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State of the art and conceptual design of robotic solutions for *in situ* hard coating of hydraulic turbines

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Abstract Hydropower turbine's blades are constantly exposed to abrasion and cavitation phenomena, demanding regular maintenance for flow stability and turbine efficiency. Hard coating techniques by thermal aspersion are used to reduce the mechanical wear, thus increasing blade's life cycle, and turbine efficiency. Currently, applying a new coating layer requires turbine disassembling, and recalibration. EMMA is a robotic system to perform hard coating by thermal spray on hydraulic turbine blades within the turbine environment, i.e., hard coating application to an installed blade, significantly reducing the turbine downtime. This document is a study of the state of the art of *in situ* hydropower turbine robotic systems, and describes the conceptual designs for EMMA. The results outlines the next steps for EMMA and future projects in the same area.

Keywords hard coating · hydropower · turbine · thermal spray · robotics · in situ

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1 Introduction

According to the world energy council, hydropower is the most flexible and consistent of the renewable energy resources. Brazil is the second country in hydropower production, and second with the highest consumption of hydropower with a 70.000 MW installed capacity, and 433 hydroelectric plants in operation. Since Brazil is one of the world's richest countries in water resources, and the hydropower is the most dominant across the country, it motivates the development and investment in hydropower generation.

In Brazil, the renovation and improvement of the built large power plants is estimated to result in a potential increase of 32.000 MW (Goldemberg and Lucon, 2007), a figure that can be achieved, in large part, by the maintenance of the hydropower turbines. These turbines are constantly exposed to abrasion and cavitation phenomena. The cavitation phenomenon (Fig. 1) is detailed in Escaler et al (2006), which outlines their types, occurrences and effects in the different hydraulic turbines. This physical phenomenon can cause erosions in the hydraulic turbines, leading to water flow instability, excessive vibrations and turbine efficiency reduction.

Hard coating techniques by thermal aspersion are used to reduce the erosion of the turbine's blade from cavitation or abrasion, thus increasing its life cycle. This solution is analogous to a paint that protects walls from environment exposure. The hard coating procedure is performed by a robotic manipulator before the

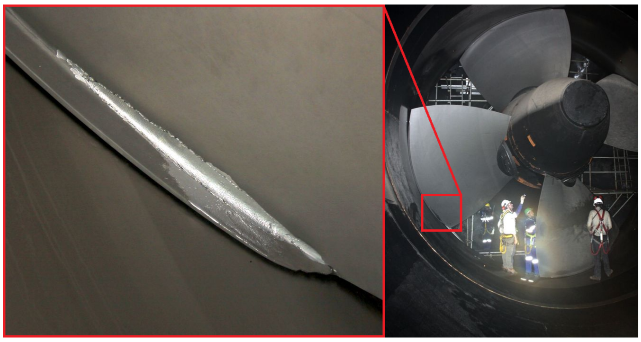

Fig. 1 Jirau hydraulic turbine's blade eroded by cavitation.

hydraulic turbine installation. It requires a robotic system due to high precision, speed, and the hazardous substances that are used, as propane and other gases. Although sufficient for blade protection, the coating also has a life cycle itself, thus it needs to be redone from time to time to ensure the blade's protection from physical phenomena.

In the specific case of the Jirau hydroelectric dam, built on the Madeira river, the number of suspended particles that the river carries intensifies the abrasion phenomena, and Rijeza, a hard coating specialized company, identified cavitation erosion on blades, further reducing the coating life cycle. Currently, coating reapplication requires stoppage of the turbine, blade removal, blade positioning for coating, turbine assembling, and recalibration. This process can take up to two months, meaning a huge loss in power generation. EMMA is a robotic system for *in situ* hard coating application. However, there are several difficulties encountered when attempting to robotize *in situ* maintenance, as accessibility, system placement and calibration.

This document is divided as follows: section 2 describes, in detail, the problem, contextualizes the reader in the Jirau environment and describes the robot's tasks; section 3 surveys the state of the art; section 4 describes the conceptual designs for the robot and mechanical bases; finally, the section 5 concludes and outlines the next steps for EMMA.

