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RJET-111: Autonomous Mobile Robot for Water Intake Channel Maintenance in Power Plant Cooling Systems

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EXTENDED ABSTRACT

This paper presents a state-of-the-art, highly specialized, autonomous mobile robot for water intake channel maintenance, in power plant cooling systems. Thermal power plant in Plomin (TE Plomin), with a total capacity of 330 MW cools down using sea water which is rerouted via 2.5km long channel shown in Fig.1. Due to the abundance of algae present in the seawater, which spread throughout the channel and clog it, the water flow reduces and the power plant efficiency drops. In present situations, in order to eliminate the clog, the power plant needs to be shutdown, so that workers can manually clean its intake channel. The proposed robotic solution is be able to clean the channel while the power plant is still in operation, providing both money savings and human safety.

1 INTRODUCTION

RJET 111 is a result of an ongoing collaboration between the University of Zagreb and Inteco Robotics in research and development of mobile robots for hydrodynamic surface treatment. So far this research yielded a modular design of a lightweight mobile robot for hydrodynamic treatment of concrete and metal surfaces [1]. Building upon the results from this project we developed the proposed robot keeping in mind the highly specialized nature of its design, replacing the former modular approaches with a specific design approach. The shier size of the intake channel and the necessity for the robot to carry the high pressure pump and the power system dictate that both robot's size and mass have to be significantly larger than our previous, modular designs. Furthermore, robot's construction was tailored for the specific dimensions of the channel, so that its tool fits inside the channel, and its body can drive on top of it and safely navigate, localize and steer throughout its entire 2.5 km long path.

RJET 111 is a semiautonomous robot, which implies that a human operator remains in the control loop, essentially having a supervisory role with most of the lower-level tasks being implemented on the robot itself. Due to the sheer size and weight of the system, this level of autonomy is an important requisite when working in the environment where unforeseen human contact can occur [2]. Introducing robots to work in power plant maintenance is not a new concept. Use of robotics and computerized tools in Nuclear Power Plants (NPPs) has been identified as a highly recommended practice by International Atomic Energy Agency (IAEA)[3]. For instance, the authors in [4] proposed several inspection scenarios using various robot prototypes. The 3 most evolved robots resulting from this research were *MagneBike* for steam chest, *AirGapCrawler* for generators and *TubeCrawler* for boiler tube. All of these prototypes, like the one proposed in this paper, were tailored for a specific role, which dictated their shape and size. Like the robots presented in [5] and [6], R JET 111 uses high pressure water jets to clean the concrete water coolant gravitational channel. High pressure water jets are highly efficient and ecologically acceptable tools to remove algae and other marine biological material that clogs the water coolant channel.

The paper presents a detailed mechanical design of the robot that encompasses: 1 degree of freedom high pressure cleaning tool tailored for the channel profile; differential drive supported with two additional passive wheel pairs; and body capable of carrying full load of the high pressure pump, power unit, drives, electrical motors and electronics. The design and implementation of necessary electronics for both communication and control is also described in the paper. Finally, we present the control system capable of steering the robot throughout the 2.5 km long channel with centimeter precision, starting from mathematical modeling and simulation, to real world implementation.

Figure 1 R JET 111 design, construction and implementation at the TE Plomin, Croatia

2 MECHANICAL DESIGN AND CONSTRUCTION

RJET 111 is designed to fit perfectly between the channel walls. Therefore, the profile of the channel shaped the design of the robot, making it over 5 meters wide. The effective channel length is 2180m, with a minimum curve radius of 25m. Minimum channel width of 460cm, along with its minimal curve, forced the design of the robot to fit in 350cm length. The cross section of the channel has a trapezoidal shape shown in Figure 2. As the tool needs to fit perfectly inside the channel to clean its walls, its shape mimics the cross section of the channel.

There are two main parts of the construction: Main body – which carries the necessary high pressure pump, the fuel, the electronics and the sensory apparatus; Tool – which can be lowered in the channel to clean the walls. Being that the coolant water used in TE Plomin is in fact sea water, it is necessary to pull the tool out of the water once the job is complete, in order to prevent the salty water to cause long term damage.

There are eight high pressure jets symmetrically placed around the tool. Only a single high pressure jet is active at a time, producing 600bar output. This is achieved using a high pressure pump working at around 600 RPM. The high pressure pump is driven using its own diesel powered engine. There is a spring damping system attached to each jet, forcing it to strap on to the channel walls while the robot is moving or turning. The whole tool weighs around 1.5 tons and is also secured with a spring damping system that allows it to move freely when the robot oscillates within the channel walls. There are six wheels (shown in Figure 3), but only two of those are active.

