameters, we choose a Dynamixel MX28 for the joints 1, 4, 5, a MX64 for the joint 3 and a MX106 for the joint 2. The parameters of the actuator are summarized in Section 7.2.4. It is possible to see that the estimated values are under the maximum nominal torques of the actuators.

3.3. ARAP90: Hardware description of the anthropomorphic arm

The ARAP90 differs from the ARAP180 for the use of a 90° probe with a single UT sensor. This solution allows to:

1. Reduce the probe weight improving the arm manoeuvrability and reducing at the same time the overall system weight.
2. Improve the system dexterity to measure also T-pipes

However, this solution requires a 6 DoFs arm to move the probe in all the required configurations. In our design, the 6 DoFs arm is obtained by adding another DoF in the ARAP180 arm wrist to obtain a spherical wrist as shown in Figure 3-5.

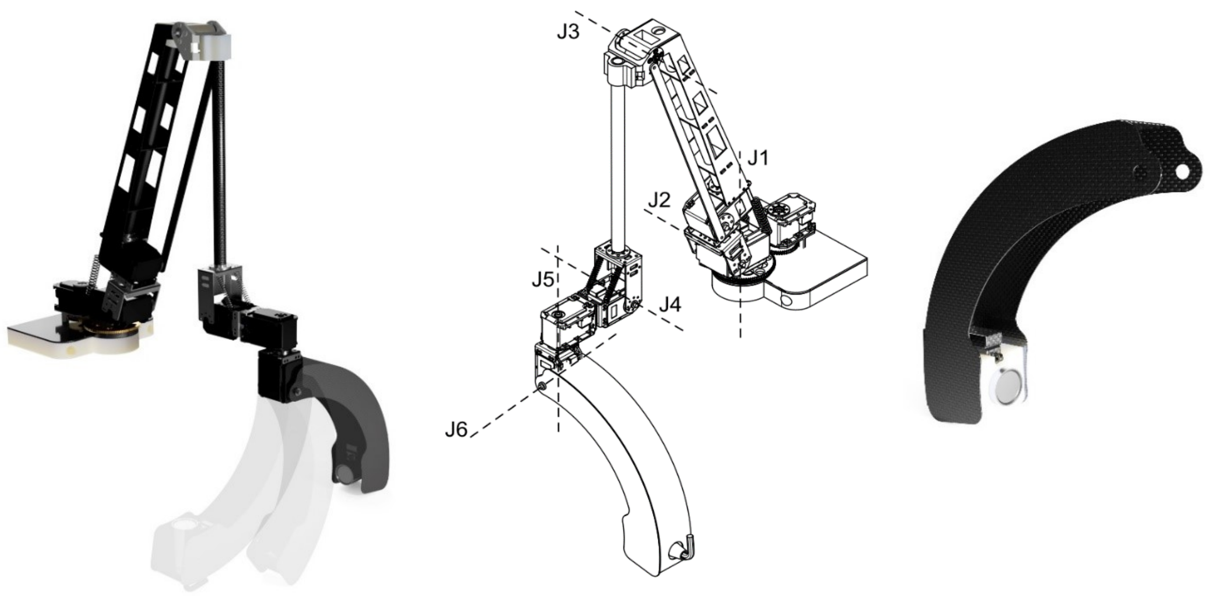

Figure 3-5. Design of the ARAP90 arm.

3.4. Electronics and control

The conceptual scheme of the ARAP arm electronics architecture is presented in the Figure 3-6. In detail, the arm is actuated by 5 or 6 Dynamixel motors (see more details in Section 7.2.4). The motors are controlled by a single wire half duplex UART connected to the main F767ZI microcontroller through a full-to-half duplex circuit (see Figure 3-7). On the other hand, a single STM32-F303 microcontroller manages the tool. The tool micro is commanded via UART by the main board included in the rover and communicate with:

1. One Actuonix motors (see details in Section 7.2.3) included in the tool to retract the UT sensors
2. One gear motor that actuate the gear-rack transmission to rotate tool around the pipe axis.
3. Four laser distance sensors inserted in the tool via I2C communication.

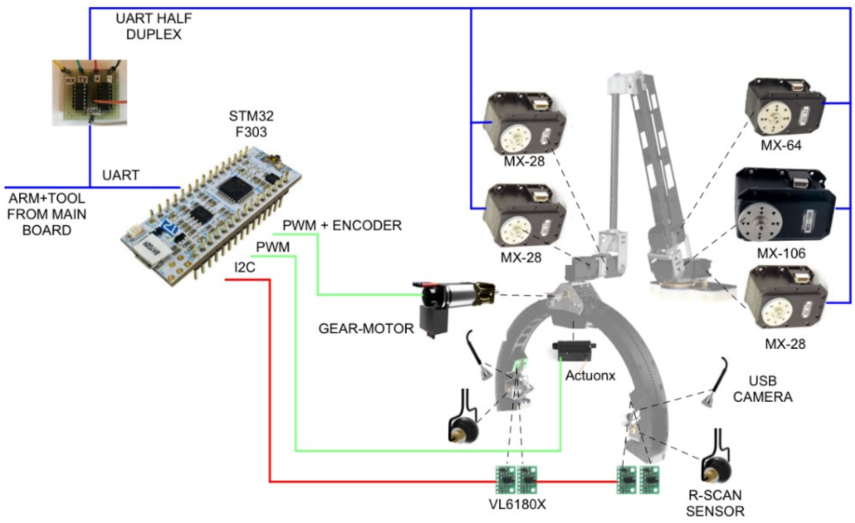

Figure 3-6. Electronics architecture of the ARAP arms.

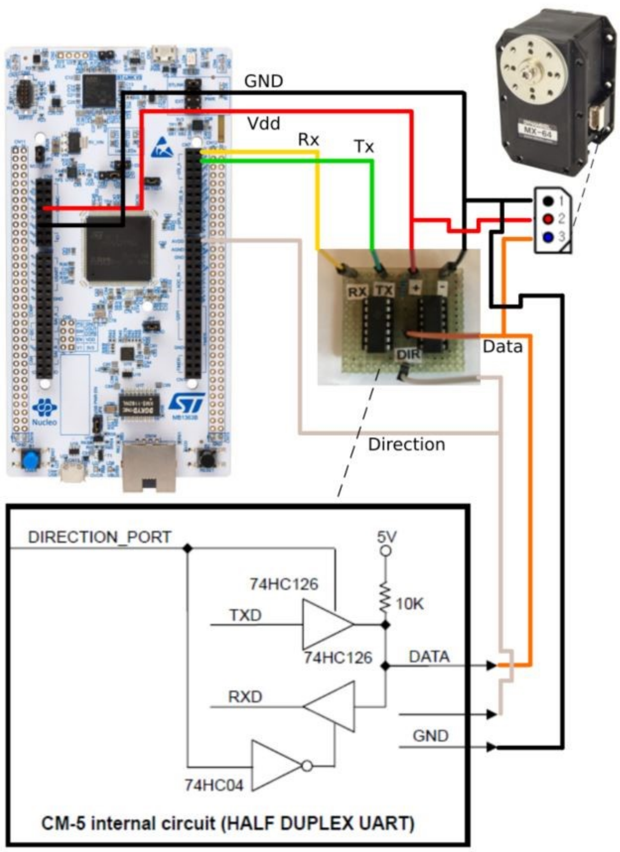

Figure 3-7. Dynamixel wiring with the microcontroller using the full to half duplex circuit.

3.5. Prototype

In the following figures our first prototype of the arm is shown connected directly on the articulated rover. Meanwhile, the final version is currently under development.

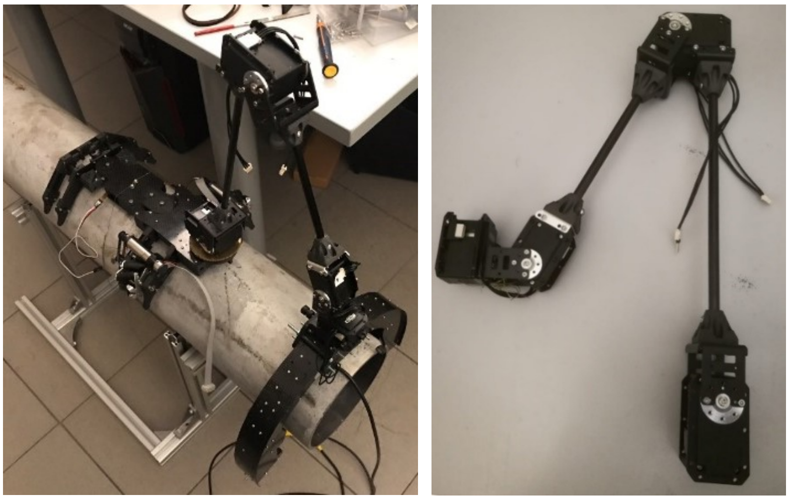

Figure 3-8. First prototype of the ARAP arm.

3.6. V-Rep simulation and first prototype

We have designed a simulator of the HYFLIERS system in V-REP to test the kinematic and develop the control strategies.

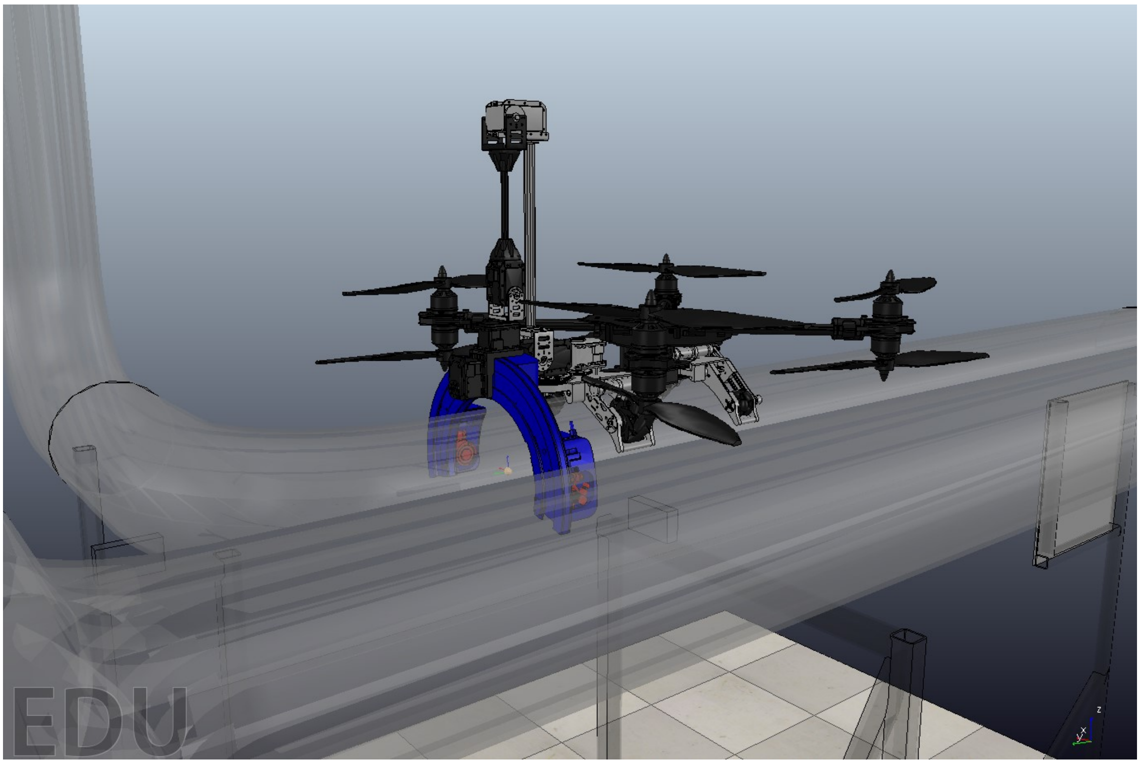

Figure 3-9. V-REP simulator of the system.

The simulator allows controlling all the rover joints and wheels as well as the arm and the tool joints. In this framework, ROS (Robotic Operating System), MATLAB or C++ and Python scripts through the V-Rep Remote API can be used to control the robot.

3.7. Capabilities

The ARAP arm allows having a good dexterity in performing measures in different operative conditions. The following figures summarize the ARAP capabilities showing the possibility to measure linear pipe sections, measure adjacent pipes, horizontal curves and vertical curves both upwards and downwards.

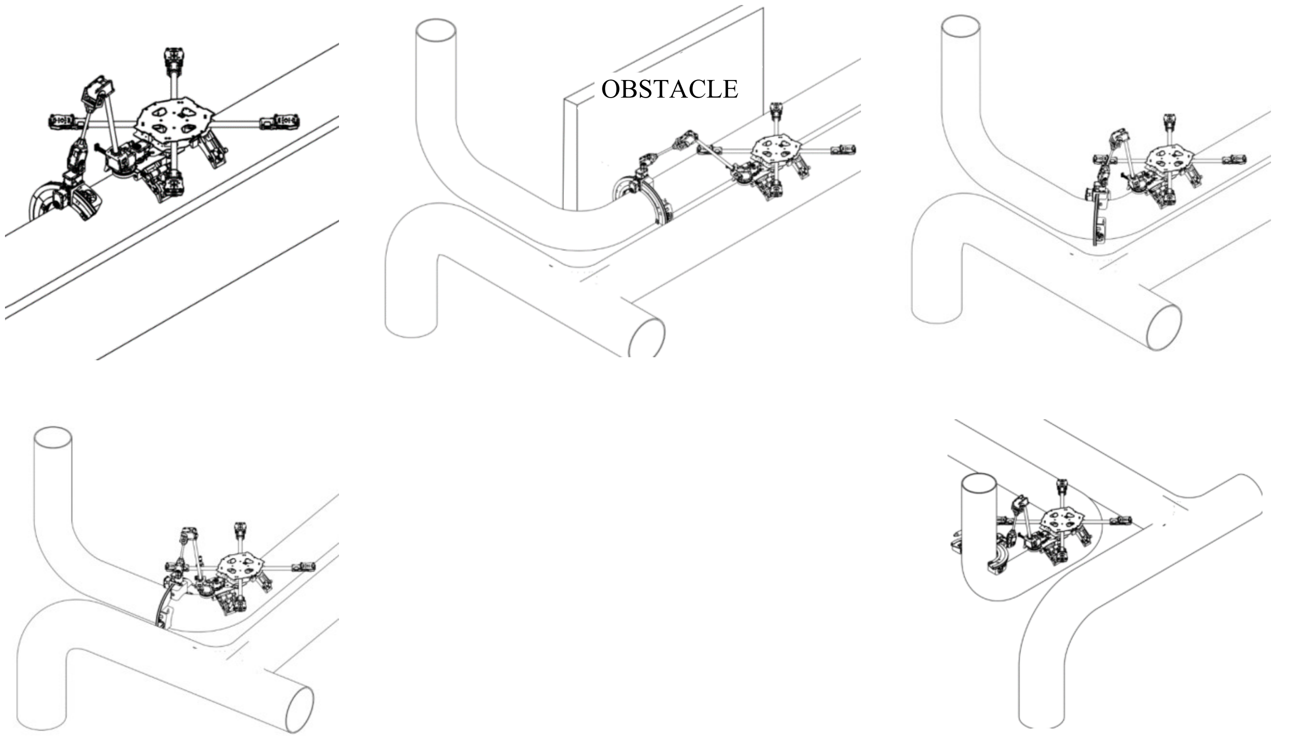

Figure 3-10. ARAP arm case studies.