2 The problem

Cavitation and abrasion in hydropower turbines erode the surface of the blades and are responsible for hydraulic profile deformation, resulting in efficiency reduction (Brennen, 2013). A preventive solution is the High Velocity Oxygen Fuel (HVOF) coating process of the blades. The hard coating creates a lamellar structure, increasing power generation efficiency, and provides greater resistance to erosion. The coating of turbine's blades is performed before turbine assembling and installation. In the specific case of Jirau, the abrasion due to a large number of particles and sediment in the Madeira river and the recent identified cavitation require recoating in short intervals (Santa et al, 2009).

Since turbine disassembling for runner's blade recoating would be a huge loss in power generation, the problem is to design a robotic system for *in situ* hydropower runner's blades coating. The robotic system must overcome turbine accessibility, as robot transportation and placement in confined space, and some common robotic problems, as localization, mapping and control.

In this section, the coating technology is addressed as the way to reduce the damage by cavitation. Also, the reader is contextualized in the Jirau facility. Finally, *in situ* robotic tasks are highlighted.

2.1 The HVOF coating process

The thermal spraying (or metallizing) is a process in which heated materials are sprayed onto a surface in order to improve or restore their properties and dimensions. The coating significantly increases the resistance to erosion or corrosion.

A thermal spraying system comprises: a spray gun, which partially melts and accelerates the particles to be deposited onto metal surface; a feeder, which provides the powder (particles) via pipes; a provider of burning material; a robot (manipulator) to handle the gun; an electric power supply to the gun; and a control console for the system.

In the specific case of Jirau, turbine blades (stainless steel 420) are coated on High Velocity Oxy-Fuel (HVOF) thermal spraying type by the Rijeza company with a robotic manipulator 150 kg payload, which is a good safety margin, since the system mass is 10 kg (cables and gun). The process takes 6 hours per side of the blade.

The HVOF consists of feeding, in a combustion chamber, the coating material (tungsten carbide), a gaseous fuel mixture (propane), and oxygen. According to the data provided by the Rijeza company, the 8 kg spray gun projects a flame of 3000°C, spraying the particles at 700 to 1000 m/s speed, and generating a 15 N recoil force.

The manipulator must have 5 mm accuracy, and the spray gun should remain at a 210 to 240 mm distance with $90^\circ \pm 60^\circ$ angle in respect to the metallic surface plane for a regular coating layer. The end effector of the manipulator must control the spray gun at a constant 40 m/min speed, and should not stop during the process with the blade in its range (*long stop*), otherwise

Table 1 HVOF process data

Component	Data
Spray gun mass	8 Kg
Cables mass	12 Kg
Flame temperature	3000°C
Spray gun recoil	15 N
Manipulator precision	5 mm
Spray gun to blade distance	230-240 mm
Spray gun to blade angle	30°-90°
Manipulator velocity	40 m/min
HVOF sound noise	100 a 140 dB
Blade temperature	up to 110°C

coating material would accumulate. The end effector direction changes are considered *long stop* too, thus direction changes should be made out of the blade range, or sacrifice plates should be used. Sacrifice plates, or masking, are metal plates placed on blade spots that should not be coated.

Regarding the operating conditions, the hydropower turbine is a confined space, the HVOF process has excessive audible noise (100-140 dB), and hazardous and potentially explosive gases are expelled; the blade can reach up to 110°C; the environment's temperature and humidity should be monitored and ideally set for the coating process; and 40% of the sprayed particles are lost during the process (Wu et al, 2006), which are spread throughout the environment. Thus, the process requires a very well ventilated environment. Table 1 summarizes the project restrictions and specifications.

2.2 Environment contextualization

The Jirau facility has horizontal axis bulb type turbines. In hydropower plants, electric power generation depends on the water level and river flow, and bulb type turbines are designed to produce enough electricity only with high water flow.

In the context of EMMA, the turbine points of interest are: 1) the variable pitch propeller, or Kaplan **blades**; 2) Runner and adjacent areas; 3) turbine's access or hatches; and 4) Draft tube.

