Localization Techniques for In-Pipe Robots in Water Distribution Systems

Saber Kazeminasab and Mohsen Aghashahi

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Saber Kazeminasab
Electrical and Computer Engineering Department
Texas A&M University
College Station, Texas, USA
saberkazemi1992@tamu.edu

Mohsen Aghashahi
Civil Engineering Department
Texas A&M University
College Station, Texas, USA
aghashahi@tamu.edu

***Abstract*—In-pipe robots are designed to go in inaccessible parts of the pipeline systems to do water quality monitoring, leak detection, and visual inspection by a camera. However, some challenges in which limit their applicability. These challenges are power considerations, wireless underground communication, mechanism flexibility, actor architecture, and control algorithm. In this paper, we propose an end-to-end methodology that lists the requirements and procedures to design and fabricate in-pipe robots. Wireless communication between Base Station (BS) and the robot operating underground is an ongoing challenge for researchers. We focus on wireless communication underground and propose two alternatives to address this issue. In the first scenario "two parallel robots" that communicate based on the Magnetic Induction (MI) communication are presented. We simulate the proposed MI communication link based on the real operating condition. The simulation result shows the received signal power can be detected with a lock-in amplifier in 1.4m distance between primary and secondary coils. Also, we propose another wireless communication solution based on Radio Frequency Identification (RFID) in 13.56MHz carrier frequency and ISO15693 standard. The mechanism in which the RFID based wireless communication works is explained an experiment is done to analyze the performance of the setup. The experiment results show that the proposed setup can penetrate the harsh and dynamic environment of water. Also, the read range was measured around 10cm which is a safe range to avoid overlap for the nearby readers that lead to confusion for the robot.**

***Index Terms*—In-pipe robots, Design and Fabrication, Wireless underground communication, Magnetic inductive communication, Radio Frequency Identification (RFID) communication.**

I. Introduction

Pipelines networks underground are critical infrastructures that carry potable water to residential area and they are vital to public health. The pipelines corrode or an incident can damage them. This damage results in leak that causes water loss or introduces contaminants to network. So, it is required to inspect pipelines and monitor quality of water in networks frequently. The solution to this aim is mobile sensors in which host sensor modules and go to inaccessible parts of the pipeline network and do the supposed task [1]. However, these mobile sensors are carried inside pipeline by flow. It is highly probable that the operator loses the sensor module in network during operation. Hence, it is necessary to design the mobile sensors that have controlled motion. In-line robots are promising options to this aim. There are different actuation methods and mechanisms for in-pipe robots. In some robots, pneumatic actuators are used as actuators [2], [3] while electrical actuators are common actuator types that provide traction force for the robots [4]–[17]. The pneumatic actuated robots need special mechanisms to transform the actuator power to the moving parts. The pipeline network comprises different pipe sizes that require the robot to be size-adaptable. Some robots are designed for specific pipe size [3], [16] while more researchers have tried to design the robots which are adaptable to pipe size changes [2], [4], [15], [17]–[20], [6]–[11], [13], [14]. The in-pipe robot operation environment is water where a rather high-speed flow [21] is present. The relative velocity between flow and the robot causes drag force [19]. So the robot should interfere with flow as least as possible to lower drag force and power consumption. The power supply for robots affects robot size and weight. Power in most robots based on literature is provided by cable [6]–[9], [11], [14], [17], [18], [20], [22], [23] while a few ones provide the required power by battery [2]. Cable limits the distance in which the robots can inspect the pipeline because the cable length is limited. As mentioned, batteries increase the size and weight of the robot. We did some interviews with utility managers in College Station, Texas and they mentioned that use of these robots is reasonable if they can transmit sensor measurements in real-time. Otherwise, the operator can manually take water sample from network. Also, because of right-of-way rules and street interconnections with the pipeline, it is undesirable to dig a hole to access pipeline. So, it is required the robots transmit their sensor measurements through wireless communication. Due to dynamic and harsh media of soil and water in pipelines environment, terrestrial wireless communication setups that work based on Electro-Mangetic (EM) are not practical for underground applications [24]. There is high path loss in soil and water for EM signals [24]. Also, the moisture content in soil affects the attenuation as well as sand and clay mixture [24]. Friis equation suggests that to gain high received signal power to input ratio, lower frequencies should be used [25]. If low-frequency signals are used, larger antennas should be used while in confined space of pipeline, it is not feasible. Magnetic Induction (MI) communication addresses this issue appropriately [26]. In [27], performance of MI communication in the soil-water environment is validated. By studying the current works in this field, the problems of the current in-line robots can be summarized as:

• They lack motion efficiency in terms of passing through special configurations of the pipelines. And among the robots that are maneuverable, complex and bulk mechanisms are used in which interfere with flow and cause disturbance and also increases power consumption.