4. Snake Arm with Pan and Tilt Probe (SAP)

The SAP is the most complex solution we developed. The prototype has been designed to further improve the dexterity and flexibility of the system, to work in a wide range of scenarios. In details, the SAP is composed of:

1. A pan and tilt motor box connecting the arm with the drone frame
2. A hyper redundant robotic snake arm
3. A pan and tilt probe with a single UT sensor.

Figure 4-1. Typical use case.

4.1. Hardware Description of the snake arm

As shown in Figure 4-7 the whole kinematic has been made only from rotational joints. This describes a structure constituted by an end effector with two degrees of freedom, a planar snake and a pan-tilt bracket that gives it two more degrees of freedom.

Focusing exclusively on the snake arm, it is a simple planar robot unable to perform all the required motions. For this reason, was developed a bracket that in addition to containing all the robot actuators and pulleys for the tendons, allow to extend the workspace, from a simple plane to a sheaf of planes, having as common line the pan rotation axis.

This choice gives it a functional three-dimensionality, while not losing the possibility of describing it simply with a planar approach.

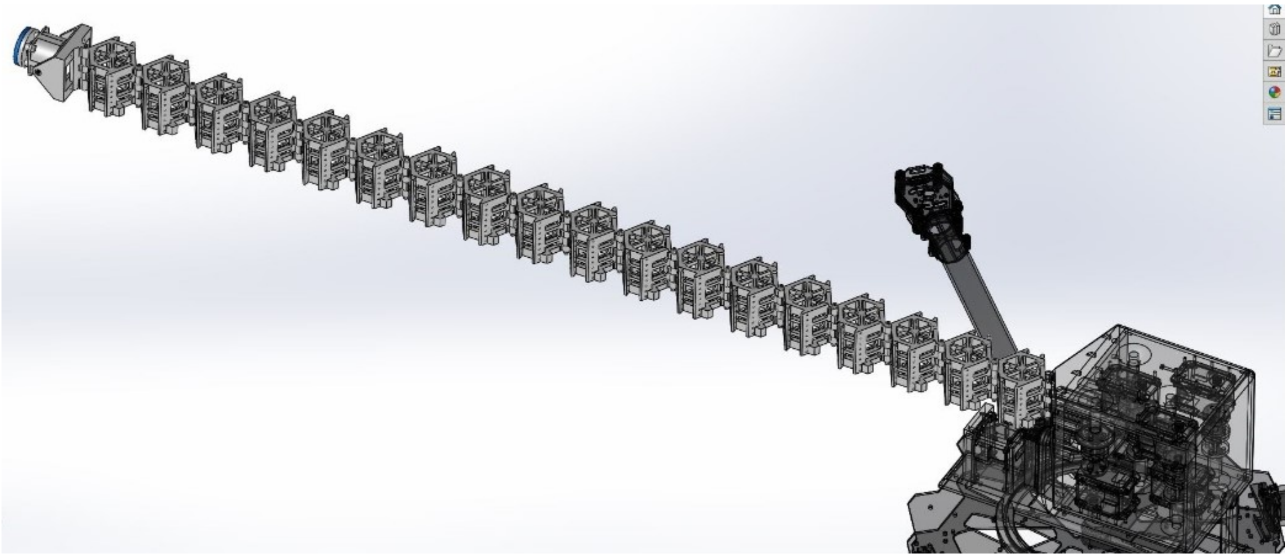

Figure 4-2. Snake arm fully stretched.

The developed snake arm is tendon driven. In this way, the most part of weight is close to the drone frame and give to it a desirable centre of gravity.

The motors sizing follows a static working principle applied in a worst condition, it depends from links working angle, to prevent every problem during works.

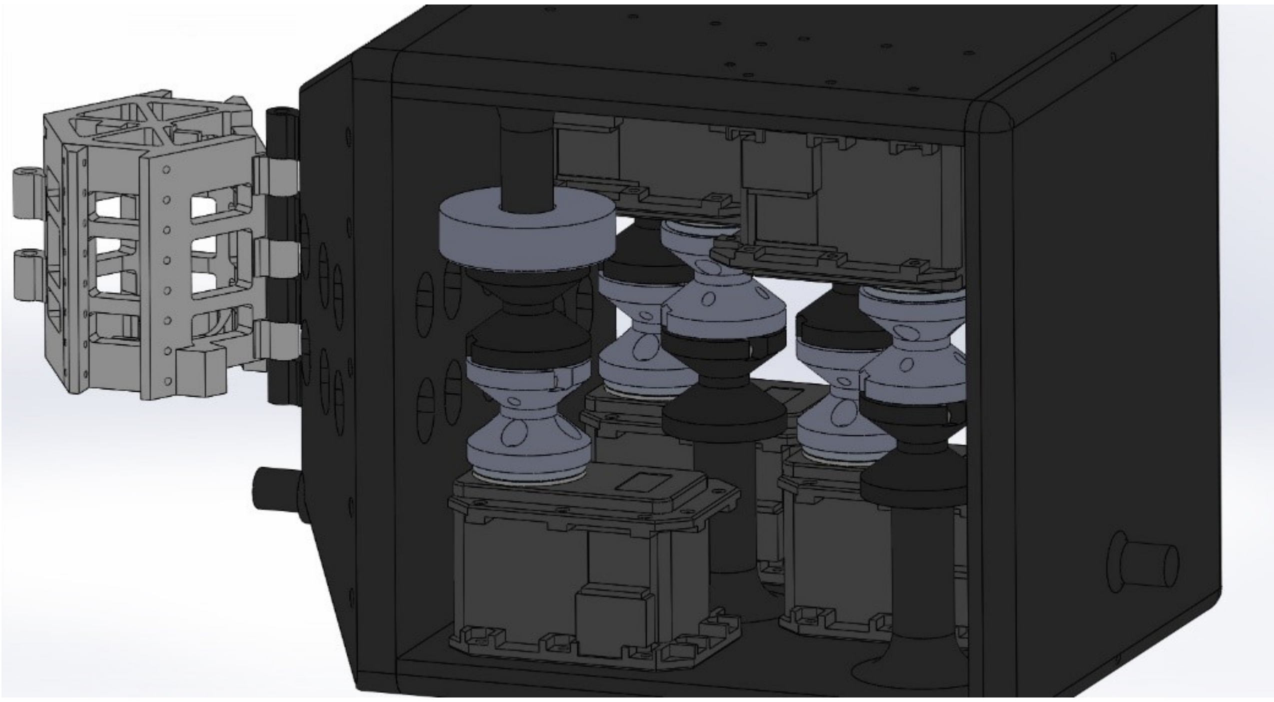

Figure 4-3. Detail of the motor housing, motors and pulleys.

To improve static mechanical compensation of a gravity force, for the last module before end-effector, we had developed a simple system to use a mechanical force of torsional springs.

In the first two images of Figure 4-4, we can see both section and perspective view that show the proposed mechanism. In the latter two images, we can see the mechanism working principle. In this example we show how and when the torsional spring works when the link is turn.

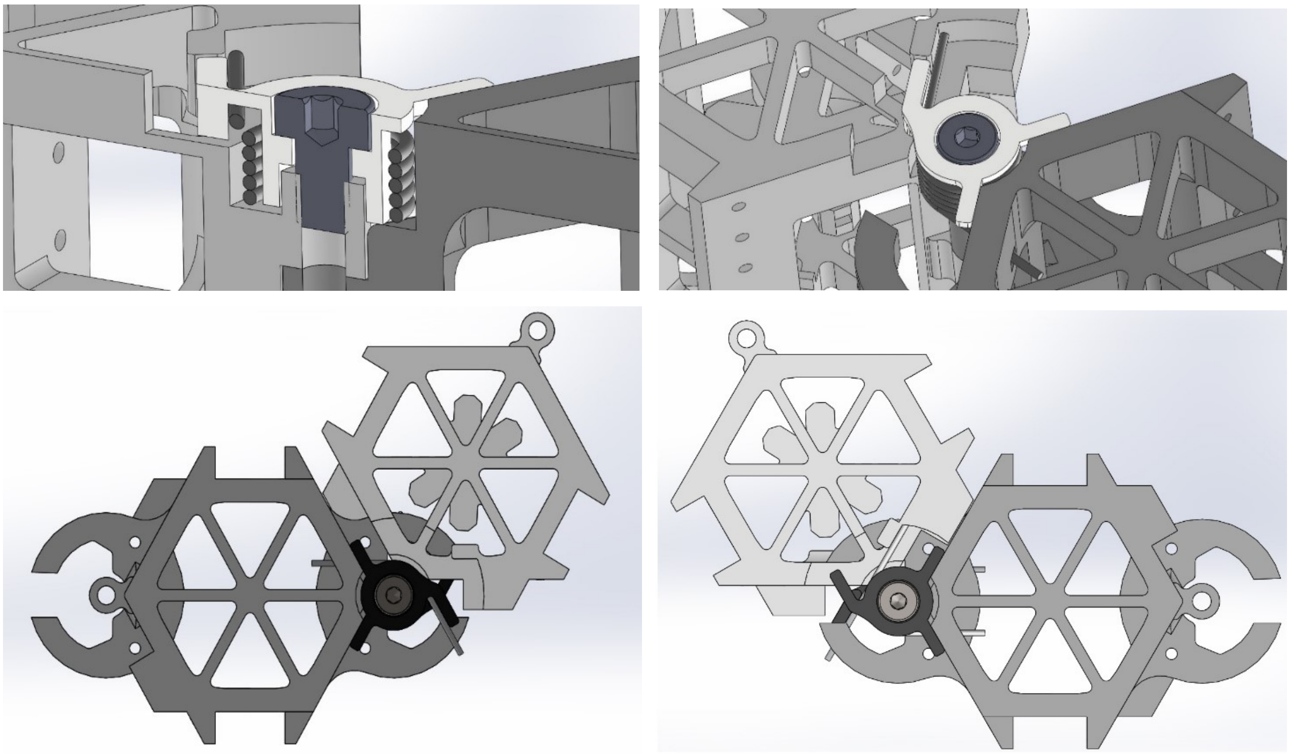

Figure 4-4. Static mechanical compensation mechanism.

4.2. Hardware Description of the probe

The probe allows adding two additional DoFs to accommodate the contact between the measure probe and pipe surface. The terminal part of the end effector, that sticks out from probe, is made up in polyurethane soft foam to indulge the curvature of pipes during the contact phase. Depending on UT probe chosen, the foam form and a thickness will be modified to correctly achieve the contact between probe and pipe. The type of probes we choose need contact and gel to realize measures, in this case the foam will be more protruding than probe and will be squeezed, during the approach phase. For this measure we need a tank to contain conductive gel and a little pipe that deposit off a little amount of gel. Other, and more advantageous probe don’t need coupling gel and in this case the contact between probe and pipe are guaranteed by a magnetic force explained by it. In this case we don’t need force to keep in touch probe and pipe but need appropriate force to separate probe and pipe after we reach a measure. Visual inspection will be performed by micro-camera mounted near UT probe. In this release the camera is not shown for simplicity.

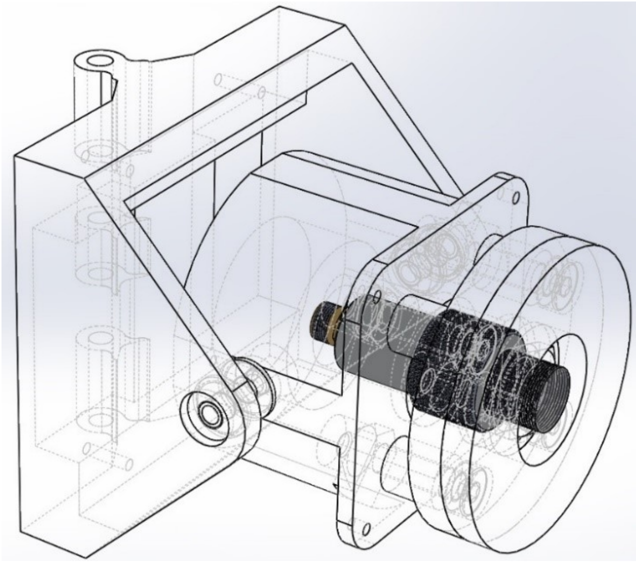

Figure 4-5. End effector and Probe.

4.3. Kinematic description

Our prototype has been designed to reduce the weight of the structure by choosing light materials (carbon fiber and reinforced 3D printed plastic) and reducing the number of actuators.

