MINIATURIZED UNDERWATER HYDRO GENERATOR FOR POWERING WIRELESS SENSOR NETWORK NODES

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Abstract: *In this work a miniaturized underwater hydro generator concept is proposed for powering wireless sensor network nodes. It is based on a small DC generator encapsulated in a watertight enclosure and a propeller driven by river flow. Management electronics is designed to regulate the obtained electrical energy and store it on a super capacitor. For determining the propeller shape, a rough verification of turbine blades performances via numerical analysis is performed. Based on these calculations, two propeller variants are used in the experiments. The assembly of the hydro generator is whence tested in real river flow conditions. Based on the performed preliminary measurements, the design of the turbine is optimised and a further set of measurements is carried out in a flow tunnel. The generated power of roughly 700 mW, corresponding to the calculated value, is obtained, while the output powers are up to 220 mW.*

Key words: pollution monitoring, wireless sensor networks, hydro generator, energy harvesting

1.INTRODUCTION

Wireless sensor networks are an emerging technological field with beneficial aspects especially in pollution monitoring. Network nodes are processing units with embedded sensors and radio transceivers capable of monitoring pollution, or any other environmental condition, and wirelessly transmit the data to the network gateway. In this framework, measurement of pollutants in rivers by using underwater sensor networks is often required. The sensors and the respective electronics must have enough power for undisturbed constant work. Given the limited lifetime of batteries, energy harvesting devices appear an attractive powering option [1, 2].

In this work, laboratory and real river flow experiments are performed on a miniaturised underwater turbine-based energy harvester. The needed power output is based on the power consumption of the load, constituted by the pollution sensors and the respective electronics, which was previously calculated and verified experimentally to be at a 100 mW level with short power bursts in average at 300 mW [3]. All the models are developed using a 3D modelling software. The first prototypes of the mechanical parts are manufactured by employing a 3D printing technique. The obtained results allow establishing that the necessary power levels are achieved. A load simulating the sensor cluster is successfully powered in real river flow conditions at the Rječina river in Rijeka, as well as in the controlled conditions of a flow tunnel at the Naval Research Institute in Zagreb.

2.MINIATURISED UNDERWATER TURBINE PROTOTYPE

The concept of the miniaturised underwater hydro generator is based on a DC generator rotated by a propeller driven by river flow (Figure 1). The generator (1) is connected with the propeller shaft (2) via an elastic coupling (3) [4]. The turbine propeller (4), whose provisional diameter of 150 mm was calculated based on first-order wind-mill equations given in [5], is connected with the propeller shaft which is centred with a bearing (5) [6]. The radial shaft (6) is mounted on the propeller shaft [6] and it ensures sealing between the shaft and the turbine enclosure which contains slots with silicone gel in order to ensure its watertight sealing (7). Two different DC generators from Faulhaber, whose parameters are listed in Table 1, are employed for building the first prototype [7]. The output powers listed in Table 1 are those given in manufacturer's manual and referred to the mechanical power which can be generated by the device when used in the motor mode. However, when the device is used in a generator mode, this value can roughly be used as an estimation of the achievable maximal power levels.

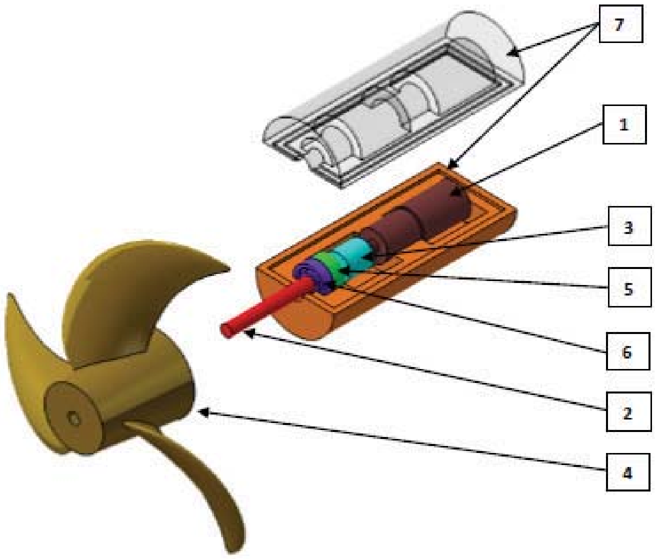


Figure 1. 3D model of the prototype of the miniaturised underwater hydro generator