1) Blades: the rotor or turbine propeller consists of the hub, the blades and the cone. Blades of Jirau's turbine is approximately 2.5 m tall and 3 m wide, they are fully reachable from the turbine interior, excepting the lips, which can be visualized through a small top hatch. The variable pitch propeller varies from 0° to 29° relative to the water flow.

The rotor can be manually rotated in both directions, but blades' angles are changed by hidraulic actuators.

2) Runner and adjacent areas: the runner area and the variable pitch guide vanes (wicket gates) have metal surface, but only the latter is composed of ferromagnetic materials, allowing magnetic fixing solutions for robotic systems. The cylindrical and sloping shape of the runner area hinders robot fixation and movement. An horizontal plane or a stiff mechanical base should be build for the system fixation. Under turbine maitenance, devices and equipments are fixed by a scaffolding anchored by ropes. Fig. 2 illustrates a turbine under maintenance.

Fig. 2 Turbine under maintenance. Scaffolding as fixation point for equipments.

3) Hatches: the two turbine accesses are the 800 mm diameter bottom hatch, located at the beginning of the draft tube and generally used by operators for maintenance; and the 357 mm diameter top hatch, located at the top of the runner and generally used for blade's lip inspection.

4) Draft tube: at the end of the discharge pipe is located the downstream stoplogs and then the riverbed. If the stoplog are not inserted, there is a 10 m wide gap, which could be used as access. However, the high water flow due to the openning of the distributor make it impossible for access.

A 3D CAD model of the turbine was built with SolidWorks® for future simulation and conceptual solution analysis (Fig. 3). The model is not fully detailed, but the upstream tunnel, the stator, the rotor, a small sector of the downstream, and the hatches are represented with great accuracy.

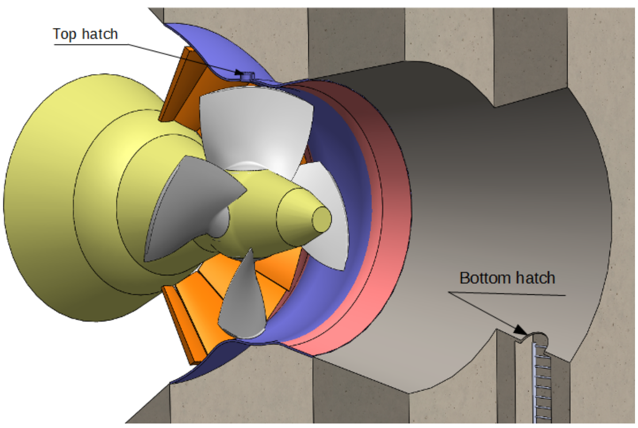

Fig. 3 3D CAD model of the Jirau turbine (SolidWorks®).

2.3 Main challenges and robot tasks

The summary of the tasks to be performed for an *in situ* hard coating application are: 1) Blade damage inspection for repair and coating; 2) Repair; 3) System mounting ; 4) Abrasive blasting; 5) Hydraulic profile modeling; 6) Calibration; 7) HVOF coating. Tasks 1 to 4 can be performed manually and tasks 2, 4, 5, 6 and 7 by robot.

A major problem for *in situ* robotic process is accessibility and placement. The robot must be brought to the turbine, operate in a confined and curved space, and has a stiff mechanical base for hard coating accuracy.

The runner's blade should conform to the template, hydraulic profile, before the coating process. Therefore, the system should build an hydraulic profile (mapping) and analyze flaws. Also, the system should be calibrated, as the blade and robot positions are not known.

In case of deep blade deformations, a repair by welding should be done. An operator can manually perform the welding because there is no hard restrictions as the coating process (accuracy, speed, load). However, the hostile and confined environment can hinder the manual execution, thus welding can also be a robot task.

If the blades conforms to the hydraulic profile, the coating erosion identification is made measuring the thickness of specific points on the surface of the blade. An operator with a specific device can manually do this process, efficiently, in ten minutes.

The abrasive blasting process is generally done before the coating operation. Rijeza company performs the abrasive blasting manually, but there are studies and companies performing abrasive blasting with robots (Ren et al, 2008).