In order to solve the problems related to under-actuated systems, in other words the presence of uncontrollable links, we decided to create the snake modules as a coupled mechanism with one degree of freedom. Hence, the kinematic model of the snake can be described as a series of rigid kinematic mechanisms with one degree of freedom composed of three links. The motion of each module is, in this way, decoupled from the motion of the others.

The single module is made with two active links and one passive. The name passive suggests a link crossed by tendon and not connected with it. The active link is connected to the next same link type by a tendon which influences its motion. For example, in a single module in Figure 4-6 identified by “L12, L23, L31’ “the rotation around joint n°3 of link L31’ and rotation of passive link L23 around joint n°2 are related. Therefore, the angular rotations made by L31’ and L23 are the same.

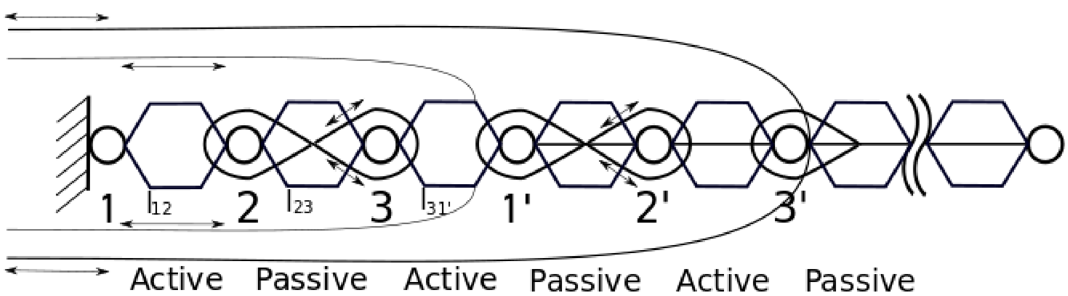

Figure 4-6. Kinematic scheme.

Denavit-Hartemberg convention has been chosen to define relative position and orientation between two consecutive links with the reference frames reported in the following figure.

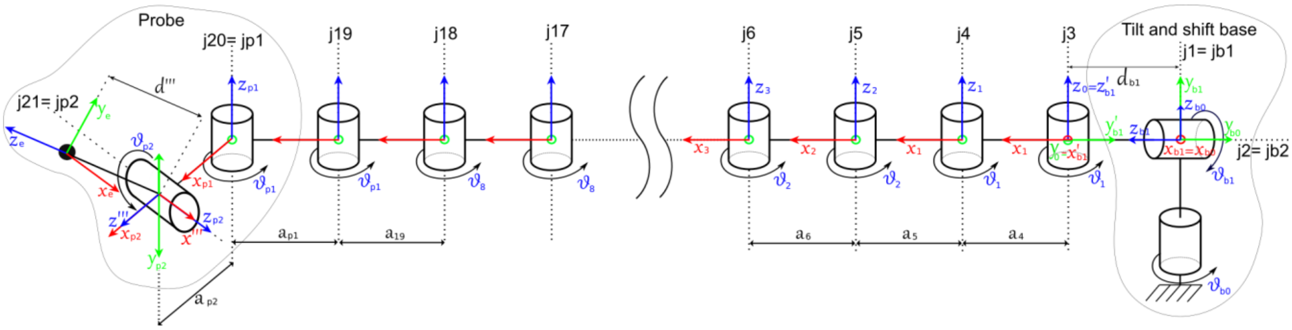

Figure 4-7. Denavit-Hartenberg reference frames.

4.4. Electronics and control

In Figure 4-8 is reported a schematic description of the electronics controls board used to move the actuators, read the measurements of the UT probe and, in the same time, the main control device (Intel Up2) provides to manage a video signal coming from USB-camera.

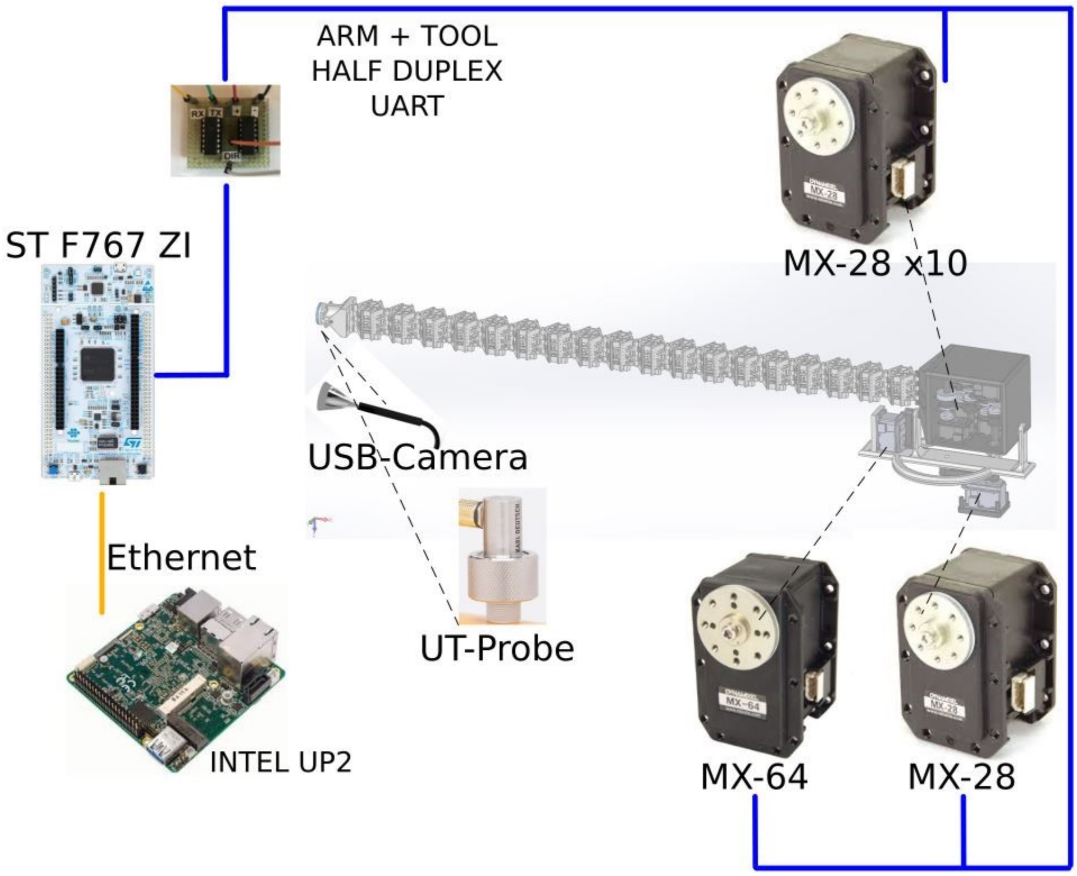

Figure 4-8. Conceptual scheme of motors, electronics, devices and protocol.

4.5. Module prototype

In Figure 4-9 the first prototype of the SAP single module arm is shown.

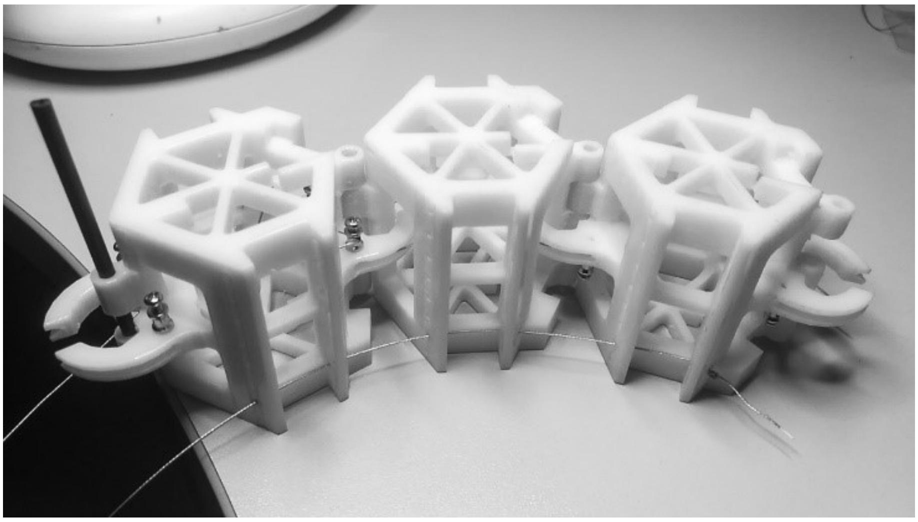

Figure 4-9. Module prototype.

Moreover, Figure 4-10 shows the SAP overall dimension drawing.

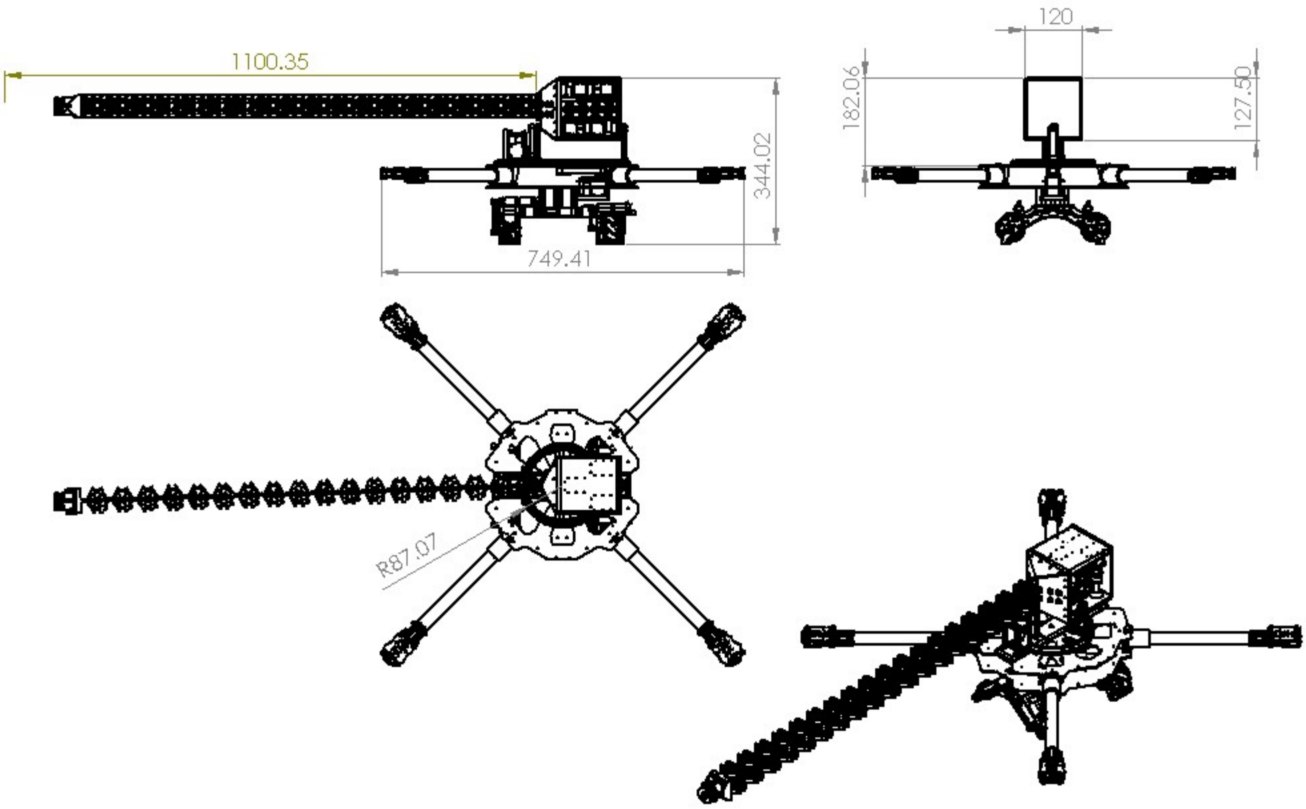

Figure 4-10. Size of the current design for the snake arm.

4.6. V-Rep simulation and first prototype

Also, in this case we developed a V-REP simulator of the system to test the kinematics and develop the control strategies. This design has been tested in different situations.

The first simulation shows a longitudinal measurement procedure along x on the $x - y$ plane, in which the secondary constraint has been implemented in the kinematic inversion to obtain a "obstacle avoidance" task.

It is evident that the robot, despite encountering a pipe during its motion, can exploit the redundancy to avoid the obstacle, leaving the required path to the probe unchanged.

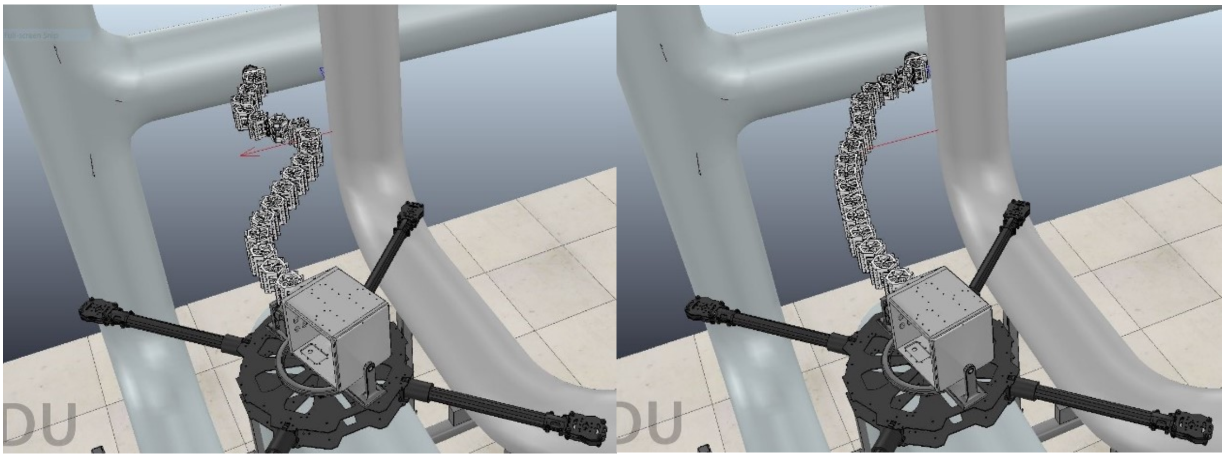

Figure 4-11. Obstacle avoidance simulations.