Table 1. DC generators and their parameters used in the first prototype

Device	Maximum output voltage, V_{max}	Output power, P_{out}	Velocity needed for maximal generated output voltage (before gearhead), n_0	Gearhead ratio, r	Velocity needed for maximal generated voltage (after gearhead), n_1
1724006SR	6 V	2.58 W	8600 rpm	19.2:1	448 rpm
1724012SR	12 V	2.17 W	7900 rpm	20.25:1	390 rpm

For determining the propeller shapes, prior to experimental investigations, a rough verification of turbine blades performances via numerical analysis is performed. Friendship Systems CAESES software [8] is used to create the parametric model of the turbine blades. The obtained results, shown in Figure 2, are those for a steady state, three dimensional, incompressible fluid flow. For the highest foreseen water velocity (v = 4 m/s), a maximum pressure value on the turbine blades (red colour on the contour plot shown in Figure 2 left) does not exceed 50 kPa which is negligible. On the other hand, Figure 2 right shows the fluid flow behaviour around the turbine blades. Based on these simulations, two propeller variants (with diameter d = 150 mm) with three propeller blades are used in the experiments: that with narrow blades and that with wider blades (Figure 3). The watertight enclosure presented in Figure 4 left is printed via a 3D printer [9], while the assembly of the first prototype of the miniaturised underwater hydro generator is shown in Figure 4 right.

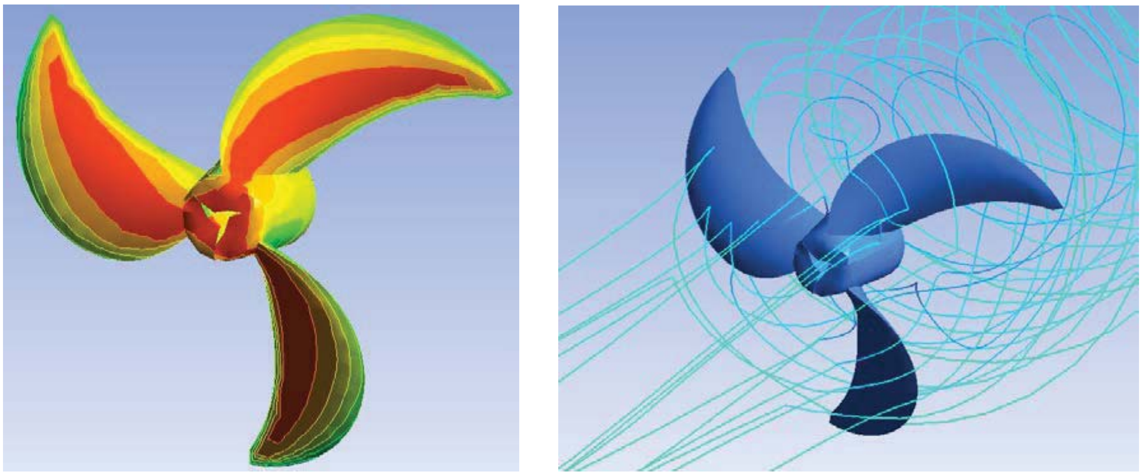


Figure 2. Pressure contours on turbine (left) and streamlines of fluid motion behaviour (right)

Figure 3. Propellers used in the experiments: narrow blades (left) and wide blades (right)

Figure 4. Printed parts of watertight enclosure (left) and assembly of miniaturised underwater hydro generator prototype (right)

Since the output voltage amplitude of the DC generator dependents on the river flow velocity, the obtained energy must be properly managed to achieve DC voltage levels compatible with the used sensors and respective electronics (respectively 3.3 and 5 V). There are several commercially available energy harvesting chips which can be employed for this function. The main purpose of this circuit is to store the harvested energy onto a (super)capacitor in order to ensure sufficient energy to power the load. The chip's input voltage, depending on its type, can be in the range from few mV up to several tens of V. In this regards, additional passive elements (resistors, capacitors and inductors) have to be added and optimized in order to efficiently use the harvested energy, as well as to ensure undisturbed operation of the connected loads [2]. In this work, a management electronics based on a Fujitsu Semiconductor integrated circuit [10], is designed, manufactured and used in all experiments. The list of the used electrical elements of the proposed design is given in Table 2, while the electrical scheme and the manufactured PCB are shown in Figure 5.