3 State of the art

The study of the state of the art of robots for HVOF coating process on hydraulic turbine blades covers systems that meet some of the following requirements: operation in hostile and confined environments; manipulator's end-effector with at least 8.5 kg payload, 5 mm precision and $0.67m/s$ speed; 2.5 m x 3.0 m system workspace; and the ability to operate on complex 3D geometry surfaces.

3.1 Robots on rails

In industry, HVOF coating process is performed by a large-sized manipulator, which offer task versatility and large work envelope. A compact robot does not have the required workspace on a fixed position, and it could be hard to mount and unmount the system several times. A prismatic joint coupled to a rail is the most common strategy for extending the robot work space, without adding weight to the manipulator.

The Roboturb (Bonacorso et al, 2006) is a robotic manipulator composed of six revolution joints and one prismatic joint coupled to a flexible rail.

The robot performs welding, filling cavities generated by erosion. The rail may be shaped and then fixed to the blade surface by a passive system of suction cups. The robot has two end-effectors: an optical sensor for erosion inspection; and a welding tool, a PWH-4A plasma torch with automatic feeder.

The Scompi robot (Bibuli et al, 2007) is a multipurpose manipulator, designed to perform repairs on *Francis* type turbines, as welding and grinding. It has six degrees of freedom: a manipulator with five revolution joints; and a prismatic joint, coupled to curved rails that are designed specifically for each application.

The systems described do not have the required payload for HVOF, which is too heavy to be fixed on the blade itself. Besides, in a similar solution, the customized rail and robot need to be repositioned, as the area in which the rail is fixed is not in the robot workspace. On the other hand, rail systems fixed on adjacent structures should considerate the installation conditions, and balance the cost-benefit of installation/removal of the rail. The solution should be modular and stiff enough due to robot vibrations during coating application.

The system advantages are: manipulator size reduction; and manipulator weight reduction. The disadvantages are: rail mounting; and rail handling.

3.2 Climbing robots

Climbing robots are systems capable of supporting its own weight against gravity, moving in simple or complex geometric structures, such as walls, ceilings and roofs, turbine blades and nuclear plants. Generally, climbers are used to provide operational efficiency in harsh environments, and to increase safety. Some applications for climbing robots are: skyscrapers inspection and cleaning, storage tanks diagnosis in nuclear power plants, ship's hull and turbine welding and maintenance (Armada et al, 2003).

The major challenges in climbers development are mobility, adhesion, power consumption, load capacity, and weight. In Maempel et al (2009) and Chu et al (2010), climbers are divided into types of locomotive mechanisms: legs; walker; translation; wheels; tracks; advance by arms; cable-driven; and biomimetics. And adhesion types: suction or pneumatic; magnetic; electrostatic; chemical; gripping; and hybrid.

The following climber robots were investigated:

- **Ships and turbines**: RRX3 for welding (Kim et al, 2004), *Climbing Robot for Grit Blasting* for cleaning (Faina et al, 2009), ICM Robot for inspection (Machines, 2015), and RIWEA (Elkmann et al, 2010);
- **Industrial**: ROME II (Balaguer et al, 2002) and CROMSCI (Hillenbrand et al, 2008), both for inspection;

The RRX3, Daewoo Shipbuilding & Marine Engineering, is a robot for ship's hull welding with manipulator. It has a gripping adhesion type, a translation locomotion type (sliding segments), and longitudinal locomotion by wheels. The RRX3 robot has a 1.5 m manipulator with three prismatic joints and three revolution joints (3P3R) for welding operation. The system weighs 120 kg with 5 kg payload, it has a manipulator with welding tool.

The *Climbing Robot for Grit Blasting*, University of Coruna, is a robot for abrasive blasting application in ships. The robot moves by two sliding platforms with magnetic adhesion. The platforms have relative motion between them and can rotate to compensate ship's hull curvatures or to deflect objects. The abrasive system is similar to HVOF, but the robot locomotion is not applicable to complex structures.

The Climber, ICM Robotics, is an inspection robot for wind turbines, coating removal, surface cleaning and coating application. It has pneumatic adhesion and locomotion by tracks. It has 25 kg base payload, and a small-sized low speed manipulator. The locomotion type presents restrictions to some curvatures.