From the first graph the distances of each link from the obstacle are highlighted, in the second one the shortest distance during simulation between the obstacle and the nearest link is displayed.

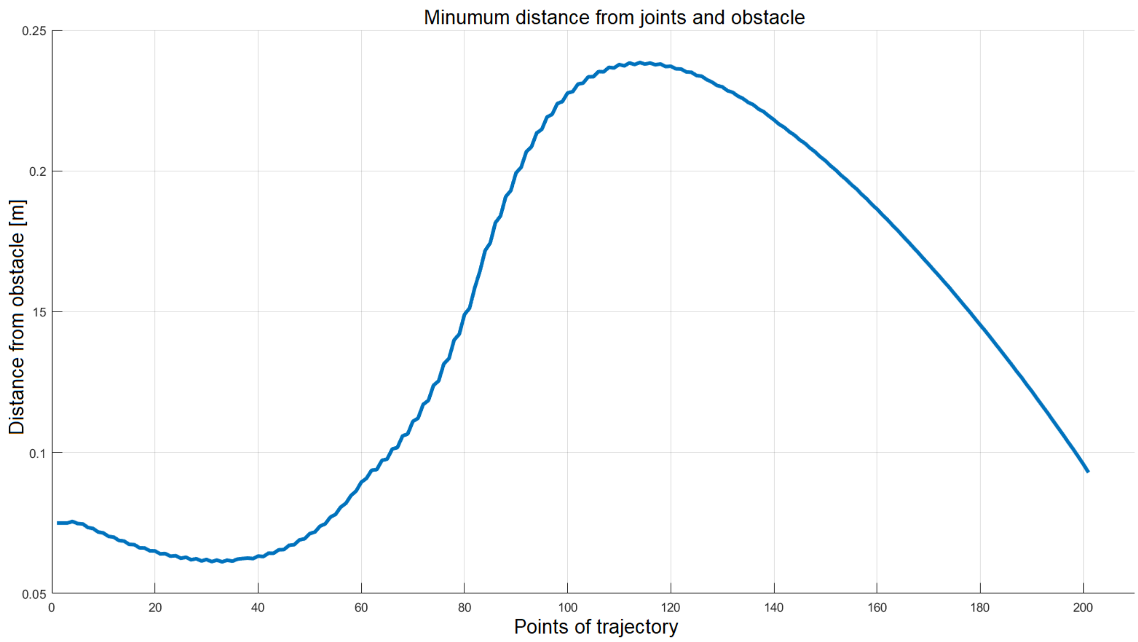

Figure 4-12. Distances between closer link and obstacle.

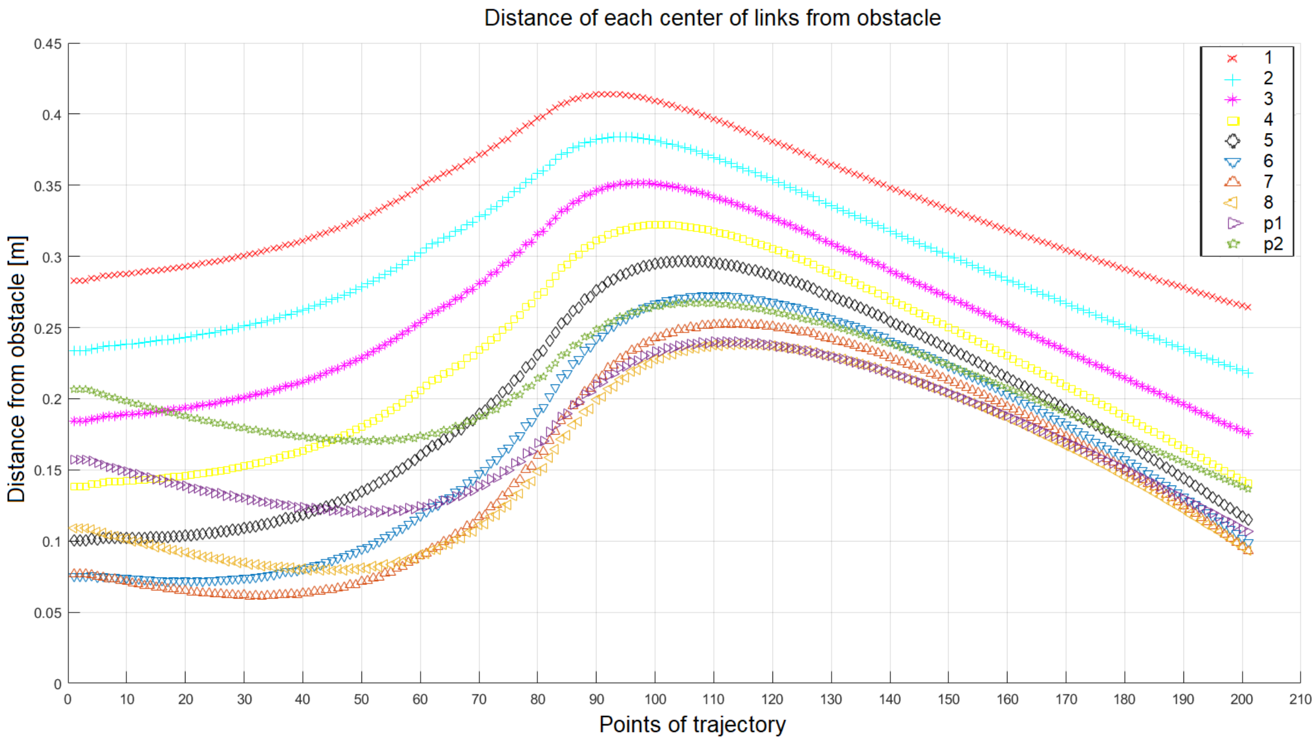

Figure 4-13. Distances between links and obstacle.

Here, the measurement capabilities of the robot are highlighted, it is clear how the longitudinal measurement tasks can be accurately obtained. In Figure 4-14 the measure it is carried out on a plane parallel to floor, and in a longitudinal way along x (referred to drone base frame). In Figure 4-16 the measure are achieved on a plane normal to floor, and in a longitudinal way along z (referred to drone base frame). This is further highlighted by the graphs showing the head of the snake along the required axes. The graphs indeed show that the head motion exclusively on the selected axes.

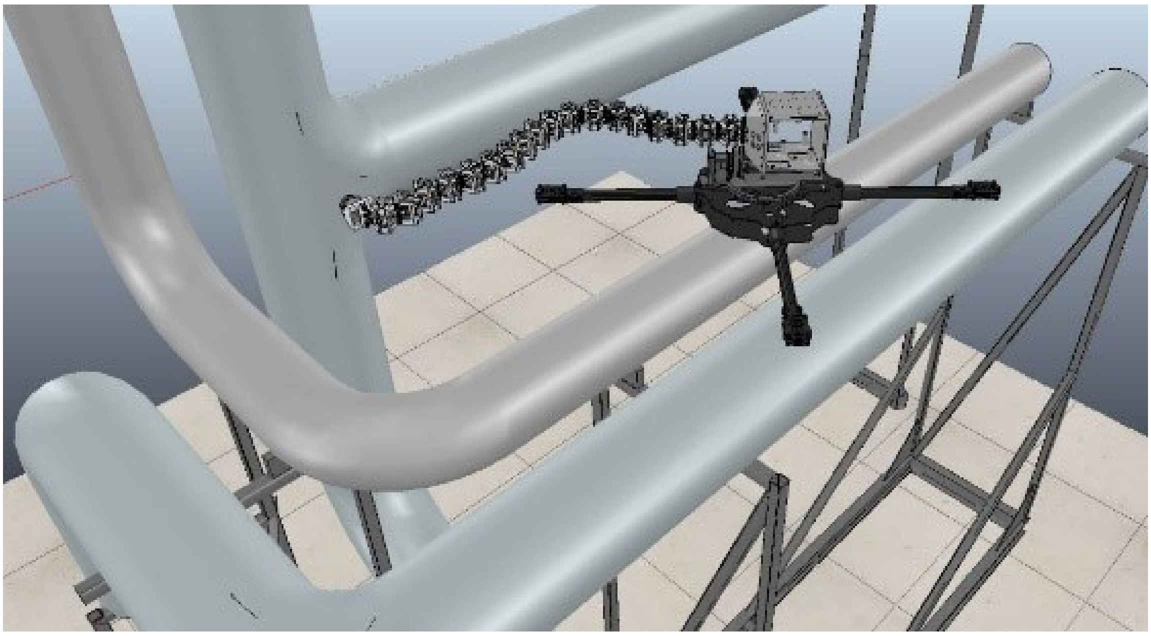

Figure 4-14. Simulations of measure capabilities along X (ref. to base frame).

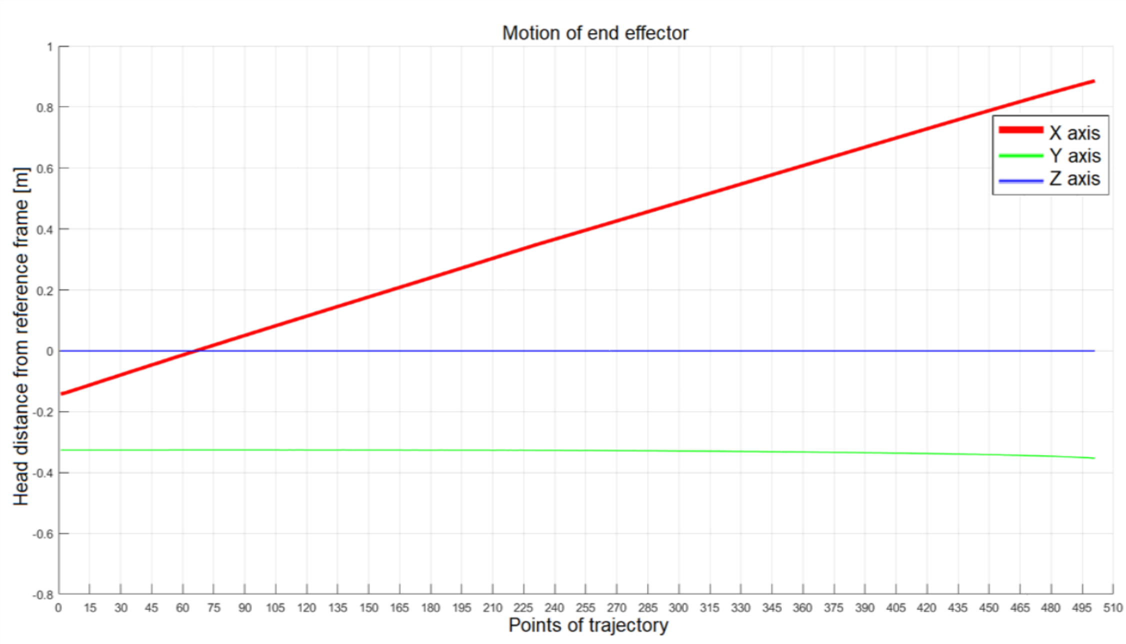

Figure 4-15. Movement of end effector on three axes.

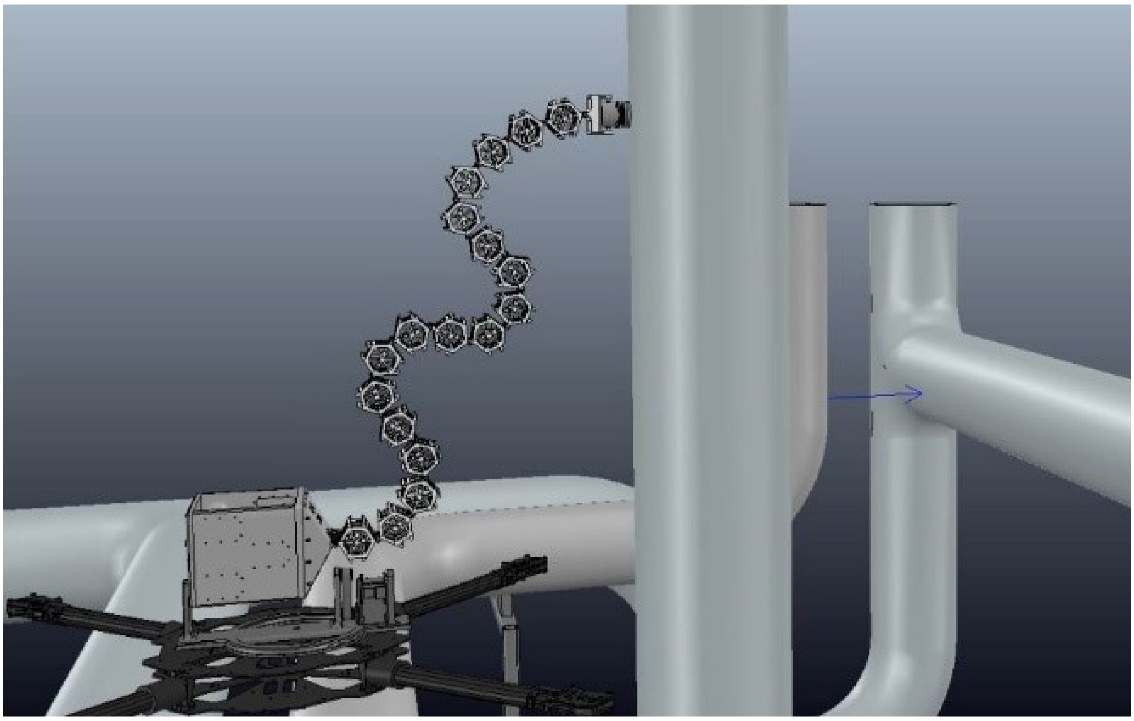

Figure 4-16. Simulations of measure capabilities along Z (ref. to base frame).