Table 2. Specification of management electronics elements

Element	Chip	C_1	C_2 (Sup. Cap.)	C_3	L_1
Value/Model	MB39C811	10 μF	5 F	4.7 μF	22 μH

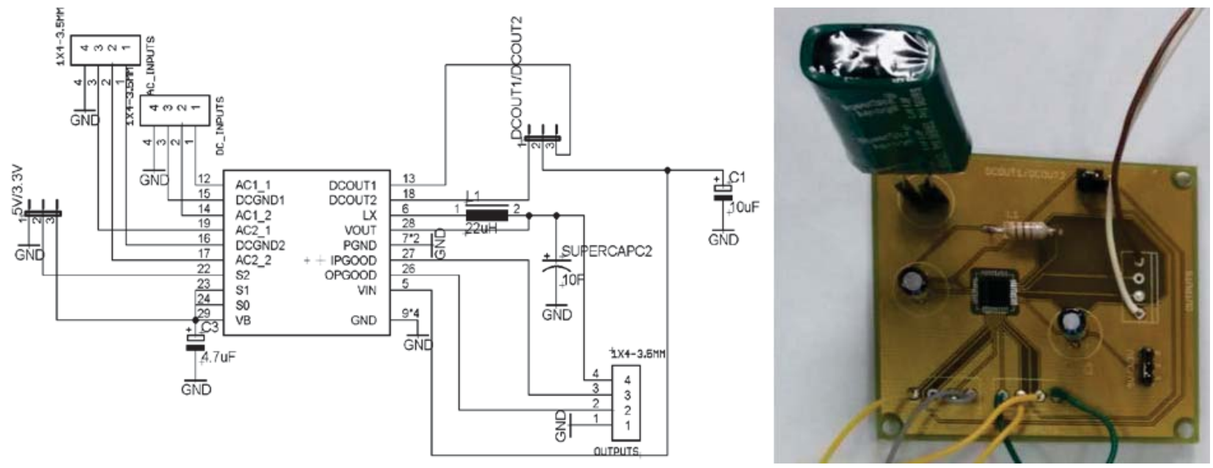


Figure 5. Management electronics scheme (left) and PCB with all electrical elements (right)

3.RIVER EXPERIMENTS ON THE RJEČINA RIVER NEAR RIJEKA, CROATIA

A set of field experiments employing the above described prototype was performed in real river conditions at the river Rječina near Rijeka, Croatia (Figure 6). The velocity of the river flow is approximately established by a simple experiment. A piece of styrofoam is thrown into the river and the time t needed to transport it for 10 meters is measured. The experiment is repeated for 10 times and an average value of the time is used to obtain the average value of velocity at the river surface.

Table 3. Average voltages at the output of the DC generator for two different river velocities

River flow velocity, v	Propeller type	Generated voltage, V_{OUT}	Average generated voltage, $V_{OUT\ AV}$
0.6 m/s	Narrow blades	0.8 to 1.8 V	1.3 V
1 m/s	Narrow blades	2.8 to 3.8 V	3.3 V
0.6 m/s	Wide blades	1 to 1.5 V	1.25 V
1 m/s	Wide blades	3.2 to 4 V	3.6 V

For the first experiment, a position with river flow velocity of approximately 0.6 m/s is chosen, whereas the river flow velocity at the position of the second experiment is about 1m/s. The first experiment is conducted with the underwater hydro generator anchored in close proximity of the river surface (Figure 6). The Faulhaber 1724006SR DC generator, which can generate up to 6 V, is used. The results for the two propeller types of Figure 3, without connecting the management electronics and the electrical load at the output (i.e. by measuring only the voltage generated by the turbine) are approximately the same (Table 3).

