Wireless Power Transfer for Gas Pipe Inspection Robots

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Abstract

Wireless power transfer in metal pipes is a promising alternative to tethered exploration robots, with strong potential to enable longer operating times. Here we present experimental results, including rectification efficiency, for a prototype gas pipe inspection robot with wireless power receiver functionality.

Index Terms

Wireless Power Transfer, Gas Pipe, Remote Inspection, Autonomous Systems, Robotics

I. Introduction

The use of high-power electromagnetic (EM) waves for Wireless Power Transmission (WPT) has been studied since the late 19^{th} century [1], with arguably one of the most famous demonstrators being the "Microwave Powered Helicopter" by W. C. Brown [2]. The two main modalities investigated by the research community are near-field non-radiative power transfer, such as magnetic, inductive, and capacitive coupling; and far-field power transfer through highly directional antennas [3], [4].

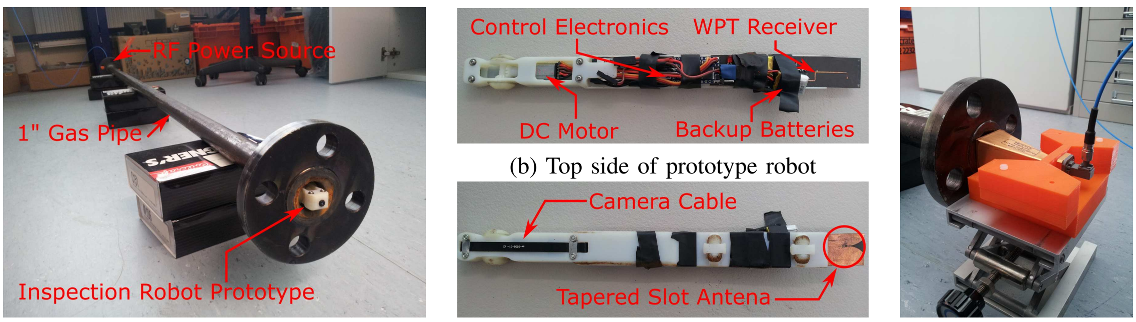
The near-field methods have successfully been adopted in commercial products for efficient charging of consumer electronics. With the increased popularity of Electric Vehicles (EV) concepts have been proposed for their continuous charging via capacitive coupling systems [5]. The main disadvantage of the near-field method of power transfer is the short maximum operating distance, which is on the order just a few centimetres [6]. On the other hand, far-field systems suffer from large propagation losses through atmospheric attenuation and absorption, limiting the amount of power that can be delivered to a receiver [7]. Furthermore, regulations on transmitted power in the Industrial, Scientific, and Medical (ISM) bands further limit the potential deployments of such systems to low-powered Internet-of-Things sensors [8]–[10].

Recently, another mode of WPT has been proposed, and that is WPT in shielded metal pipes, which can potentially deliver higher power, on the order of several Watts, at distances up to tens of metres [11]. This is enabled by considering the pipes as circular waveguides, which support low-loss EM propagation [12]. This in turn opens up exciting opportunities for remote powering and charging of pipe inspection robots, eliminating the need for a tethered power connection.

In this paper, we present experimental results of WPT to a small robot, designed to fit in and inspect 25.4 mm diameter gas pipes. Details of the robot prototype are given, as well as measurements of the electromagnetic propagation environment within the pipe used for these tests. Finally, a short discussion on the WPT module performance is included.

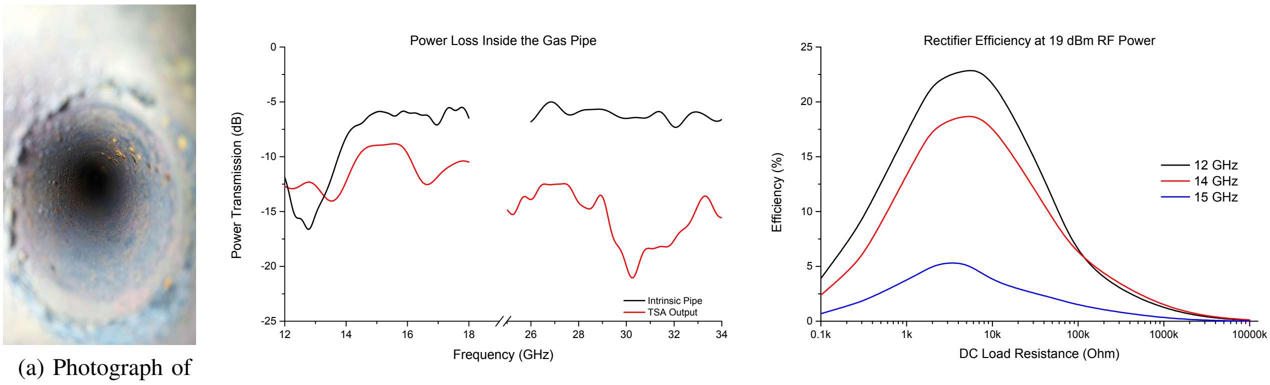
II. Scenario Description and Robot Prototype