The Rome II , University Charles II of Madrid, is an inspection robot for complex environments. It has pneumatic adhesion and moves like a caterpillar (biomimicry). Rotation and planning trajectory are performed optimally to ensure stability and obstacle avoidance.

CROMSCI , Kaiserslautern University of Technology, is an inspection and autonomous robot for large concrete walls, as pillars of bridges and dams. Its adhesion system is composed of seven vacuum chambers (suction), valves and pressure sensors for system control. The locomotion system has omnidirectional wheels.

RIWEA is a purely cabling robot, as it has no other type of position adjustment, for cleaning wind power turbines. It is an open frame concept robot which uses four ropes to move up and down. It has five main parts, which automatically adjust to the blade surface during its movement (Jeon et al, 2012). Its greatest advantage lies in the ability to adapt to the curvature of the blade while maintaining a foothold on it, and it is also less susceptible to vibration.

Climbing robots are widely applicable, have different adhesion solutions and mobility. There is not, so far, a climber that fulfills all the HVOF requirements for the large hydropower turbine's blades, but some of the systems, such as *The Climber* (ICM Robotic), can generate complete solutions with adaptations.

The advantages of climbers are: easily installation, small-sized manipulator, small base, lightweight, autonomy; and the disadvantages are: complex locomotion system, complex mechanics, manual installation on blade, required a well-developed safety system, it generally has limited battery or an umbilical management system.

4 Design of a robotic system for *in situ* HVOF

The robotic system design for HVOF in hydraulic turbine blades is a solution that meet all the requirements. Thus, the envisioned robots of this section merge some technologies exhibited in section 3 in the context of the Jirau hydroelectric dam.

In section 2, the runner area accesses were described and their restrictions are essential for the elaboration of the solution. This section is divided into robotic solutions for both accesses, since they are the most important development restriction, as they limit robot's dimensions, features, and accessibility.

4.1 Top hatch

The top hatch, at the top of the runner area, has only 357 mm diameter (Fig. 3). Using the top hatch as the access for the robot has the following advantages: base stiffness (robot fixation stability), fixed reference point (facilitating localization system, mapping, control and calibration), built logistics (conveyor gantry to position the robot and the HVOF system); and the following disadvantages: robot size (only 357 mm diameter), system must be removed to rotate the blades, and it is not a general solution (specific to Jirau installations).

Climbers and rail systems are not suitable for the top hatch due to its dimension. These solutions will be detailed in Section 4.2, since the top hatch do not pose logistic gain for these approaches.

The proposed solution for this access point is to use an industrial manipulator that fits through the hatch, anchored on the external part of the turbine. The choice of the robot is primarily associated with reach, but only a small share of off-the-shelf manipulators can fit. Thus, the study was focused on the KUKA Light Weight (LBR iiwa 14 R820), which weighs 30 kg, has seven joints and 14 kg payload, enough to carry the coating equipment, but further dynamics tests should be done to validate the robot, at the speed and accuracy required.

To place the LBR in a position where it is able to process all the blade, a hinged base model was proposed. The mechanical system consists of three telescopic links interconnected by a revolute joint, and the first link is attached to the top hatch itself. To cover the entire blade, the mechanical base must be able to assume different angles with respect to the insertion axis, and the base's links must be telescopic with prismatic joints. The links are cylinders with maximized diameter at low thickness, which features a high polar moment of inertia and light weight, providing great bending stiffness, and minimizing positioning errors and excessive vibration. A recirculating ball actuator was chosen for low backlash and high precision. Fig. 4 shows the mechanical system concept in two configurations: retracted and extended.