Figure 6. Miniaturised underwater hydro generator anchored in the Rječina river

Since the generated voltage is lower than that needed to power the foreseen sensors and electronics, in the second set of experiments a Faulhaber 1724012SR DC generator having a 12 V maximum output voltage is employed. Management electronics described in Section 2. is also used, as is the load connected to the output (Table 4). A super capacitor C_2 = 5 F and a "dummy load" composed of 5 LEDs is employed in the experiments. As shown in Figure 7a, at the turbine (i.e. at the input into the system), roughly 10 V and 70 mA, corresponding to a generated power of ca. 700 mW, are obtained. The power value corresponds to that obtained from the mention preliminary calculations for the propeller dimensioning. The corresponding measured output electrical parameters are about 4.5 V and 110 mA, i.e. roughly 500 mW in one (Figure 7b) and 3.3 V at 35 mA (115 mW) in the other configuration (Figure 7c) are provided.

(a) *(b)* *(c)*

Figure 7. Input and output electrical parameters obtained by using the miniaturised underwater hydro generator with a larger generator at the Rječina river

4.FINAL DESIGN OF THE MINIATURISED UNDERWATER HYDRO GENERATOR

Via the measurements on the Rječina river, it is confirmed that the proposed prototype of the miniaturised underwater hydro generator, together with the designed management electronics, can ensure the needed power levels to sustain the foreseen sensors and electronics and, at the same time, charge the supercapacitor. In order to perform the final measurements in a controlled environment, the turbine assembly is hence enclosed in a manufactured brass (due to its good anticorrosive properties) enclosure. In addition, with respect to the prototype design, other minor modifications are adopted. In Figure 8 is depicted the 3D model of the final design of the miniaturised underwater hydro generator where the main components of the assembly are basically the same (and indicated with the same indexes) as in Figure 1. In this case, however, the watertight enclosure (7) is composed of three parts and designed taking into account the dimensions of the system's elements. Part 8, made from compliant rubber, constitutes the cable feedthrough.

