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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 demand regular maintenance for flow stability and turbine efficiency as they are constantly exposed to abrasion and cavitation phenomena. Hard coating techniques by thermal aspersion are used to reduce the mechanical wear, thus increasing its life cycle, and to increase turbine efficiency. Currently, applying a new coating layer requires turbine disassembling, and recalibration. EMMA is an R&D project of 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 downtime for hard coating process. This document makes a survey of the state of the art of *in situ* turbine systems, and describes the conceptual designs for EMMA's robot. 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

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.

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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.

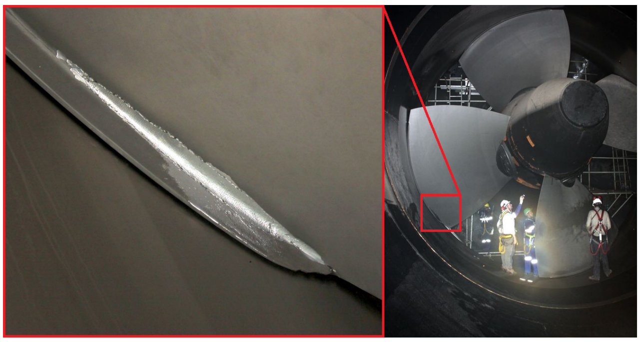

Fig. 1 Jirau hydraulic turbine's blade eroded by cavitation.

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 before the hydraulic turbine installation by a robotic manipulator. The procedure 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. With the current available technology, to reapply the coating layer, it would require stoppage of the turbine, removing the blades, positioning the blades for coating, coating application, turbine assembling, and recalibration. This process can take up to two months, meaning a huge loss in power generation.

EMMA is an R&D project by Universidade Federal do Rio de Janeiro (UFRJ), in partnership with Rijeza company, Agência Nacional de Energia Elétrica (ANEEL) and Energia Sustentável do Brasil (ESBR). Its first stage is a technical feasibility study of a robotic system to perform coating by thermal spray on hydraulic turbine blades within the turbine environment.

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 the EMMA project.

2 The problem

Cavitation and abrasion in hydropower turbines cause surface erosion and blade's 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. In the case of the Jirau hydroelectric dam, the coating of turbine's blades is performed before turbine assembling and installation. However, 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).

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 hydroelectric plant problem. Finally, robotic tasks are highlighted to solve the problem.

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, responsible by partially melting and accelerating 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^oC, spraying the particles with 700 to 1000 m/s speed, and generating a 15 N recoil force.

The robotic manipulator must have 5 mm accuracy, and the spray gun should remain at a 230 to 240 mm distance with $90^o \pm 60^o$ angle in respect to the metallic surface plane. 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 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), hazardous gases and potentially explosive gases are expelled; the blade can reach up to 110^oC; the environment 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. Table 1 summarizes the project restrictions and specifications.

Table 1 HVOF process data

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

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

2.2 Environment contextualization

The Jirau plant has horizontal axis bulb type turbines. In hydropower plants, electric power generation depends on the water level and river flow, however 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) Propeller and blades; 2) Runner area and adjacent areas; 3) Hatches; and 4) Draft tube.

1) Propeller and 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 blades' angles relative to the water flow can be from 0^{o} to 29^{o}. Rotor position can be changed manually and be rotated in both directions without limit. But blades' angles changes requires hidraulic actuators.

2) Runner area and adjacent areas: the runner area and the distributor area 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 an efficient and robust 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.

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 area 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.

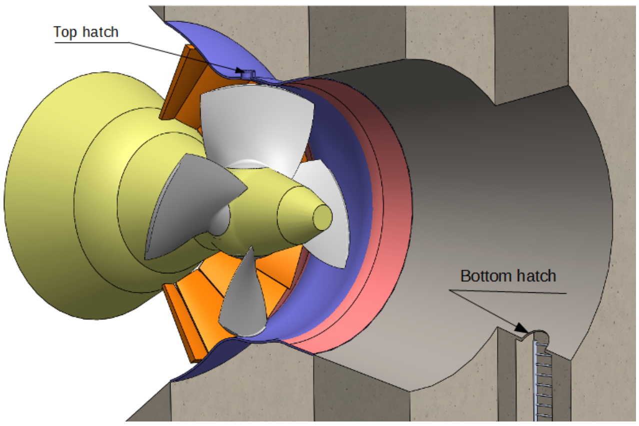

Fig. 3 3D CAD model of the Jirau turbine (SolidWorks®).

2.3 Robot tasks

The summary of the tasks to be performed for a hard coating *in situ* 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 and 5 to 7 by robot.