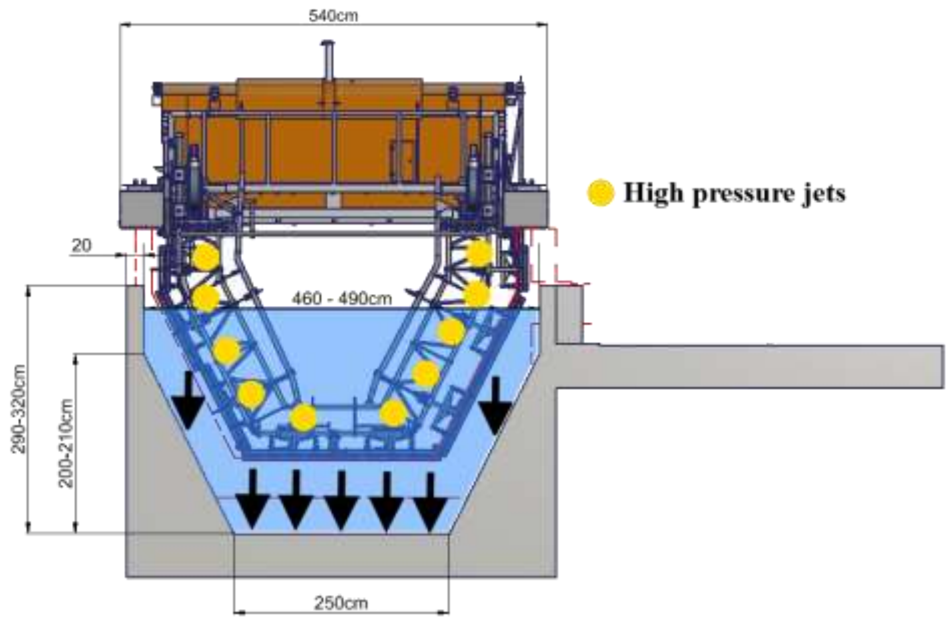

Figure 2 R JET 111 design takes its shape after the trapezoid cross section of the channel

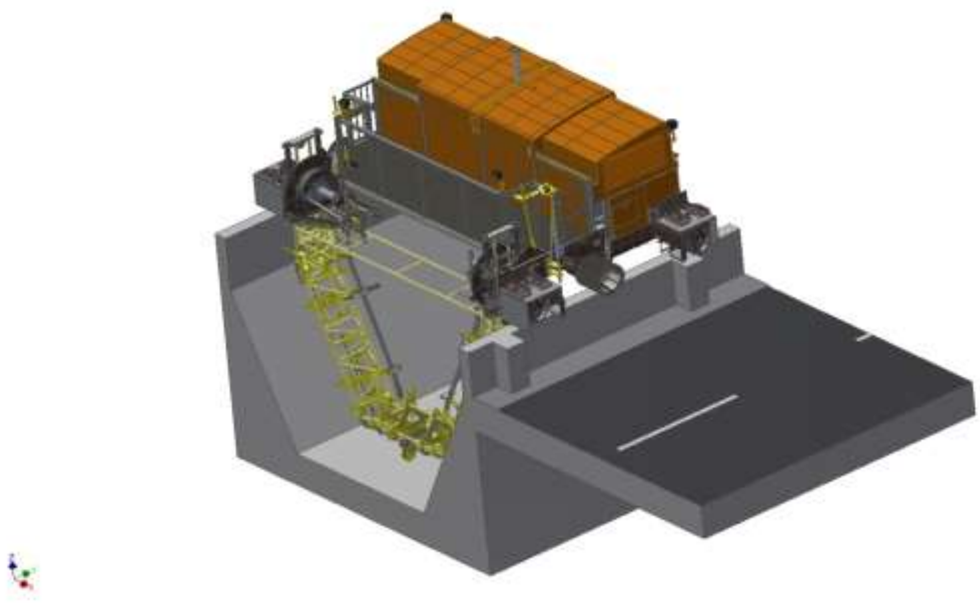

Figure 3 3D model of R JET 111 placed on top of the channel, with the tool lowered in.

When the channel was built, engineers did not foresee a scenario in which a robot would be driving on top of it. Therefore, throughout its entire length there are variations in both width and height. Channel width varies almost 30cm between its narrowest and widest point. To overcome this problem, an innovative differential drive system aided with passive wheel compensation, which can reduce almost 60% of friction forces produced when the robot changes direction, is devised. This design allows almost 8 tons heavy robot to achieve speeds of up to 10 cm/s using only two 2kW electrical servo motors.