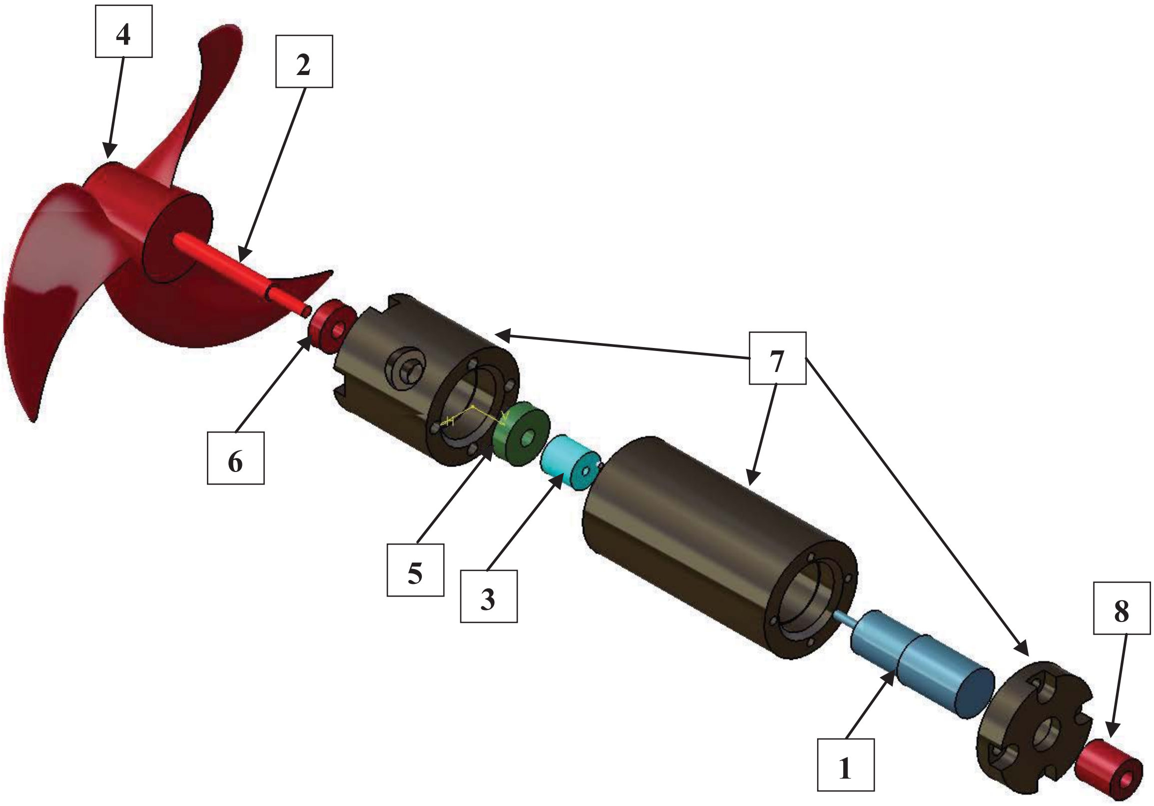


Figure 8. Final miniaturised hydro generator components

The machined enclosures and the other elements of the assembly of the miniaturised underwater hydro generator are shown on Figure 9.

Figure 9. Final miniaturised underwater hydro generator

5. FLOW TUNNEL EXPERIMENTS AT THE NAVAL RESEARCH INSTITUTE IN ZAGREB, CROATIA

With the described final configuration of the miniaturised underwater river flow energy harvesting generator, a further set of experimental measurements is performed in a flow tunnel with a free surface at the Naval research institute in Zagreb, Croatia [11]. The aim of these measurements is to investigate the behaviour of the developed device with controllable flow conditions. In fact, computer controlled flow velocities of up to 8 m/s can be achieved in the used tunnel whose layout is visible in Figure 10 left. The developed miniaturised hydro generator is fixed to the flow tunnel via a suitable support as depicted in Figure 10 right.

Figure 10. Flow tunnel assembly (left) and miniaturised underwater hydro generator in the flow tunnel (right) at the Naval research institute in Zagreb, Croatia

In this set of experiments, the 1724012SR generator is used again [7]. The foreseen load is simulated via a “dummy load” constituted by 10 LED diodes, where for a 5 V set-up R = 150 Ω resistors are used, while for the 3.3 V set-up R = 68 Ω resistors are used. The scheme of the mounted electrical set-up is given in Figure 11.

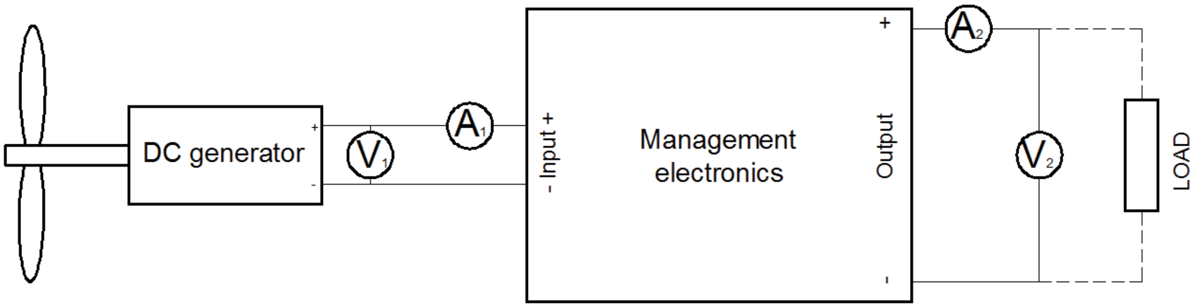


Figure 11. Electrical set-up used in the measurements at the Naval research institute in Zagreb, Croatia

The measurements are performed as follows:

1. The water flow velocity is increased continuously from 0 to a value at which the propeller starts to rotate. The rpm velocity of the propeller is measured by a stroboscopic device.
2. The velocity is increased continuously from the above value to a value when the super-capacitor starts charging.
3. When the supercapacitor is charging, the flow velocity is further increased and the measurements are performed without and with electrical loads. The time needed to charge and discharge the capacitors is also monitored.
4. The maximum permissible velocity is achieved when the maximum voltage is generated.
5. Cyclic tests are used to verify the repeatability of the results.