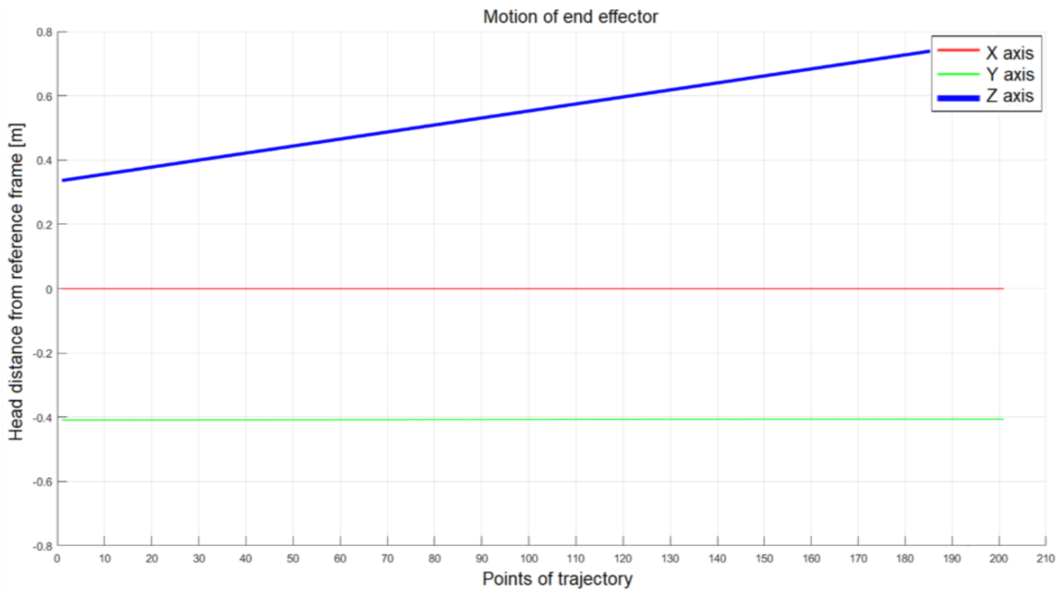

Figure 4-17. Movement of end effector on three axes.

4.7. Capabilities

This section presents the poses that can be adopted by the robot designed in this work. In Figure 4-18 the first image at the top left a), shows the folded configuration used during the flight phases, in order to avoid the impact between propeller and robot and to enhance a mass distribution. The other images b) c) d) show the measurements phases in different scenarios.

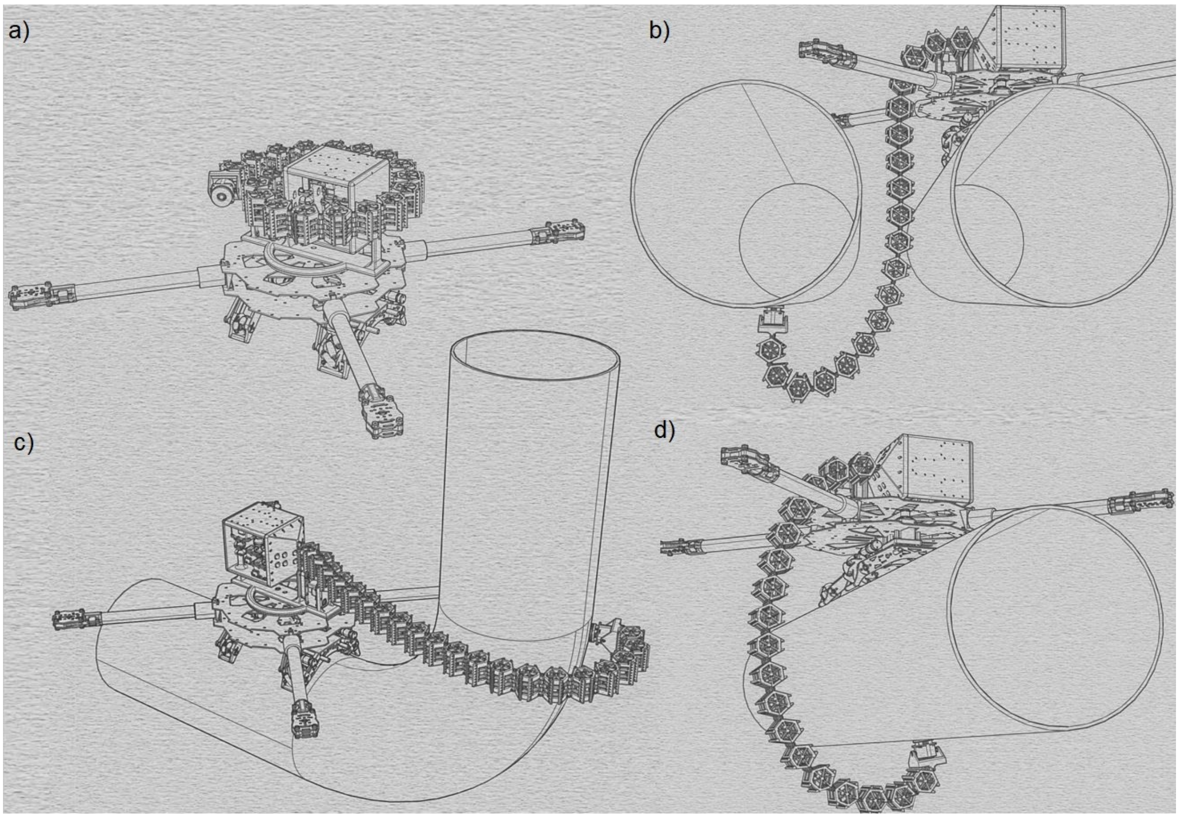

Figure 4-18. Example of use cases.

As shown in Figure 4-18 a geometric study was carried out to evaluate the arm configurations in different contexts.

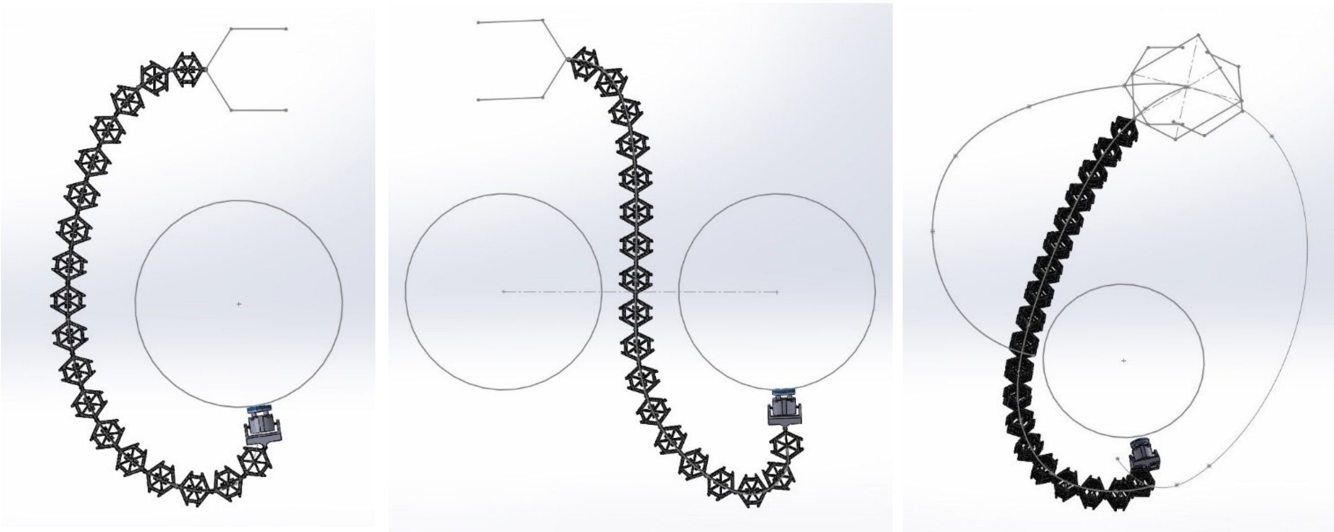

Figure 4-19. Feasibility geometrical study.

In Figure 4-19 is shown the geometric study carried out to evaluate the snake arm curvature in different operative conditions.

5. Mounting on the hybrid drone system

The three arm concepts are linked to the main system (drone + vehicle) in different way. More in details, some solutions can be linked to the drone, some other requires an add-on to be fully functional. In this section this aspect is analysed in detail.

5.1. FAP180 case

The FPA is the only arm designed specifically to work in conjunction with the articulated rover introduced in D2.1 and fully described in this document in Section 6. The two DoFs of the rover are used in combination with the two arm DoFs to articulate the tool in order to follow the pipe curvature. In the front of part of the rover is placed a revolute joint developed using one axial roller bearing and one radial sphere bearing. This joint represents the first DoF of the FAP180 arm as is described in Section 2. The joint is linked to the rover using carbon fiber structural element. Moreover, the joint is actuated using one Actuonix linear motor that allows the joint to rotate in the range [-30, 30] deg.

On the other hand, the rover is carried by the drone and it is linked to its frame using four elastic elements.

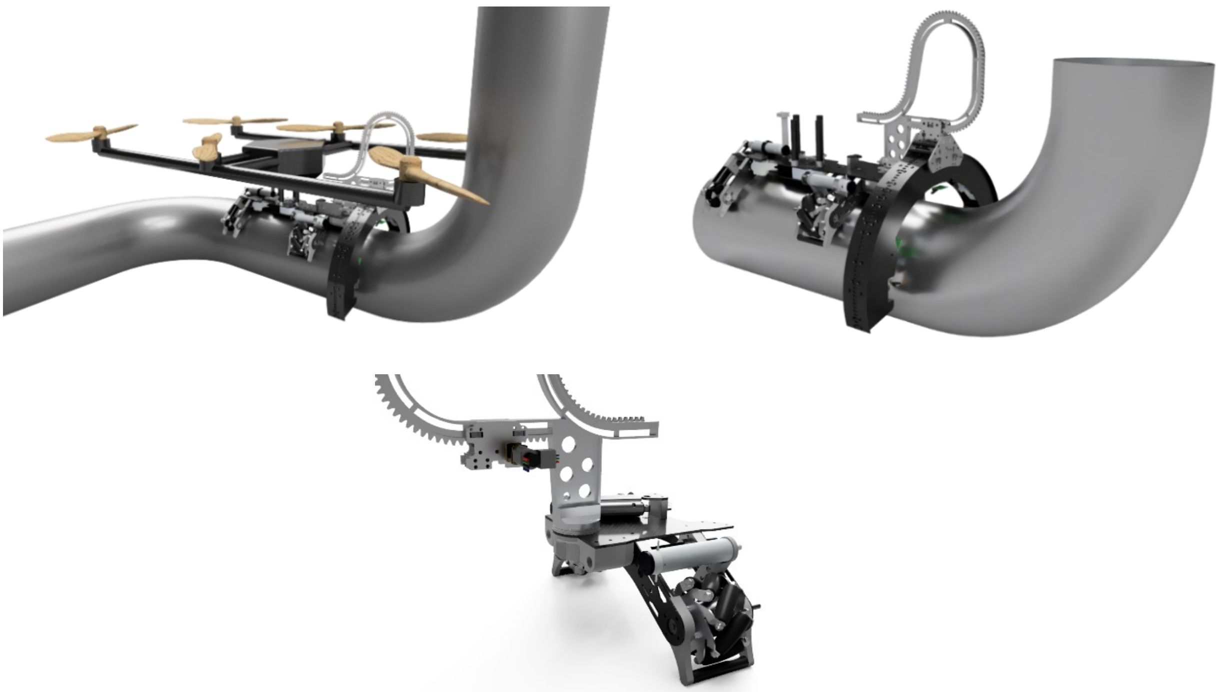

Figure 5-1. FAP arm connected to the rover front.

5.2. ARAP case

The ARAP case is like the FAP case but with some differences:

1. The ARAP arm is bigger and heavier hence we design a second version of the joint with a higher permitted load.
2. In the ARAP arm, the joint is actuated using a Dynamixel MX-28 servo motor. This choice was made to have higher torque and to have homogeneous motors for the whole arm using the same motors type for all the joints. The Dynamixel arm actuates the joint using a gear transmission as reported in the figure.

The ARAP arm can be linked directly on the drone using carbon pipes and plates, as shown in Section 3. In a different version, it can be also linked on different add-ons presented in the D2.1, such as the articulated rover, (see Figure 5-2 and Figure 5-3). This choice is motivated by the possibility to use the rover articulation to improve the arm dexterity along pipe curves.

Figure 5-2. The ARAP arm mounted on the system.

Figure 5-3. The ARAP arm mounted on the rover.

5.3. SAP case

In the SAP case, the robotic arm is connected directly to the aerial subsystem of the HRA. A revolute joint composed of a carbon reinforced plastic bracket, allows the rotation of the Motor box and snake connected with it, around the vertical axis. Therefore, in a nutshell its joint is made both to allow rotation and support motor box and snake.

