Energy-harvesting WSNs for structural health monitoring of underground train tunnels

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I. Introduction and motivation

Thanks to recent advances in energy harvesting techniques and in ultra low-power hardware architectures, energy-autonomous embedded systems that can last virtually forever are becoming reality [1]. One of the many application scenarios that can benefit from such emerging technology is structural health monitoring (SHM) [2], [3]. SHM allows to detect deteriorations and potential damages of a structural system by observing the changes of its material and geometric properties over long periods of time. SHM is a vital tool to help engineers improving the safety of critical structures, avoiding the risks of catastrophic failures. Wireless sensor networks (WSNs) are a very promising technology for structural health monitoring, as they can provide a quality of monitoring similar to conventional (wired) SHM systems with lower cost. In addiction, WSNs are both non-intrusive and non-disruptive and can be employed from the very early stages of construction. However, the extensive use of WSN-based structural health monitoring systems has so far been prevented by the fact that the lifetime of WSNs is severely limited by their scarce energy resources. In fact, SHM systems should ideally monitor engineered structures for decades or even perpetually, but traditional wireless sensor nodes are powered by short-lived batteries that, lasting a few years at most, fail to meet the lifetime requirements of long-term deployments. Applying emerging energy harvesting techniques to wireless sensor motes allows to overcome the energy bottleneck suffered by traditional WSNs, thus removing the limits that make current WSN-based monitoring systems unfit for SHM applications.

The main goal of this work is to investigate the feasibility of a WSN with energy-harvesting capabilities for structural health monitoring, specifically targeting underground tunnels. Previous works have described deployments of WSNs in tunnels [4], [5], but they mainly focus on connectivity issues in tunnel scenarios, and none of them reported the deployment of WSN nodes with energy harvesting capabilities. To assess the energy availability in a real-life scenario, we instrumented an underground train tunnel in Rome with Telos B motes interfaced with wind micro-turbines, collecting air-flow data for more than a month. We analyzed the collected data to quantify the energy availability in terms of typical WSN operations, including communication, storage and sensing. In addition, we investigated the energy requirements of a typical sensor for underground tunnels SHM, namely a vibrating-wire strain gauge. Strain gauges are used to monitor concrete and steel deformations, which are critical factors to evaluate the stability of a tunnel and its expected shape deformation. Vibrating wire strain gauges consist of a length of steel wire, tensioned between two end-blocks embedded within the structure being studied, such that deformations of the structure will alter the tension of the steel wire. The tension of the wire is determined by using an electromagnet to excite the wire, and then by measuring its resonant frequency of oscillation. Such measurements, obtained by the nodes through a dedicated interface board, result quite expensive for an ultra low-power system in terms of energy consumption, thus making energy-harvesting especially appealing in this scenario.

(a) (b) (c)

Fig. 1. (a)(b) Snapshots of nodes deployed in an underground train tunnel in Rome; (c) A sensor node interfaced with a vibrating wire strain gauge.

II. Real-life air-flow data collection

Our data collection was performed in a tunnel of the new Rome Underground *Metro B1* line and took place during the post-construction testing phase of the tunnel. We instrumented 220m of tunnel with six Telos B motes [6] equipped with wind micro-turbines, which collected air-flow data generated by passing trains for 33 days. Figure 2 shows the nodes deployment in the tunnel and their distance from the "Conca D'Oro" train station. The nodes were all placed approximately at the same height along one side of the tunnel. The distance between consecutive nodes was variable, in order to test air-flow data correlation in different conditions. The AC output of each wind micro-turbine was converted into a DC signal by a passive rectifier, realized through a schottky diodes full wave bridge. The energy harvested from the micro-turbine was then stored in a supercapacitor. A dedicated TinyOS [7] application was developed to track the voltage of the supercapacitor every 2 seconds.

TABLE I
MEAN ENERGY HARVESTED BY EACH NODE PER TRAIN PASSAGE & NUMBER OF OPERATIONS THAT CAN BE PERFORMED WITH THE GATHERED ENERGY.