A typical set of obtained results is shown in Table 4. It can thus be observed that the measured no-load voltage is close to the nominal one within the accuracy of the measurements of the propeller velocity. The generated power is again, as during the Rječina river experiments, on the level of about 700 mW, while the output powers are up to 220 mW.

Table 4. Results of the measurements performed at the Naval research institute in Zagreb, Croatia

Water flow velocity (m/s)	**Propeller velocity w/o electrical load (rpm)**	**Propeller velocity with electrical load (rpm)**	**Measured no-load generated voltage (V)**	**Calculated no-load generated voltage (V)**	**Generated voltage with load (V)**	**Generated current with load (mA)**	**Output voltage with load (V)**	**Output current with load (mA)**	**Remarks**
0,8	-	-	5	-	-	-	-	-	Capacitor not charging
1	250	-	7,7	7,2	7,6	-	-	-	Slow capacitor charging
1,1	293	273	9	8,4	8,3	33	2	12,8	Threshold for charging at ca. 8 V
1,2	336	300	10,4	9,7	8,4	60	2	12,8	
1,3	377	-	11,7	10,9	9,9	49	2	13,7	
1,5	451	434	14	13,0	12,3	48	2,5	42	W/o load the capacitor is charged in 60 s
1,6	489	471	15,2	14,1	13,6	51	3	72,7	Stable operation

6. CONCLUSION AND OUTLOOK

This work describes the functional laboratory and river experiments performed on an innovative miniaturised underwater turbine-based energy harvester, with the correspondingly developed management electronics, used for powering the sensors and electronics to be employed for measuring river pollution.

Prior to experimental investigations, all the components of the miniaturised hydro generator are designed using a 3D modelling software. For determining the propeller shapes, a rough verification of turbine blades performances via numerical analysis is performed. 3D printing technique is employed to manufacture the first prototypes of the mechanical parts.

Preliminary experiments in real river flow conditions, allowed establishing that roughly 700 mW of power can be obtained, which corresponds to calculated values. Based on these measurements, the design of the miniaturised hydro generator is optimised and a further set of measurements is carried out in a flow tunnel at the Naval Research Institute in Zagreb, Croatia. It is hence proven that the measured no-load voltage is close to the nominal one. The generated power is again on the level of about 700 mW, while the output powers are up to 220 mW. A "dummy load" composed of LEDs, simulating the not yet available sensor cluster, has thus been successfully powered.

In future work, the developed miniaturised hydro generator will be used in the foreseen final configuration with all the sensors, conditioning electronics, transceivers and gateways in a large river streambed. In parallel, an investigation of a concept of “water wheel driven generator” as depicted in Figure 12 will be investigated as an alternative to the concept proposed in this work. In this concept, the water inlet is designed as a convergent channel so as to increase the inflowing water velocity and to direct the water stream directly to the wheel blades.