A photograph showing the experimental setup is given in Fig. 1a. The pipe used is a decommissioned 2 metre long cast iron pipe. A Keysight E8267D Vector Signal Generator is used to provide the EM signal, which can then be coupled to the pipe through a standard gain horn antenna, as shown in Fig. 1d.



(a) Main experimental setup (b) Top side of prototype robot (c) Bottom side of prototype robot (d) RF source setup

Fig. 1: Pipe measurement setup, including prototype robot and method of supplying RF power.



(a) Photograph of the inside surface (b) Electromagnetic propagation loss (c) Rectifier efficiency

Fig. 2: Overview of the electromagnetic performance of the measurement setup.

In this scenario, the aim is to deliver as much power as possible when the robot is at the far end of the pipe, with input RF power limited by the capabilities of the E8267D.

The details of the robot prototype are presented in Fig. 1b and Fig. 1c. The body of the robot is 3D printed as a whole using a Stratasys Objet1000 Multi-Material 3D printer, and houses the MCU (Pololu Baby Orangutan), a single brushed DC motor, backup batteries (2 x 3.7 V 100 mAh LiPo), as well as a night-vision camera. The robot also includes the WPT module, which is discussed in Section III.

III. Pipe Propagation Measurements and WPT Module

As mentioned earlier, metal pipes act as circular waveguides from an EM propagation point of view. The lowest cut-off frequency, i.e. the frequency below which propagation in the waveguide cannot occur, is an important parameter of any waveguide, and is dependent on its diameter. For the pipe used in this experiment, this was found to be 6.922 GHz [13].

Furthermore, the assumption for low loss is dependent on the surface roughness of the inside of the pipe being low [14]. In the case of the cast iron pipe used in this paper, this was found to not be the case, as illustrated by Fig. 2a. The propagation loss inside the pipe was then measured using a Keysight N5247 PNA-X, resulting in Fig. 2b. Loss results are shown both for the pipe on its own, as well as a composite loss when a Tapered Slot Antenna (TSA) [15] is used at the receiver end. The frequency ranges for which data is presented correspond to those for which horn antennas were available at the time of the experiments.

Once the total propagation losses are known, and the RF input power level can be calculated, an RF-to-DC rectifier can be designed. It has been shown that the efficiency of a rectifier is a function of input power level, frequency, input impedance, and DC load resistance [16]. It is also dependent on the type of semiconductor element used, i.e. a diode or a transistor, as well as overall circuit topology [7], [16].

For the WPT receiver used with the prototype robot, an 8-stage voltage doubler topology was thus selected, using commercially available low-barrier Schottky diodes (Avago HSMS-286C). The circuit was implemented on a low-loss PTFE substrate (Duroid 5880), with a TSA used to couple the incoming EM energy to the rectifier. The output of the rectifier can then be connected to a voltage regulator and a battery charging circuit, although physical space might become an issue. Details of the rectifier circuit are included in Fig. 1b and Fig. 1c.

The rectifier, as well as the TSA, were designed with dual-band operation in mind, with the bands being Ku-band (12 GHz – 18 GHz) and Ka-band (26.5 GHz – 40 GHz). Rectification efficiency, defined as $\eta = P_{DC}/P_{RF}$, was found to be better for lower frequencies, with best performance (23%, 18 mW P_{DC}) obtained at a frequency of 12 GHz and 19 dBm of RF power at the input of the rectifier. A comparison between several frequencies in the Ku-band for different DC load resistances is presented in Fig. 2c.

IV. Conclusion

Experimental results on EM propagation in a metal pipe, as well as WPT for powering and charging of a prototype robot have been presented and discussed. We have successfully demonstrated RF-to-DC rectification with up to 23% efficiency at the end of a 2 metre long gas pipe, which can be used to extend the operating lifetime of an autonomous inspection robot.

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