As mentioned, the turbine blade should conform to the template (hydraulic profile) before the coating process. Therefore, robot should build an hydraulic profile (mapping) and analyze flaws.

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 normally required 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. The robots were organized by fixation technologies.

3.1 Robots on rails

In industry, HVOF coating processes are performed by robotic manipulators, which offer tasks versatility and large workspace, required for this type of application. Meanwhile, a robotic arm capable of coating all the turbine blade's surface on a fixed position is not compact or mobile, and hard to be mounted/unmounted. A prismatic joint coupled to a rail is a common strategy for extending the robot working space, without adding weight to the manipulator, and the rail can use the structures in the environment as a support.

The Roboturb (Bonacorso et al, 2006) is a robotic manipulator composed of six revolution joints and one prismatic joint coupled to a flexible rail (Fig. 4). 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.

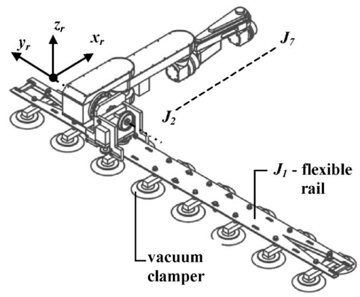

Fig. 4 Roboturb

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 robotic manipulator with five revolution joints; and a prismatic joint, coupled to curved rails that are designed specifically for each application.

The HVOF system is too heavy for a robotic system on rails fixed on the blade itself. Besides, this solution would require rail reposition, as the entire blade surface should be coated and 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: 1) manipulator size reduction; 2) manipulator weight reduction. The disadvantages are: 1) rail mounting and unmouting; 2) rail handling if fixed on the blade.

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. Climbers provide operational efficiency in hazardous environments, and increase operators health and 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.

In the specific case of the HVOF coating problem in hydropower turbines, the following climber robots should be investigated, as all of them have millimetric accuracy, and resistence:

- **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 (Fig. 5), Daewoo Shipbuilding & Marine Engineering, is a robot for ship's hull welding with manipulator. Its adhesion is gripping type, locomotion is translation 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, but low speed end effector. Regarding the HVOF application, the locomotion type is not efficient.

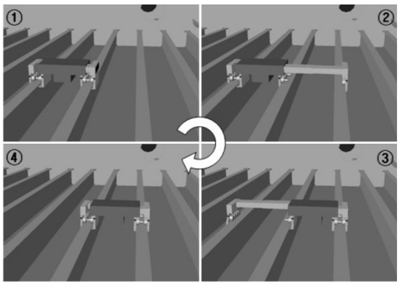

Fig. 5 RRX3 translation locomotion.

The *Climbing Robot for Grit Blasting* (Fig. 6), 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 (Fig. 7) , 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).

Fig. 6 Climbing robot for Grit Blasting

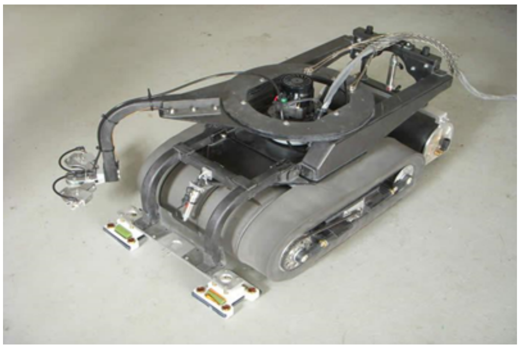

Fig. 7 *The Climber*

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 wind power turbines cleaning. 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 move (Jeon et al, 2012). Its greatest strength lies the ability to adapt 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 turbine blade coating, 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, well-developed robot safety system, limited battery or umbilical management system.

4 Design of an autonomous robot for *in situ* HVOF process

The autonomous system design for HVOF in hydraulic turbine blades include solutions that meet all the application's 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 demand different logistics.

4.1 Top hatch

The top hatch, localized 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: robot fixation stability, 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: difficulty in finding robots of such size (357 mm diameter), the robot 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 na 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 commercial robots has the dimension to fit the top hatch restriction. Thus, the study was focused on the KUKA Light Weight (LBR iiwa 14 R820), robot whose base diagonal is less than 357 mm.

The LBR R820 weighs 30 kg, has seven joints and has 14 kg payload, enough to carry the coating equipment. However, further studies are needed to validate the robot, on the speed and precision requirements when coating.

To place the LBR R820 in a position where it is able to process all the blade, a hinged base model was proposed. The base 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 base must be able to assume different angles with respect to the insertion axis, the links must be telescopic type with prismatic joints.

The base's structure would consist of cylinders with maximized diameter and small 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. 8 shows the manipulator' base concept in two configurations: retracted and extended.