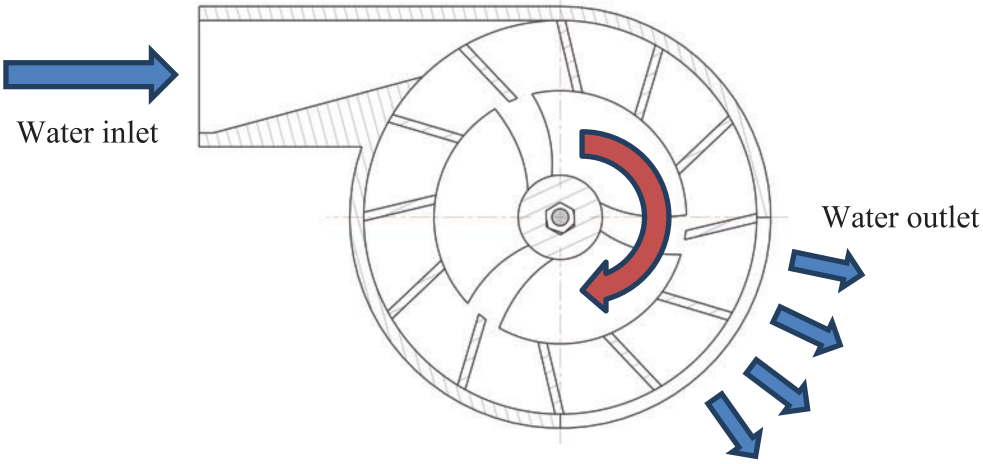
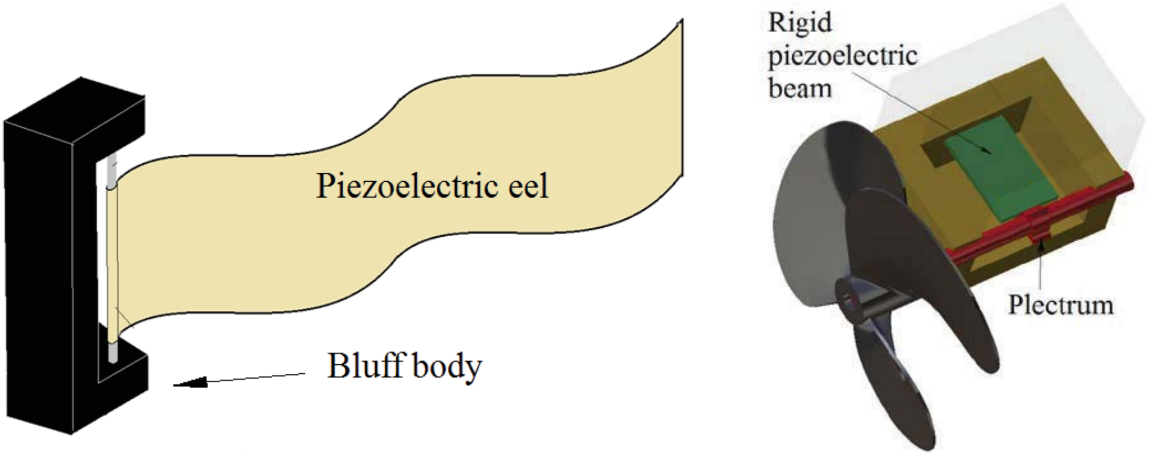


Figure 12. Schematic view of the “water wheel concept”

Concurrently, alternative energy harvesting principles to be used to power the same wireless sensor network is also considered. These will be based on piezoelectric eels (Figure 13a) and a hybrid solution where a cam driven by the turbine is used to “pluck” a piezoelectric beam (Figure 13b).



(a) *(b)*

Figure 13. Alternative energy harvesting concepts: piezoelectric eel (a) and "plucked" piezoelectric beam (b)

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MINIJATURIZIRANI PODVODNI HIDROGENERATOR ZA NAPAJANJE MREŽE BEŽIČNIH SENZORA

Sažetak: *U ovome radu se predlaže konstrukcijsko rješenje minijaturiziranog hidrogeneratora za napajanje mreže bežičnih senzora. Koncept se temelji na malom istosmjernom generatoru u vodonepropusnom kućištu te propeleru pokretanom tokom rijeke. Razvijena upravljačka elektronika regulira dobivenu električnu energiju i pohranjuje ju na superkondenzatoru. Oblik lopatica propelera se provjerava približnom numeričkom analizom na temelju koje se u eksperimentima koriste dvije inačice propelera. Hidrogenerator se zatim testira u stvarnim radnim uvjetima u riječnome toku. Konstrukcija generatora je unaprijeđena na osnovu preliminarnih rezultata mjerenja pa se daljnja mjerenja vrše u protočnom tunelu. Generira se snaga od oko 700 mW što odgovara proračunskim vrijednostima, dok je izlazna snaga na razini od oko 220 mW.*