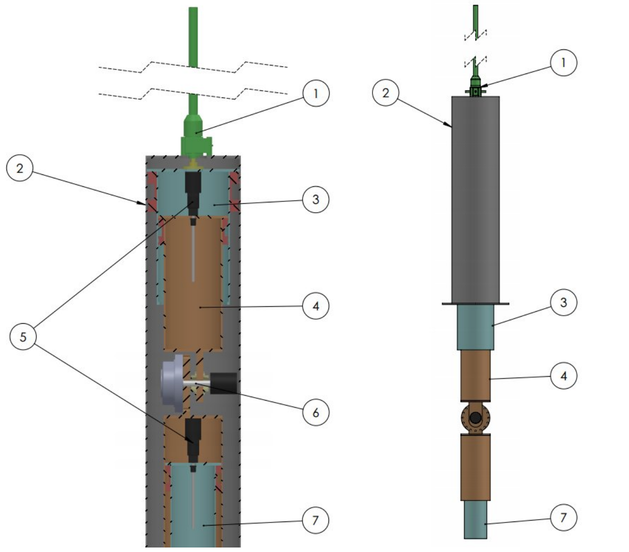

Fig. 4 Initial and extended configuration of the base.

The main components of the base are shown in Fig. 4: 1) worm gear linear actuator; 2) fixed base; 3) prismatic arm #1; 4) prismatic arm #2; 5) linear actuators; 6) revolute joint; 7) prismatic arm #3. Fig. 5 shows the mechanical system and the LBR R820 manipulator.

Inserting the mechanical system and the manipulator in the top hatch requires special care, as the system total length is greater than the distance from the top of the runner area to the turbine nose. In extended configuration, the arm and the base will need to be rotated during the insertion, which will result in system's central mass misalignment with respect to the perpendicular axis of the hatch, which demands compensations to the generated torque.

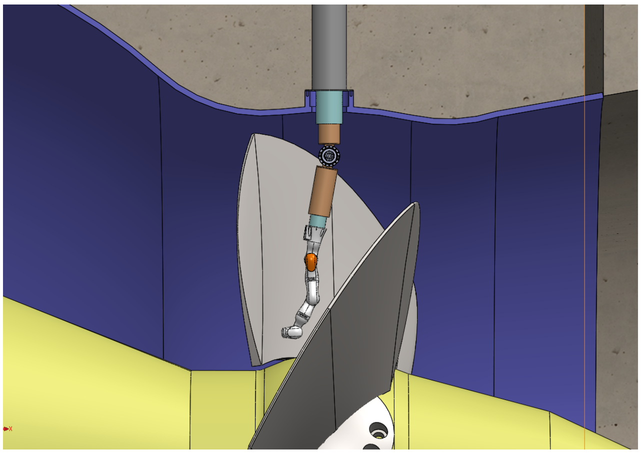

Fig. 5 Base and KUKA LBR R820 manipulator

4.2 Bottom hatch

The bottom hatch, at the middle of the draft tube, is a 800 mm diameter hole. Accessibility is a major problem, as the bottom hatch is 10 m far from the blade and 4 m above the external ground level, thus the system should be manually hoisted, transported on the slippery, conical and sloping environment, and placed close to the blade. Using the bottom hatch as the access for mid-sized robots has the following advantages: large enough for mid-sized robots, free access, it is generally used by operators for turbine maintenance. And the following disadvantages: the hatch is not big enough for large-sized manipulators, complex logistics (scaffolding and hoists), hard robot transportation and positioning.

The system solution is focused on mid-sized manipulators, and a modular base. Solutions were divided into subsections in accordance to fixation strategies: mobile robots that move on rails fixed on the blade; climbers; industrial manipulators that move on rails fixed on the floor.

4.2.1 Rail guided robot fixed on blade

A rail guided manipulator fixed on the blade satisfies all requirements for the HVOF and inspection. The development of a compact system for easy transportation and installation on the runner area are possible, since the manipulator dimensions are reduced due to the extra mobility provided by the rail.

In the context of the proposed application, the solution consists in a system similar to Roboturb, presented in section 3.1. Thus the rail should be flexible to be able to follow the blade curvature, it should allow several placement options, and, as the blade is not ferromagnetic, the adhesion would be done by active suction cups made of a special material to work on large temperature variations.

Solution conclusion Fixing a rail on the blade has some complexities: rail and robot manual installation for each blade side; design of customized flexible rails; and design of special active suction cups for high temperature variation and payload. It is possible to use an off-the-shelf manipulator, such as the LBR R820, making the design focused on signal processing, mapping, localization, control, and the rail construction.