3 COMMUNICATION AND ELECTRONIC DESIGN

As RJET 111 is devised as a semiautonomous robot, it needs to be supervised by a human operator while at work, cleaning the channel. The supervisor is stationed within the power plant, with no direct line of site towards the robot, which is shown in Figure 4. Operator therefore relies on the data received from the robot. Robot collects all the sensory data which is provided to the supervisor together with video images from an onboard pan/tilt/zoom camera.

Communication is based on Modbus TCP/IP protocol, which is transmitted via internet. Since the robot is mobile, it connects to the internet via GSM modem, which is the bottleneck of the proposed communication network. Nevertheless, since the robot is moving very slowly (i.e. up to 10 cm/s), even on mobile connection the rate of information exchange still satisfies system’s needs. Tasks which are considered to be too dangerous to be remotely controlled are executed on site, via provided wired controller.

Besides the aforementioned 70kW diesel powered pump engine, there is an additional power unit capable of supplying up to 14kW of electrical power. This unit is used to power the entire robot, including: motor drives, programmable logical controller, network components, camera, etc.

Figure 4 Modbus based TCP/IP communication network for the remote control and supervision of R JET 111

4 LOCALIZATION AND CONTROL

R JET 111 is required to traverse throughout the 2.5km long gravitational water coolant channel. In its path, the robot has to surmount curvatures of various sizes and radii. To that end, a control algorithm capable of precise navigation of the robot, which will be described in this chapter, has been devised. Longitudinal localization is achieved through sensor fusion using onboard encoders and specific markers placed throughout the channel. The markers are detected using onboard ultrasound sensor placed on one side of the robot, which detects the distance between the robot and the ground and detects obstacles and markers when the robot passes over them.

4.1 Kinematic model

Since the robot is driven using a standard differential drive, its linear speed v_L is a mean value of both active wheels of the drive:

$$v_L = \frac{v_1+v_2}{2} \tag{1}$$

where v_1 amd v_2 denote left and right wheel speed, respectively, In order for the robot to change direction, each wheel needs to rotate at different speed. This in turn causes the robot to traverse a circular path of radius R shown in Figure 5. Angular velocity of the robot is then calculated via the following set of equations:

$$v_1 = \Omega\left(R - \frac{D}{2}\right), v_2 = \Omega\left(R + \frac{D}{2}\right) \tag{2}$$

$$\Delta v = \mathrm{v}_2 - \mathrm{v}_1 = \ \Omega\mathrm{D} \tag{3}$$

with Ω denoting angular speed of the robot, and D being the distance between the two wheels.

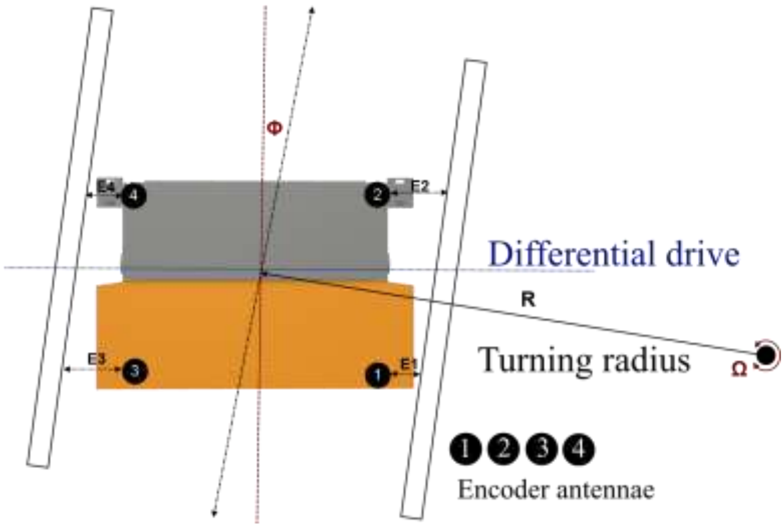

Figure 5 R JET 111 positioned on a section of the coolant water channel, with its respective turning radius, position and orientation toward the channel walls

There are four encoder antennae placed on each side of the robot. Antennae are designed to measure the distance between the chassis of the robot and the side walls of the channel. The antennae are marked E_1 through E_4 in Figure 6. Using the antennae measures, and both left and right distances between the sensors (i.e. L_{12} and L_{34}), one can calculate the left ϕ_L and right ϕ_R angles between the robot and the channel walls:

$$\phi_R = \operatorname{asin}\left(\frac{\mathrm{E}_2 - \mathrm{E}_1}{\mathrm{L}_{12}}\right) \tag{4}$$