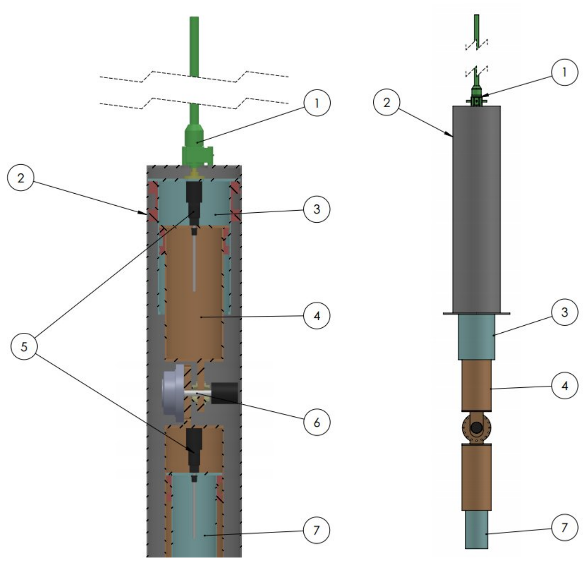

Fig. 8 Initial and extended configuration of the base.

The main components of the base are shown in Fig. 8: 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. 9 shows the base and LBR R820 manipulator.

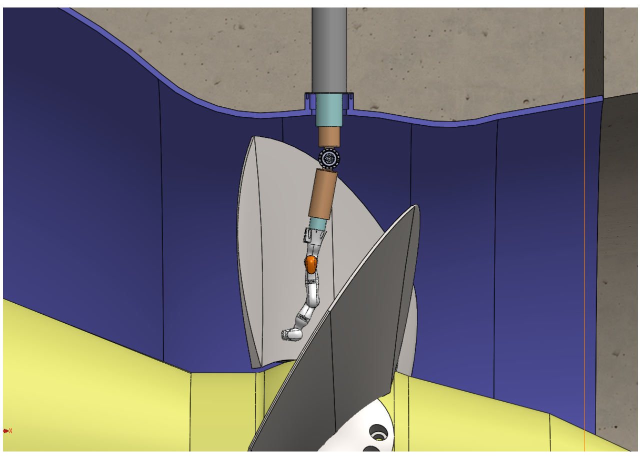
Fig. 9 Base and KUKA LBR R820 manipulator

Inserting the system, composed of the base and 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 process, which will result in system's central mass misalignment with respect to the perpendicular axis of the hatch, thus it will require a guide to compensate the generated torque.

4.2 Bottom hatch

The bottom hatch, localized at the bottom of the Runner area, has 800 mm diameter, enabling mid-sized robots entry. As logistical challenge, 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 Runner area's floor and positioned near the blade. Using the bottom hatch as the access for robot has the following advantages: large enough for mid-sized robots, free access, it is normally used by operators to turbine maintenance. And the following disadvantages: not large enough for large robots, complex logistics to the hatch (scaffolding and hoists), difficulty for robot moving and positioning in the Runner area due to the slippery and sloping floor.

The system solutions is focused on mid-size 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 Design of a mobile robot and rail fixed on blade

The concept solution of a robotic manipulator and rail base fixed on blade satisfies all requirements for the HVOF coating and the inspection process. The development of a compact system for easy transportation and its 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 and uninstallation for each blade side; design of customized flexible rail; and design of special active suction cups for high temperature variation. It is possible to use an industrial 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 Design of robotic climbers

In this subsection, the robotic solutions for HVOF coating are the fusion of technologies documented in subsection 3.2. They will be an adaptation of *The Climber*, ICM, given their ability to reconfiguration.

The Climber, ICM, is a commercial solution which meets many of the HVOF specifications and enables improvement without compromising its structure. The robot's adhesion is suction type and the motion is flexible mats. The system has already been tested in hazardous environments, as wind turbines, hydroelectric plants and others. We can divide the 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 example. *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 process, a manipulator applies the coating while the robot travels along the blade. The robot locomotion on the blade rises some design issues: the blade temperature during the procedure requires an active suction chamber special material; and mats and 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 supply of the HVOF gases in case of fall. The solution of a mobile robot path planning increases safe operation and the optimal control of the adhesion mechanism can limit the maximum suction force.

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 the design.

The climber's manipulator would be complex and should have the following characteristics: to be lightweight, avoiding base complex adhesion and balance; to be fast and accurate as required by the HVOF application; to be modular, as the operation is performed in confined spaces; to be small, improving mobility, but capable to operate on blade's edges with 230 mm minimum distance; and to have high payload and vibration resistance. The smaller industrial manipulators with required the 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 their 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 required for motion between blades complicates the design. Thus, the exchange between blades should be manual.