The solution should be suitable for the application, but the required rail customization does not make it a simple and general solution. Besides, a rail attached to the blade requires a compact and lightweight robotic system, which is very complex for the HVOF requirements.

4.2.2 Robotic climbers

In this subsection, the robotic solution for HVOF are the fusion of technologies documented in subsection 3.2. It is an adaptation of *The Climber*, ICM, given its ability to reconfiguration.

The Climber, ICM, is a commercial solution which meets many of the HVOF specifications and some improvements do not compromise its structure. The robot's adhesion is suction and it moves through flexible mats. The system has already been tested in harsh environments, as wind turbines, hydroelectric plants and others. We can divide the robotic system design into four systems: mobility, adhesion, manipulator and autonomy.

The Climber uses only one vacuum chamber instead of the suction cups in Kim et al (2008), for instance. *The Climber*'s flexible mats allow smoothly and continuously motion. The solution with a single chamber seems more advantageous, as the robot can move on curvatures up to 30 cm radius. In the specific case of the HVOF, a manipulator applies the coating while the robot travels along the blade. The robot locomotion on the blade rises some design issues: blade's temperature variation during the procedure, which requires active suction chamber with special material; mats and the suction chamber must work on highly curved surface.

In adhesion by suction, an intelligent security mechanism should be implemented, with accelerometers, gyros and other sensors to ensure the shutdown of the electronics, and the HVOF gases. A path planning generation could increase the operation safety.

Solution conclusion Although tempting because of the autonomy, the surface complexity of the turbine blade, the confined environment, and the required speed and payload are major challenges to this solution.

The climber's manipulator should have the following characteristics: to be lightweight; to be fast and accurate; to be modular, as the operation is performed in confined space; to be small, improving mobility, but capable to operate on blade's edges with 230 mm minimum distance; and to have 10 kg payload and vibration resistance. Off-the-shelf manipulators with the required payload weighs 30 to 50 kg. Therefore, manipulator, HVOF gun and cables weighs 50 to 80 kg. The manipulator greatly increases the dimensions of the mobile base, and hence diminishes its workspace, slowing the process.

Finally, the climber as described above does not switch automatically between blades. A climber with arms to switch between blades is a costly solution in terms of control and mechanical structure. Another solution would be a robot with locomotion by sliding segments, as RRX3, and adhesion by suction, but the flexibility for motion between blades complicates the design.

Compared to alternative solutions, a climber would be a general solution, it has logistical advantages, but it is a robotic challenge.

4.2.3 Proposed solution

There are several large-sized off-the-shelf manipulators which fulfill the HVOF requirements, and compatible with the bottom hatch dimensions. However, those manipulators are too big to operate behind the blade, on the distributor side, due to environment collisions, and joint constraints. Besides, manipulators with such workspace are heavyweight, thus the robot placement and motion would be complex inside the turbine. A feasible solution is a mid-sized manipulator, and a customized modular rail base to place and move the robot.

The mechanical base consists of two modular non-actuated and customized rails: the main rail (transport) and the secondary (positioning) rail, both fixed by magnetic fixtures or welding. The transport rail moves the robot from the bottom hatch to the blade, solving a logistic problem. The positioning rail is assembled to the transport rail by a rotary joint, and it positions the robot along the blade, solving the horizontal coverage of the blade. The mechanical system can be summarized in three joints: prismatic (main rail), revolution (joint between main and second rail), and prismatic (second rail) (P-R-P). As the robot can not vertically cover the entire blade, vertical positions should also be manually selected. The blade can be coated on linear or circular motion, and, in both cases, the manipulator will be responsible for speed, position and the gun orientation.

The solution for end effector direction exchange (*long stop*) is an actuated valve to redirect the coating particles.

Regarding turbine accessibility, a mid-sized manipulator should be hoisted through the bottom hatch, placed on the transport rail and carried to the blade, as in Fig. 6. At the runner area, the robot is manually switched to the secondary rail. On it, the solution is similar to the *ex situ* operation: a manipulator in a fixed position, at the front or at the back of the blade, with a coating gun. However, a simple geometric study with blade's actual dimensions shows that a mid-sized (1400 mm workspace) manipulator cannot fully cover the blade. Therefore, the secondary rail must be able to move the robot horizontal and vertically (Fig. 7).