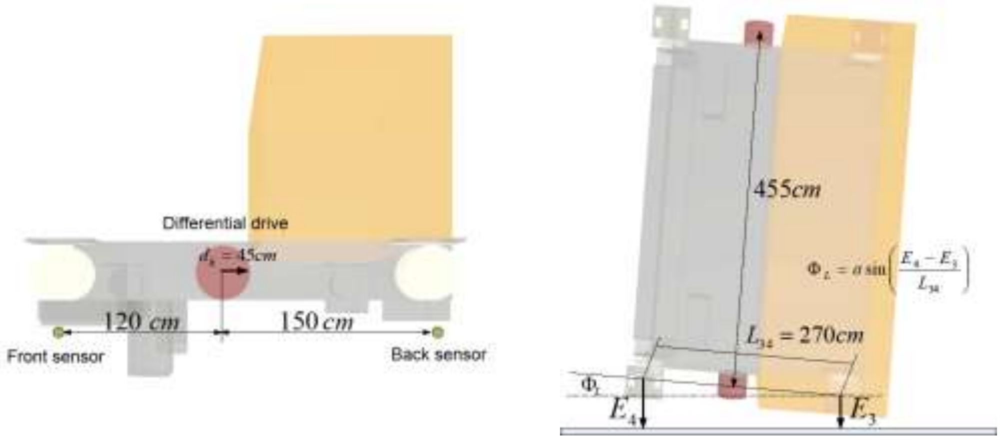

Figure 6 R JET 111 size and dimensions crucial for the kinematic model and localization within the channel walls

$$\phi_L = \text{asin}\left(\frac{\mathrm{E_4 - E_3}}{\mathrm{L_{34}}}\right) \tag{5}$$

In a similar manner, the same sensors are used to calculate the overall distance of left and right side of the robot. The distance is calculated as a geometric center between the two sensors placed within the differential drive of the robot:

$$E_R = \frac{\mathrm{P_2E_2 + P_1E_1}}{\mathrm{P_2 + P_1}} \tag{6}$$

$$E_L = \frac{\mathrm{P_3E_3 + P_4E_4}}{\mathrm{P_3 + P_4}} \tag{7}$$

where P_1 through P_4 are adjusted so that the distance from the walls is observed from the position of the differential drive. This is crucial for the stability of the devised controller.

4.2 Dynamic model and control

Since the controller cannot simultaneously adjust both sides of the robot, one needs to calculate the mean angle ϕ of the robot:

$$\phi = \frac{\phi_R + \phi_L}{2} \tag{8}$$

together with the error between the left and right distance to the walls of the channel

$$\Delta y = \mathrm{E_R - E_L} \tag{9}$$

The goal of the proposed algorithm is to keep the robot in the middle of the channel (i.e. $\Delta y \rightarrow 0$). This is achieved through a cascade loop shown in Figure 7. The inner loop of the controller is designed to control the angle ϕ towards the walls of the channel. The outer loop controls the distances between the center of the channel by turning the robots towards and from the walls. We assume of course, that the robot traverses through the channel with given linear speed v_L.

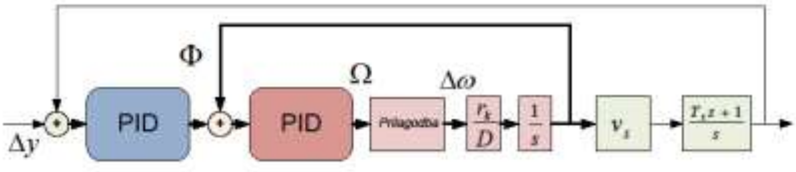

Figure 7 Channel wall following cascade control loop

5 CONCLUSION

R JET 111 was designed to clean the water intake channel of TE Plomin, while the power plant is still in operation, providing both money savings and human safety. Even though the system is tailored for the specific power plant, it is easy to imagine adapted robotic system working in different power plant and in different intake channel profiles.

The fact the R JET 111 uses sea water, notorious for its abrasive characteristics, to clean the walls of the channel, makes us confident that it could work in any non salted water conditions. With minor design adaptations such a robotic system could be applied to cleaning any intake or discharge channels in either thermal or nuclear power plants. Its mechanical design innovations, along with the proposed novel control system make it possible to apply similar designs to channels with large width and height variations.

We therefore, strongly believe that R JET 111 could be utilized to help improve nuclear power plant maintenance, ensuring money savings and providing humans with safe working conditions.

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