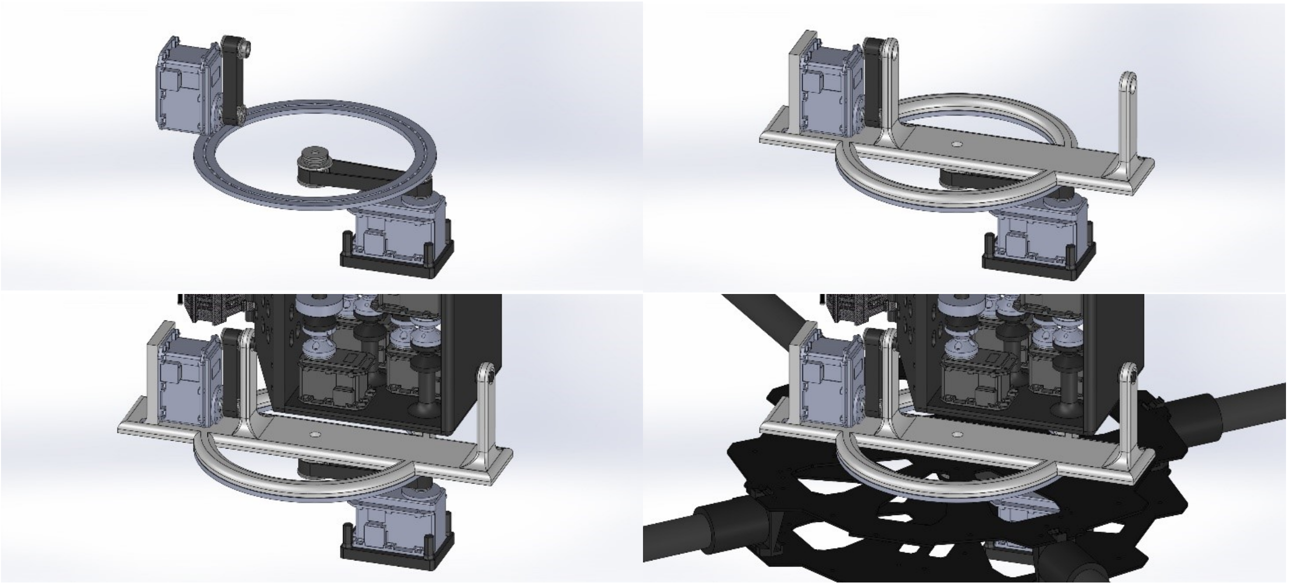

Figure 5-4. Teardown of motor box to frame connection

This mechanism allows the workspace of snake robot from a simple plane to the sheaf of plane centred on rotational axis of tilt motor.

6. Articulated rover detailed design

In this section, the vehicle concept presented in D2.1 is presented in detail. We design FAP180 and the ARAP arms to be mounted both on the drone and on the rover. However, as has been discussed in Section 2, the rover can be used to augment the FAP kinematics to perform measures along horizontal curves and move along the pipe at the same time. Hence, we discuss in detail this design in this deliverable.

6.1. Rover hardware description

In this section, the rover hardware is described focusing on the main aspects regarding mechanics, electronics and the general control architecture.

6.1.1. Mechanics

To reduce the rover weight, we used a combination of pipe and plates of carbon fibre material and 3D printed plastic elements.

The wheel position and the rover structure have been designed to be adaptable to pipe with different diameters. In details, we are building a prototype able to walk on pipes with diameter in the range [6, 10] inch that are the most common in refinery.

Moreover, we developed the rover to be articulated using two revolute joints. The two actuated articulations are designed to allow the rover to move along the pipe standard curve (curvature ratio of 1.5D).

We used a total of three gear-motors to actuate the four wheels (two for the Meccanum-wheels and one coupled for the Omni-wheels). Maxon gear motors with a gear ratio of 1:103, a maximum torque of 0.8 Nm and provided with encoders have been chosen.

Moreover, in this first prototype, the two joints are actuated using two Actuonix linear motors (https://www.actuonix.com/) with a linear displacement of 20mm. This translates into a maximum angular displacement of the two joints in the range [-30, 30] deg.

Figure 6-1. Articulated rover.

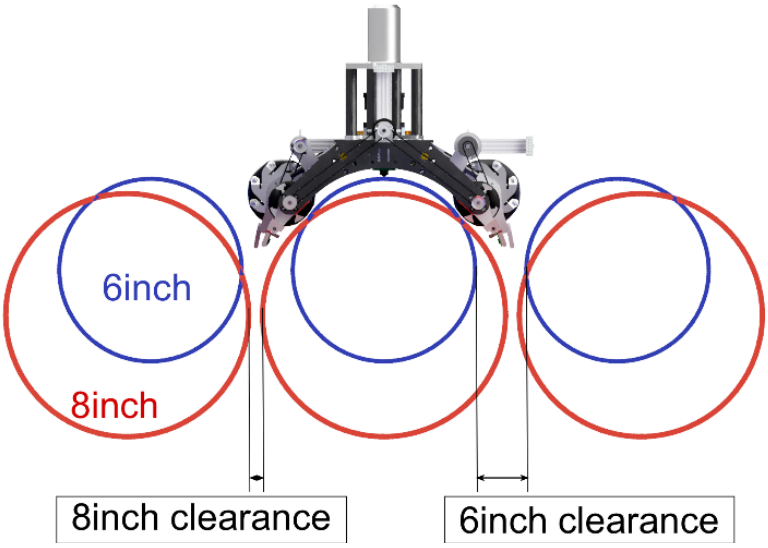

Figure 6-2. Articulated rover: pipe clearance.

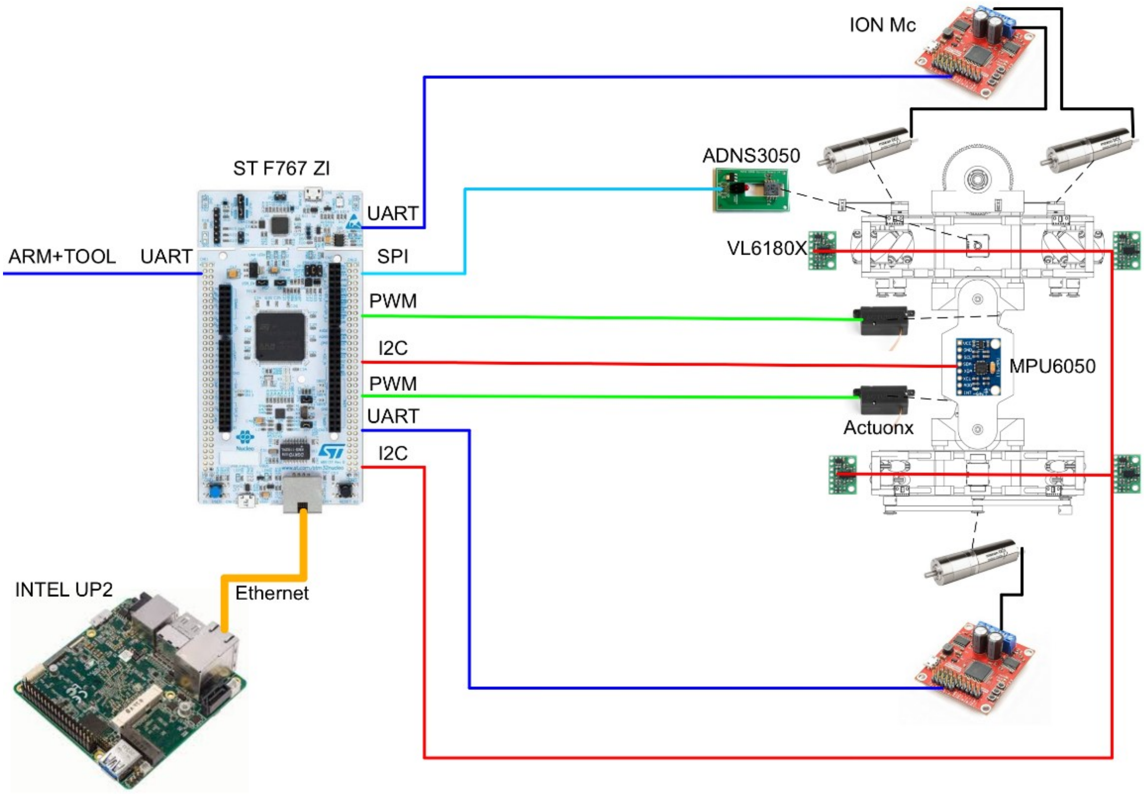

Figure 6-3. Rover control architecture.

6.1.2. Electronics and control

We used commercial hardware for the electronics of the rover. In details, two ION Motion controllers (https://www.basicmicro.com/) have been used to actuate the three gear-motors. These controllers have been chosen for the high flexibility and due to the easy motor calibration given by the powerful provided software. In our architecture an ST F767ZI board is the control core of the system. It commands the two ION Motion controller using a UART interface, take the angle signal from an IMU MPU6050 using an I2C connection and control the two Actuonix servo motors using a PWM control. The rover kinematics and the stabilization control are directly embedded in the board code. Moreover, using the ethernet interface, it is possible to send to the rover the control inputs (e.g. forward velocity and desired pitch) and receive the rover state. Using this architecture, the control loop runs at 300Hz.

6.2. Rover kinematic analysis

Novel kinematics have been chosen using two different wheels models: two Meccanum-wheels for the rover front and two Omni-wheels for the retro. This configuration allows to have the three decoupled degree of freedom required: forward walking following the pipe centreline; stabilization along the pipe circumference; reorientation along the vertical axis.

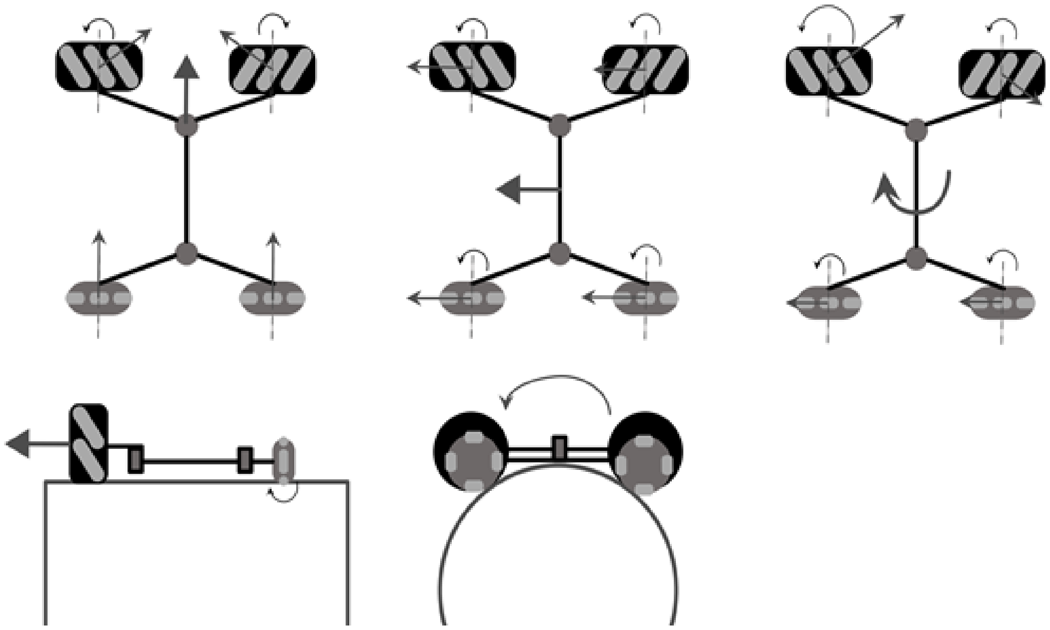

Figure 6-4. Rover wheel kinematics.

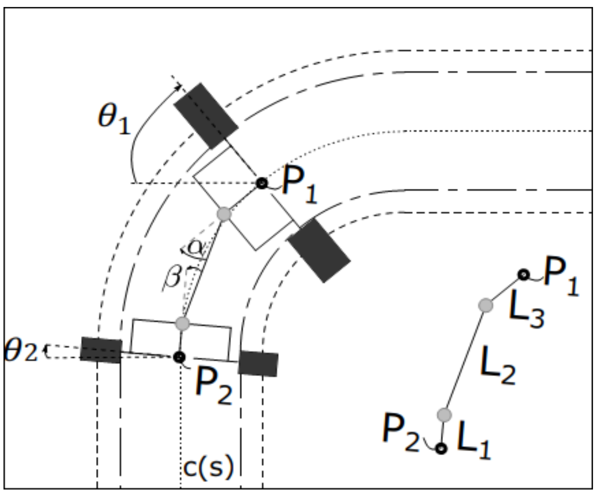

Figure 6-5. Rover two joints articulation.

The rover locomotion kinematics is described by the following equations:

$$\begin{bmatrix} \omega_{DX} \\ \omega_{SX} \\ \omega_R \end{bmatrix} = S \begin{bmatrix} v_F \\ \omega_S \end{bmatrix}$$

$$S = \begin{bmatrix} \frac{R_{DX}}{R_M r_F} & \frac{P}{r_F} \\ -\frac{R_{SX}}{R_M r_F} & \frac{P}{r_F} \\ 0 & \frac{P}{r_R} \end{bmatrix}$$

where, P is the pipe radius, $\omega_{DX}, \omega_{SX}, \omega_R$ are respectively the wheels angular velocities expressed in rad/s; v_F, ω_S are respectively the forward velocity expressed in m/s and the stabilisation angular velocity along the pipe circumference expressed in rad/s; r_F, r_R are the wheels front and retro radius and R_{DX}, R_{SX}, R_M are the pipe right, left and middle curvature radius. The left and right curvature radii change if the curve is clockwise or anticlockwise and it can be set to 1 if the rover is on a rectilinear segment of the pipe. In our control strategy, we used the laser information to understand the pipe curvature direction and change the matrix S accordingly.

6.3. Rover stabilization

First experiments have been conducted in the Prisma Lab to test the rover stabilization capabilities.

We are testing two different control strategies:

- Simple unconstrained linear control of the pitch angle. To do that, the rover wheels have been controlled in velocity using the ION Motion controllers. A proportional controller of the pitch angle has been developed to obtain the rover stabilization. With this strategy, we can control the pitch angle in the range [-20, 20] degrees considering a weight of 4 kg on the top.
- A nonlinear Model Predictive Control (MPC) strategy using also the drone propellers and a constrained optimization approach to maximise the rover stabilization capabilities also when the tangent wheel forces are bigger than the wheels friction force. This control prevents the wheel slippage and maximise the maximum stabilization angle.

The achieved results of the first control strategy are depicted in Figure 6-6 and Figure 6-7. The former figure from the left shows the behaviour of the pitch angle that the robot performs around the circumference of the pipe. The latter figure illustrates the time histories of the control inputs necessary to stabilize the system.