Node id	Mean energy harvested per train passage (mJ)	Rx [KB]	Tx [KB]	Flash read [KB]	Flash write [KB]	Humidity	Temperature	ADC reads	Strain measurements per day
7	5.09	2.25	3.32	1.88	1.23	49	16	802	1
4	47.80	21.14	31.12	17.77	11.56	463	158	7530	13
2	51.72	22.88	33.67	19.24	12.51	501	171	8148	14
5	75.68	33.47	49.27	28.15	18.31	734	250	11924	21
6	66.60	29.46	43.36	24.78	16.11	646	220	10493	18
3	132.95	58.80	86.56	49.45	32.17	1290	439	20946	36

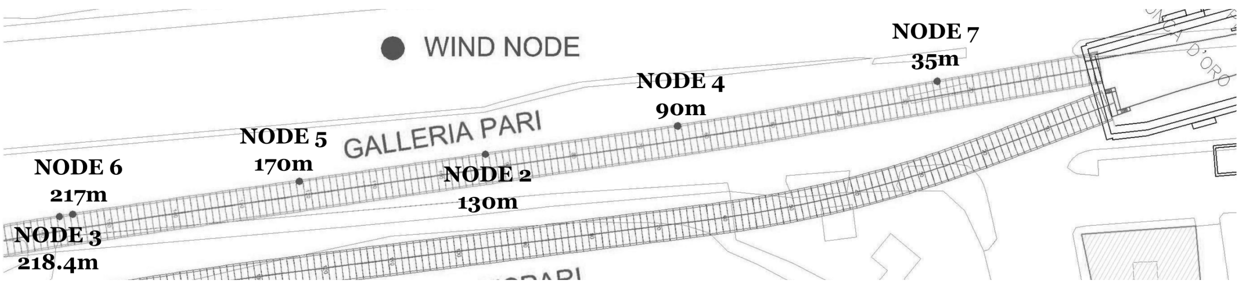

Fig. 2. Motes deployed in the tunnel and their distances from the train station. (Site plan courtesy of Roma Metropolitane and Tre Esse Engineering).

III. RESULTS

Table I shows the average energy harvested by each node from passing trains. As can be seen from the table, the mean energy harvested per train passage varies significantly for different nodes, depending on their position in the tunnel. Node 7, being located close to the station, was exposed to weaker air-flows, because of the limited speed of trains approaching the station. Indeed, node 7 registered an average energy intake of only 5.09 mJ per train passage, while nodes located further away from the station obtained more than 47 mJ per train passage, with a maximum of $\approx$ 133 mJ harvested by node 3. Table I also shows how the energy gathered per train passage can be employed to perform WSN operations. In particular, we quantified how such energy intake can be used: 1) for communication (in terms of the amount of data that can be received and transmitted); 2) to read/write data from the flash memory; 3) to perform sensing activities (e.g., monitoring humidity and temperature through Telos B on-board sensors); and 4) to read values from the ADC.

Finally, we quantified the energy necessary to operate strain gauges SHM sensors. The device used during the construction of the *Metro B1* line is the OVK4200VC00 model by SISGEO, with a typical frequency of 800Hz and a sensitivity of $1.0\mu\epsilon$. Sensor readings were performed through a dedicated interface board, which draws 100 mA at a voltage of 7.2 V. Based on our experiments, about 1 second is needed to perform the strain measurement, thus leading to a total energy consumption of 720 mJ. As reported in Table I, by using the energy scavenged from train passages, the deployed nodes are able to carry out 1 to 36 strain measurements per day, depending on their position in the tunnel and on their harvesting patterns. The resulting sampling frequency is well within the SHM company specifications, which require the system to perform a strain measurement once per day in normal operating conditions.

To conclude, preliminary results are promising and confirm the feasibility of long-lasting, environmentally-powered wireless sensor network systems for structural health monitoring in underground train tunnels.

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