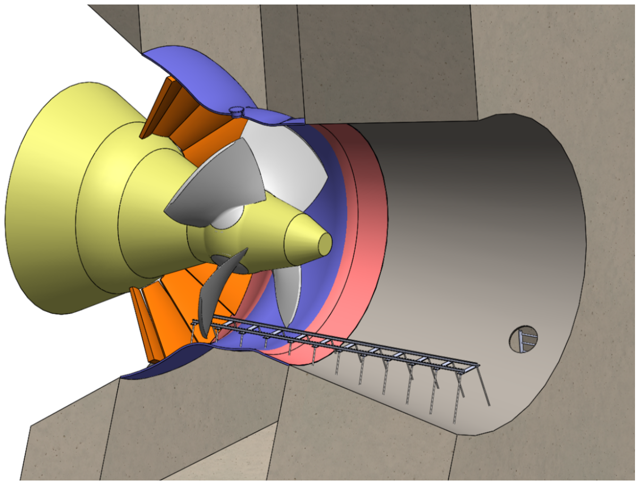

Fig. 6 Transport rail mounted inside the turbine.

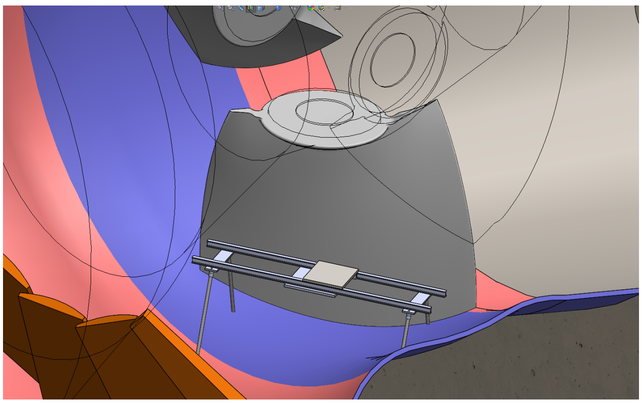

Fig. 7 Positioning rail behind the blade.

Solution conclusion In terms of robotics, a rail guided industrial manipulator with magnetic fixtures is the simplest among all solutions. Off-the-shelf manipulators are available and fulfill the HVOF requirements, thus the mechanics will be responsible for the mechanical base design, stiff and modular rails, and the magnetic fixtures. The robtic challenges, as path generator and calibration are well discussed in the literature.

5 Conclusion and future work

The maintenance of hydroelectric turbines is essential for fully operation, as it substantially increases the power plant potential. The maintenance of the hydraulic profile of runner's blades is a major concern for turbine efficiency, thus regular inspections, repairs and coating application for cavitation and abrasion protection should be performed.

Currently, *ex situ* recoating operation would be costly, it will require turbine disassembling and recalibration. This document aimed to: analyze the constraints of the *in situ* thermal spray coating process; characterize the environment where the process is taking place; make a state of the art survey of similar problems; and design conceptual solutions.

The feasibility study for an *in situ* coating application is promising and some possible solutions were investigated for each turbine access. As a conclusion, EMMA's hardware concept solution is an industrial manipulator on customized modular rails. If the top hatch access is chosen, the solution is a small-sized manipulator, and a telescopic actuated mechanical base; in the case of the bottom hatch, the solution is a mid-sized industrial manipulator with two rails and magnetic fixtures.

Climbers, systems fixed on the blade, and mobile robots were analyzed. However, those solutions are not suitable for: the HVOF process, due to speed and payload requirements; or the geometric complexity and confined space of the hydropower turbine (sloping and slippery floor). The proposed solutions raise some logistical and technical challenges.

The bottom hatch's solution is the most general among the proposed solutions, since the top hatch is a peculiarity of Jirau's power plant. Thus, for future work, the concept solution for the bottom hatch access will be fully detailed in terms of mechanics, electronics, software and control.

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