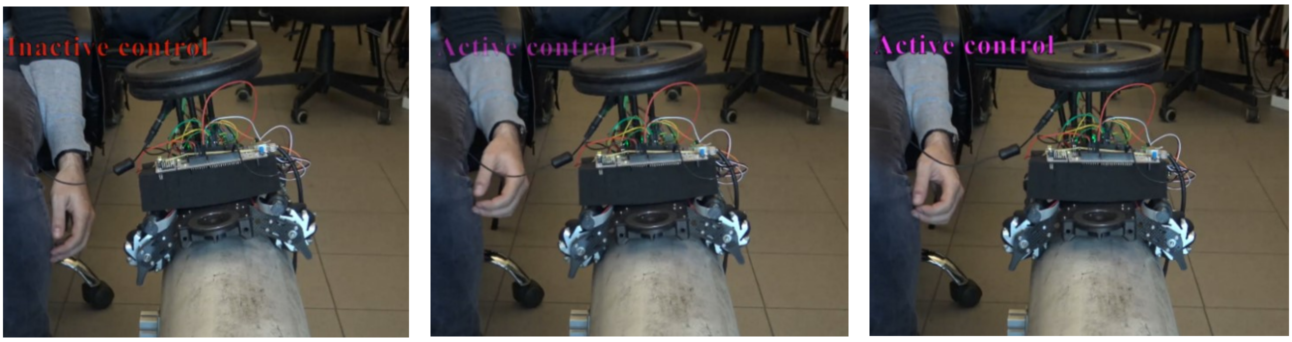

Figure 6-6. Screenshot of the rover stabilization.

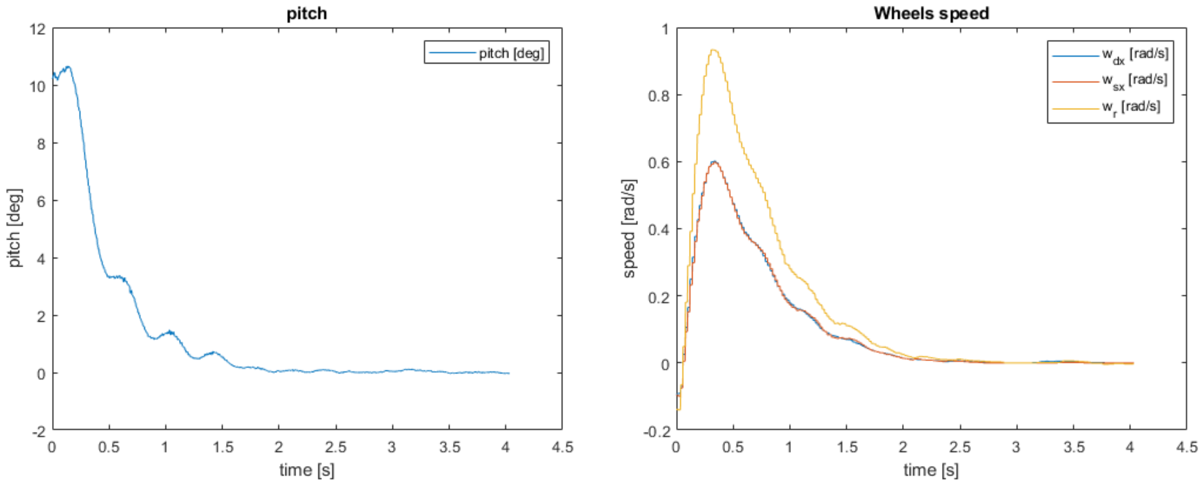

Figure 6-7. Rover stabilization: pitch time variation (left), wheels velocity (right).

The second control strategy is currently under development and some results have been submitted in Zhao et al., RAL 2019 using a simplified mock-up

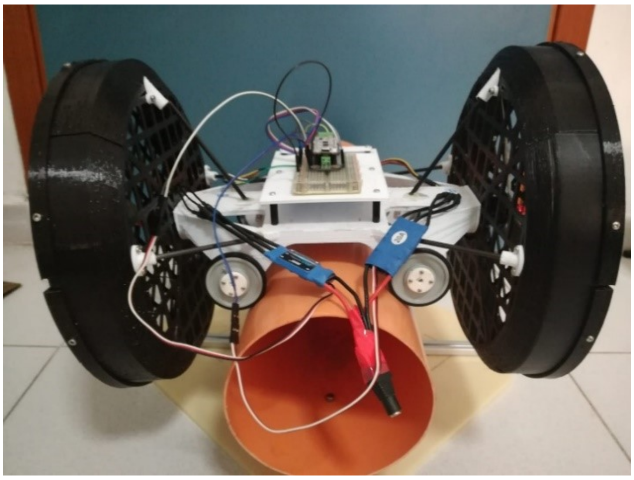

Figure 6-8. Stabilization testing mock-up.

7. Sensors and actuators overview

In this section, we summarize all the sensors and actuators used for the articulated rover and the different arm versions.

7.1. Sensors

The system is provided with different sensors to obtain the system state and make the required measurements. In this section, the most important sensors are summarized focusing on the interface with the main control system.

7.1.1. IMU

A 6 DoFs IMU have been used to stabilize the system on the pipe. In details, an MPU6050 have been chosen for our application. The IMU is provided with a 3-axis accelerometer and a 3-axis gyroscope. In Table 4 are reported the MPU6050 main specifications.

Table 4. IMU specifications

AD converter	Power supply	Com. protocol	Range gyro	Range acc.
16 bit	3-5 V	I2C	±250 to ±2000°/s	2 to 16 g

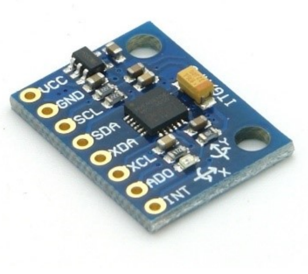

Figure 7-1. IMU MPU6050.

7.1.2. Distance time of flight laser sensors

Several time of flight distance sensors have been disposed on both, the rover and the tool structure, to reconstruct the pipe curvature. The VL6180X time-of-flight sensor has been adopted for this purpose. In Table 5 are reported the VL6180X main specifications.

Table 5. TOF specifications

Maximum range	Minimum distance	Com. protocol	Sensor resolution
60cm	~15mm	I2C	~1mm

Figure 7-2. TOF distance sensor.

7.1.3. Cameras

We included one hi-resolution camera for each UT sensor. This allows the operator to verify the correct execution of each measuring procedure. The provided camera specifications are summarized in Table 6.

Table 6. Cameras specifications

Resolutions	Focal distance	Lights	Waterproof cls.	Interface	Size
1.5 M px	4mm to ∞	6 LED	IP 67	USB	5.5 ø [mm]

Figure 7-3. Camera.

7.2. Actuators

In this section we summarize the main specifications of the actuators used in both rover and arm.

7.2.1. Maxon motors + IONMc motion controller

In our design, the rover wheels are actuated using three custom Maxon DC gear motors provided with quadrature encoders. The motor specifications are reported in Table 7.

We chose a commercial motor driver to control the motors developed by the company Basicmicro that develops motor drivers with different size. We chose the 2x7A model that provides enough power to control the Maxon motors. Each driver can pilot two DC motors provided with quadrature encoders and can be controlled with different communication protocols summarized in Table 8. In our design, we control the IONMc with the ST F767ZI board via packet RS232 UART communication.

Table 7. Rover Maxon gear motor specifications

Motor voltage	GearBox ratio	Maximum continuative torque	Nominal current
9 V	103:1	0.8 Nm	0.845 A

Table 8. ION motion controller specifications

N of channels	Max continuative current for channel	Max voltage	Controls
2	7.5 A	34 V	USB – Analog – Packet RS232 -RC pulse – Position and velocity control

Figure 7-4. Maxon motor.

Figure 7-5. ION motion controller.

7.2.2. Pololu gear-motors

As described in the previous sections, the tool rotation for both the FAP and the ARAP arms as well as the guide rail, in the case of the FAP arm, have been actuated with miniaturized Pololu gearmotors which are provided with encoder. In details, we used a 1000:1 gear motor for the FAP arm guide rail movement and a 210:1 gear motor for the probe rotation. The other specifications are reported in Table 9.

Table 9. Pololu specifications

Motor voltage	GearBox ratio	Maximum continuative force / speed	No-load speed (RPM)	Interface
6V	1000:1 or 210:1	1Nm or 0.25Nm	35 rpm or 160 rpm	PWM + quadrature encoder

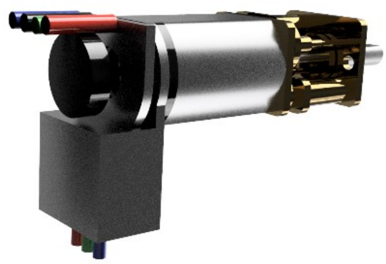

Figure 7-6. Pololu geared motor.

7.2.3. Actuonix linear motors

Several Actuonix linear motors have been used in the rover, arm and tool. In details, we used two Actuonix motors in the rover to move the central joints, one in the FAP arm to move the first arm joint and, one or two, in the tool to move or retract the UT sensors. In Table 10 the specifications are summarized.

Table 10. Actuonix specifications

Motor voltage	GearBox ratio	Maximum continuative force / speed	Linear displacement	Control
6V	100:1	20N @ 8mm/s	20mm	RC control

Figure 7-7. Actuonix linear motor.

7.2.4. Dynamixel servo motors (MX-Series)

The actuators used in some of those arms are the MX series of Dynamixel.

The actuators reference information provided by the manufacture (see Table 12) allow to define a performance graph obtained from a different measurement method to design a graph as compared to characteristic curves of electric motor obtained through two characteristic values that is Max Velocity and the Stall Torque.

Figure 7-8. Dynamixel MX-series.

On a classic curve, the stall torque is a measured value of the momentary torque that it can reach. This is generally how RC servos are measured. On a graph below indeed, which is measured with the gradually increasing load. The most common operation environment is closer to the performance graph, not stall torque method. For this reason, the performance graph is broadly used in the industrial field. Generally, Max Torque of the Performance Graph is less than the Stall Torque.

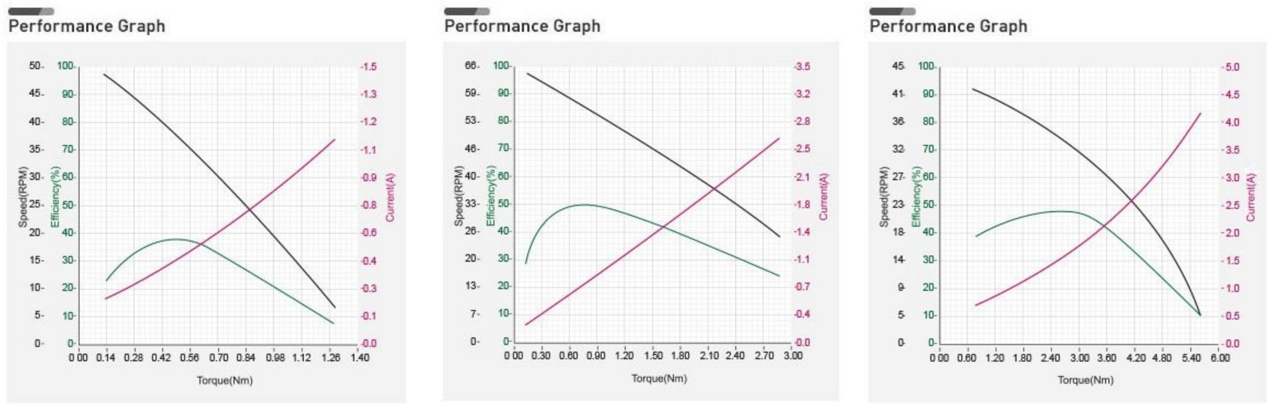

Figure 7-9. Performance graphs.

But to have a complete mechanical characterization of motor, we have performed ad experimental set up to obtain a measured value of Nominal torque and stall torque (see Table 11).

The communication protocol selected are 2.0 because, as it is suggested on Dynamixel site, it is greatly enhanced from the protocol 1.0. Accessing some of the control table area might be denied if protocol 1.0 is selected. The protocol 2.0 it is equipped with a 16-bit CRC calculation code that checks if the packet has been damaged during communication. The type of code is a common CRC-16 (IBM/ANSI) Polynomial: x16 + x15 + x2 + 1 (polynomial representation: 0x8005) with an initial value = 0.