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 industrial manipulators which fulfill the HVOF requirements. Companies as Fanuc, Motoman, ABB and KUKA, for example, manufacture manipulators compatible with the bottom hatch dimensions and HVOF requirements, and workspace that the entire turbine blade could be coated at a fixed base position. However, those manipulators are too big to operate behind the blade, on the distributor side, due to environment collision, joint constraints, and robot manipulability. Besides, manipulators with such workspace are heavyweight, thus the robot placement and motion would be complex inside the Runner area. A feasible solution would be to select a mid-sized manipulator and made a rail base to place and move the robot.

The base consists of a transport rail and a positioning rail, both fixed in the Runner area by magnetic coupling and/or welding. The first solves a logistic problem, as it starts at the bottom hatch entry and goes to the blade, moving the robot through the Runner area. The latter is coupled to the main rail and positions the robot close to the blade, enabling displacement along it, solving the horizontal HVOF cover of the blade.

The base may 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, there is still the need of different vertical positions, which should 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 gun orientation. The solution for gun direction exchange (*long stop*) is an actuated valve to redirect the coating particles.

A mid-sized robot manipulator should be hoisted through the bottom hatch, placed on a rail base with magnetic holders and carried to the blade, as in Fig. 10. At that position, the robot should switch to the other rail.

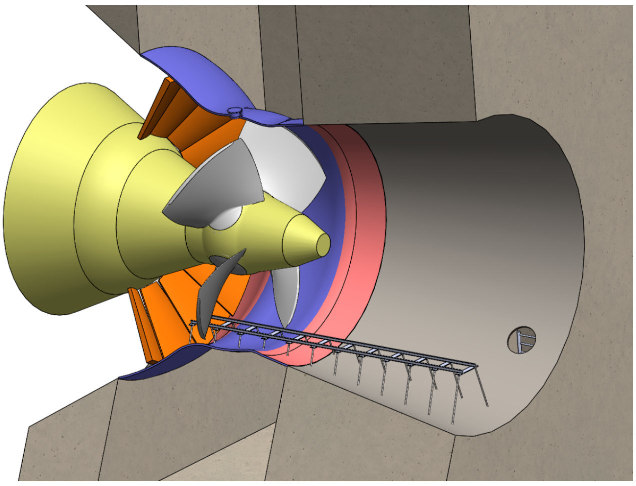

Fig. 10 Transport rail mounted inside the turbine.

Fixedly positioning a robotic manipulator with magnetic holders at the front or at the back of the blade for HVOF process is a natural solution, since it is similar to the companies procedure. However, a purely geometric study, using the real dimensions of the blade, shows that the manipulator must have more than 2.5 m reach for full blade cover. To perform this task, workspace analysis was conducted to confirm the geometric study and a mid-sized robot can not reach the entire blade. Therefore, its base should be able to move horizontally and vertically (Fig. 11).

Solution conclusion In terms of robotics, industrial manipulators on a rail base is the simplest among all solutions for the bottom hatch. There is no mechanical design for the manipulator, since it will be acquired in one of the aforementioned manufacturers, but the mechanics will be responsible for the base design (rigid and modular), the magnetic couplings, and logistics.

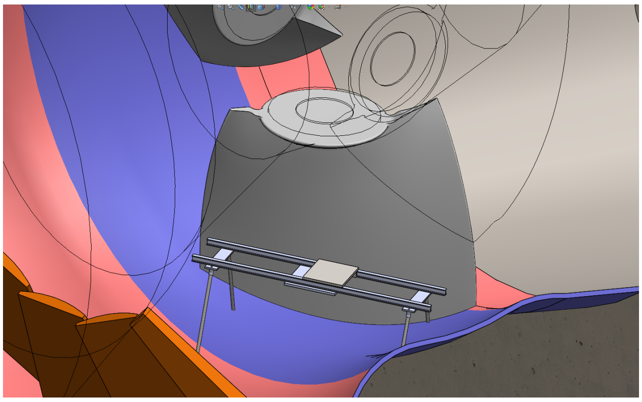

Fig. 11 Positioning rail behind the blade.

5 Conclusion and future work

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

The current hard coating operation is costly, as it requires 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 study 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 of the proposals, the concept solution is to use an industrial manipulator on a customized base. The characteristic of the manipulator and the base varies with the hatch (top or bottom). If top hatch, the solution is a small sized industrial manipulator and custom telescopic base, electronically operated; in the case of the bottom hatch, the solution is a mid-sized industrial manipulator with two rail type based and magnetic holders.

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 environment of the hydropower turbine, sloping, slippery, high temperature and humidity. The proposed solutions run into some logistical and technical challenges, which will be detailed at the development of EMMA project.

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

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