Table 11. Dynamixel measured values

Motor model	MX-28	MX-64	MX-106
Nominal Torque [Nm]	1.38	2.15	3.60
Stall Torque @12V [Nm]	2.50	6.00	8.40
Weight [g]	77.00	135.00	153.00
min step resolution [deg]	0.09	0.09	0.09
(%) of stall torque usable as Nominal	55.20	35.83	42.86

Power to weight ratio	0.0179	0.0159	0.0235
(%) increment of weight respect previous size		75.32468	13.33333

Table 12. Dynamixel MX series reference data

MCU	ST CORTEX-M3 (STM32F103C8 @ 72 [Mhz], 32Bit)
Position Sensor	Contactless absolute encoder (12Bit, 360 [°])
	Maker : ams(www.ams.com), Part No : AS5045
Motor	Coreless (Maxon)
Baud Rate	8,000 [bps] ~ 4.5 [Mbps]
Control Algorithm	PID control
Resolution	4096 [pulse/rev]
Backlash	20 [arcmin] (0.33 [°])
Operating Mode	Current Control Mode
	Velocity Control Mode Position Control Mode (0 ~ 360 [°]) Extended Position Control Mode (Multi-turn) Current-based Position Control Mode PWM Control Mode (Voltage Control Mode)
Weight	
Dimensions (W x H x D)	40.2 x 65.1 x 46 [mm]
Gear Ratio	
Stall Torque	
No Load Speed	
Radial Load	(10 [mm] away from the horn)
Axial Load	
Operating Temperature	-5 ~ +80 [°C]
Input Voltage	10.0 ~ 14.8 [V] (Recommended: 12.0 [V])
Command Signal	Digital Packet
Protocol Type	TTL Half Duplex Asynchronous Serial Communication with 8bit, 1stop, No Parity RS485 Asynchronous Serial Communication with 8bit, 1stop, No Parity
Physical Connection	RS485 / TTL Multidrop Bus
ID	253 ID (0 ~ 252)
Feedback	Position, Velocity, Current, Realtime tick, Trajectory, Temperature, Input Voltage, etc
Material	Full Metal Gear Engineering Plastic (Front, Middle, Back) 1 Metal (Front)
Standby Current	100 [mA]

MX-28 AT	MX-64 AT	MX-106 AT
x	x	x
x	x	x
x	x	x
x	x	x
x	x	x
x	x	x
x	x	x
x	x	x
o	x	x
x	x	x
x	x	x
x	x	x
o	x	x
x	(Voltage Control Mode)	(Voltage Control Mode)
77 [g]	126 [g]	165 [g]
35.6 x 50.6 x 35.5 [mm]	40.2 x 61.1 x 41 [mm]	40.2 x 65.1 x 46 [mm]
193:01:00	200:01:00	225:01:00
2.3 [Nm] @ 11.1 [V], 1.3 [A]	5.5 [Nm] @ 11.1 [V], 3.9 [A]	8.0 [Nm] @ 11.1 [V], 4.8 [A]
2.5 [Nm] @ 12 [V], 1.4 [A]	6.0 [Nm] @ 12 [V], 4.1 [A]	8.4 [Nm] @ 12[V], 5.2 [A]
3.1 [Nm] @ 14.8 [V], 1.7 [A]	7.3 [Nm] @ 14.8 [V], 5.2 [A]	10.0 [Nm] @ 14.8 [V], 6.3 [A]
50 [rev/min] @ 11.1 [V]	58 [rev/min] @ 11.1 [V]	41 [rev/min] @ 11.1 [V]
55 [rev/min] @ 12 [V]	63 [rev/min] @ 12 [V]	45 [rev/min] @ 12 [V]
67 [rev/min] @ 14.8 [V]	78 [rev/min] @ 14.8 [V]	55 [rev/min] @ 14.8 [V]
30 [N]	40 [N]	40 [N]
15 [N]	20 [N]	20 [N]
x	x	x
x	x	x
x	x	x
x	x	x
x	x	x
x	x	x
x	x	x
x	x	x
x	x	x

8. Coverage Analysis with Project Requirements

Table 13 presents the analysis of the project requirements coverage related to the HRA version and its arm/tool subversions.

Table 13. Coverage analysis with project requirements

ID	Description	FAP180	ARAP180/ARAP90	SAP
UR-01	System small enough to be transported by van or pallet	Complete system is small enough for transporting it by a car, indeed a person should be able of it.	Complete system is small enough for transporting it by a car, indeed a person should be able of it.	Complete system is small enough for transporting it by a car, indeed a person should be able of it.
UR-02	System small enough to be transported by helicopter	Complete system is small enough for transporting it by helicopter.	Complete system is small enough for transporting it by helicopter.	Complete system is small enough for transporting it by helicopter.
UR-03	System small enough to be transported by airfreight cargo	Complete system is small enough for transporting it by airfreight cargo.	Complete system is small enough for transporting it by airfreight cargo.	Complete system is small enough for transporting it by airfreight cargo.
UR-05	Gas detection system on-board the robotic vehicle	System will integrate a gas sensor	System will integrate a gas sensor	System will integrate a gas sensor
UR-07	Batteries protected against impacts	Protection mechanism must be designed.	Protection mechanism must be designed.	Protection mechanism must be designed.
UR-08	Maximum weight of transporting box 30 kg	Transporting box will weigh less than 30 kg. Box has not been designed yet.	Transporting box will weigh less than 30 kg. Box has not been designed yet.	Transporting box will weigh less than 30 kg. Box has not been designed yet.
UR-13	Only brushless motors can be used	Brushless motors currently integrated.	Brushless motors currently integrated.	Brushless motors currently integrated.
UR-14	Robotic vehicle must be collision proof (for example mechanical protection around propellers)	Propellers have been protected against collisions.	Propellers have been protected against collisions.	Propellers have been protected against collisions.
UR-16	Confirm clear areas for landing on top of pipes	FAP180 will send video information to the operator and it will be able of obtaining additional information from the sensors integrated in the tool one for each UT sensor	ARAP arms will send video information to the operator and it will be able of obtaining additional information from the sensors integrated in the tool one for each UT sensor	SAP will send video information to the operator and it will be able of obtaining additional information from the sensors integrated in the tool.

UR-17	Pipe diameter from 8 to 20 inches (nominal)	FAP180 will be able of landing on pipes between 6 to 20 inches. However, the arm structure (actuated guide) is more suitable for 6-10 inches tools	ARAP will be able of landing on pipes between 6 to 20 inches. Tools for pipes of each diameter must be designed. However, we suggest considering the ARAP solution only for pipes with diameter in the range 6-12 inches. Bigger diameters can be considered with the solution ARAP90.	SAP will be able of landing on pipes between 6 to 20 inches. However, the arm is designed to make measures to pipes with diameters in the range 6-12 inches.
UR-18	Pipes with 6 inches (nominal) diameter	FAP180 will be able of landing on pipes of 6 inches	ARAP will be able of landing on pipes of 6 inches	SAP will be able of landing on pipes of 6 inches
UR-19	Pipe diameter from 20 to 24 inches	FAP180 is not expected to land on Pipes bigger FAP180 than 20 inches	ARAP is not expected to land on Pipes bigger than 20 inches	SAP is not expected to land on Pipes bigger than 20 inches
UR-20	Magnetic pipes	FAP180 will be able of landing on magnetic pipes but it isn't a requirement for the correct working of the system	ARAP will be able of landing on magnetic pipes but it isn't a requirement for the correct working of the system	SAP will be able of landing on magnetic pipes, but it isn't a requirement for the correct working of the system
UR-21	Non-insulated pipes	FAP180 will be able of landing on non-insulated pipes	ARAP will be able of landing on non-insulated pipes	SAP will be able of landing on non-insulated pipes
UR-25	The robotic system should be able to cross 5 mm high welds	System has been designed for being able to cross 5 mm high welds. Pending tests	System has been designed for being able to cross 5mm high welds. Pending tests	System has been designed for being able to cross 5 mm high welds. Pending tests
UR-26	The robotic system should be able to cross horizontal elbows	System can cross horizontal elbows.	System can cross horizontal elbows.	System can cross horizontal elbows.
UR-27	Robotic system able to move along the pipe	The system can move along the pipe.	The system can move along the pipe.	The system can move along the pipe.
UR-28	It is needed to assess the surface condition of top of the pipe	The system will incorporate the sensors that allow the pilot to assess the condition of the pipe. In this case, the FAP180 will have integrated several cameras.	The system will incorporate the sensors that allow the pilot to assess the condition of the pipe. In this case, the ARAP will have integrated several cameras.	The system will incorporate the sensors that allow the pilot to assess the condition of the pipe. In this case, the SAP will have integrated several cameras.
UR-29	Assess surface condition 360º around the pipe	The FAP180 will have integrated several cameras. For knowing if it is able of covering	The ARAP will have integrated several cameras. For knowing if it is able of covering 360º it is	The SAP will have integrated several cameras. For knowing if it is able of covering

		360º it is necessary to perform some tests.	necessary to perform some tests.	360º it is necessary to perform some tests.
UR-30	Locate the weld	The system will incorporate cameras that allow the pilot to locate welds in real time.	The system will incorporate cameras that allow the pilot to locate welds in real time.	The system will incorporate cameras that allow the pilot to locate welds in real time.
UR-31	Accuracy location at 1 cm level to the weld and with respect to 3, 6, 9 and 12 positions	System has been designed for being able to localize itself with a relative accuracy of 1cm with respect to welding section. Pending tests	System has been designed for being able to localize itself with a relative accuracy of 1cm with respect to welding section. Pending tests	System has been designed for being able to localize itself with a relative accuracy of 1cm with respect to welding section. With respect to the ARAP and FAP solutions the accuracy of the arm can be reduced
UR-32	Accuracy location at 2 cm level to the weld and with respect to 3, 6, 9 and 12 positions	System has been designed for being able to localize itself with a relative accuracy of 1cm with respect to welding section. Pending tests	System has been designed for being able to localize itself with a relative accuracy of 1cm with respect to welding section. Pending tests	System has been designed for being able to localize itself with a relative accuracy of 1cm with respect to welding section. With respect to the ARAP and FAP solutions the accuracy of the arm can be reduced
UR-34	Be able to save and display in real-time A-SCAN data from the ground	Ultrasonic HMI allows displaying and recording SCAN data from the ground	Ultrasonic HMI allows displaying and recording SCAN data from the ground	Ultrasonic HMI allows displaying and recording SCAN data from the ground
UR-35	Be able to control de ultrasonic sensor from the ground	Ultrasonic HMI allows controlling the ultrasonic sensor from the ground	Ultrasonic HMI allows controlling the ultrasonic sensor from the ground	Ultrasonic HMI allows controlling the ultrasonic sensor from the ground
UR-36	Pipe temperature will be less than 60ºC	To be tested: different materials for the rover wheels must be tested	To be tested: different materials for the rover wheels must be tested	To be tested: different materials for the rover wheels must be tested
UR-37	Pipe temperature can be as high as 100ºC	To be tested	To be tested	To be tested
UR-38	Robotic system MTOW less than 8 kg	In first instance, FAP180 has been designed to weigh less than 15 kg. However, almost sure it will weigh less than 8 kg.	In first instance, ARAP has been designed to weigh less than 15 kg. However, almost sure it will weigh less than 8 kg.	In first instance, SAP has been designed to weigh less than 15 kg.

UR-39	Robotic system MTOW less than 15 kg	FAP180 has been designed to weigh less than 15 kg.	ARAP has been designed to weigh less than 15 kg.	SAP has been designed to weigh less than 15 kg.
UR-41	Quadrant horizontal elbow inspection: 4 points (3, 6, 9 and 12 positions) close to first weld, 4 points close in the middle and 4 points close to second weld	The arm of the FAP180 will be able to perform ultrasonic inspection at 3, 6, 9 and 12 positions in the first, middle and second welds	The arm of the ARAP will be able to perform ultrasonic inspection at 3, 6, 9 and 12 positions in the first, middle and second welds	The arm of the SAP will be able to perform ultrasonic inspection at 3, 6, 9 and 12 positions in the first, middle and second welds
UR-42	Quadrant vertical elbow inspection: 4 points (3, 6, 9 and 12 positions) close to first weld, 4 points in the middle and 4 points close to second weld	The FAP180 arm will be able to perform only upwards vertical elbow ultrasonic inspection at 3, 6, 9 and 12 positions in the first, middle and second welds	The ARAP arm will be able to perform vertical elbow ultrasonic inspection at 3, 6, 9 and 12 positions in the first, middle and second welds	The SAP arm will be able to perform vertical elbow ultrasonic inspection at 3, 6, 9 and 12 positions in the first, middle and second welds
UR-43	Grid inspection on elbows	The FAP180 arm will be able to perform grid inspection on elbows	The ARAP arm will be able to perform grid inspection on elbows	The SAP arm will be able to perform grid inspection on elbows
UR-44	Grid inspections on horizontal T joint inspection in 1 and 3 areas (including impact area)	The FAP180 will not be able to perform horizontal T joint inspection	The ARAP arm, only in the ARAP90 configuration, will be able to perform horizontal T joint inspection	The SAP arm will be able to perform horizontal T joint inspection
UR-45	Horizontal quadrant T joint inspection in 1 and 3 areas (including impact area)	The FAP180 will not be able to perform horizontal T joint inspection	The ARAP arm, only in the ARAP90 configuration, will be able to perform horizontal T joint inspection	The SAP arm will be able to perform horizontal T joint inspection
UR-46	Grid inspection on reducers and T joint in area 2	The FAP180 will not be able to perform T joint and reducers inspection	The ARAP arm, only in the ARAP90 configuration, will be able to perform T joint and reducers inspection	The SAP arm will be able to perform reducers and T joint inspection
UR-47	Reducers and T joint in 2 quadrant inspections	The FAP180 will not be able to perform T joint inspection	The ARAP arm, only in the ARAP90 configuration, will be able to perform T joint inspection	The SAP arm will be able to perform T joint inspection
UR-48	Horizontal pipe quadrant inspection until first weld whatever the configuration	The FAP180 arm will be able to perform horizontal pipe quadrant inspection until first weld whatever the configuration	The ARAP arm will be able to perform horizontal pipe quadrant inspection until first weld whatever the configuration	The SAP arm will be able to perform horizontal pipe quadrant inspection until first weld whatever the configuration

UR-49	minimum pipe-to-pipe distance 75 mm	FAP180 is able of inspecting pipes with a separation of 75 mm	ARAP is able of inspecting pipes with a separation of 75 mm	SAP is not able of inspecting pipes with a separation of 75 mm
UR-50	Take into consideration pipes that are close to each other	FAP180 can perform an inspection in a close pipe. But the complete inspection can be obtained if the distance pipe-to-pipe is less more than 55 mm	ARAP can perform an inspection in a close pipe. But the complete inspection can be obtained if the distance pipe-to-pipe is less more than 55 mm	SAP can perform an inspection in a close pipe. But the complete inspection can be obtained if the distance pipe-to-pipe is less more than 100 mm
UR-57	Be able to change or recharge batteries onsite (in safe areas only)	Batteries can be charged in anywhere	Batteries can be charged in anywhere	Batteries can be charged in anywhere
UR-58	Be able to reload ultrasonic coupling onsite (if applicable)	Ultrasonic coupling can be reloaded easily onsite	Ultrasonic coupling can be reloaded easily onsite	Ultrasonic coupling can be reloaded easily onsite