• Pipe diameter range at which the robots can adapt to is low if they can be adjustable.

• Most of the robots are powered with cables which prevent long traveling distance for the robot.

• Among the battery-powered robots, wireless communication is not addressed appropriately. In this paper, we provide an end-to-end methodology to design and fabricate in-pipe robots. Also, two wireless communication scenarios are presented. The remainder of this paper is organized as follows: In section II, the methodology is presented. In section III, two-parallel robot mechanism based on MI communication is presented and analyzed. In section IV, the Radio Frequency Identification (RFID) based wireless communication mechanism is presented and analyzed. In section V, the paper is concluded.

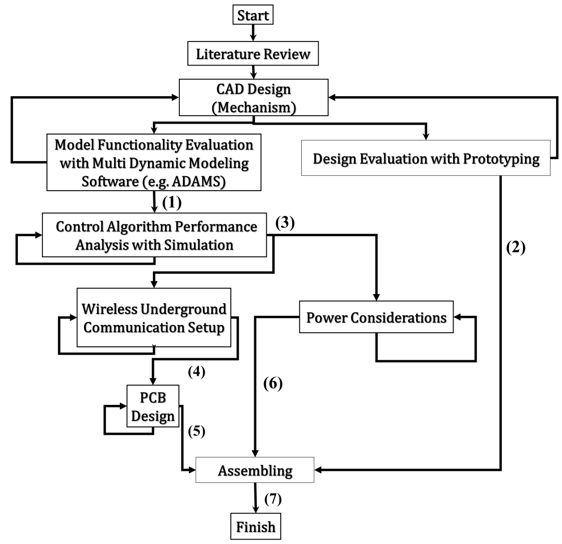

Fig. 1. Procedure for design and fabrication of in-pipe robots based on battery and wireless communication.

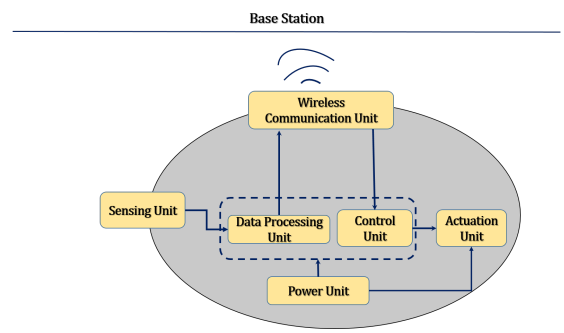

Fig. 2. The water quality monitoring robot and the operating units.

II. Methodology

Shao, et al. have done a comprehensive comparison between different in-pipe robots with various mechanisms and actuators in [28]. Screw-type robots and wheeled wall-press robots proved to be more reliable mechanisms for an in-line robot. Screw-type robots are rather invasive to flow as they need complex mechanism for motion inside pipe. Also, their motion is one-way direction. And in some cases, the screw-type robots cannot pass the branches in pipelines [29]. The wheeled wall press robot motion is not efficient enough and their steerability is a difficult task. The procedure for design and implement in-pipe robots is presented in Fig. 1. To better understand the diagram, the following statements are numbered and used in Fig. 1. In flowchart in Fig. 1, if the answer to any of the questions in each step (block) is no, the designer should modify its design in that step.

(1) Does the robot move smoothly in pipe based on the simulation results? During motion at bends, is the length and height of the robot complaint with the criterion developed in [30]?

(2) Considering work condition presented in [30] and internal forces acting on the robot, are the robots components especially their connections, strong enough to bear forces (stress analysis)?

(3) Is the system controllable/observable?

(4) Is wireless communication feasible in soil and water environment? Is it bi-directional (not necessarily full-duplex)? Is antenna for the wireless communication module compact enough to locate on the robot (inside or outside of the robot)? If not, is it possible to design the antenna suitable for this design considering the material used for robot body?

(5) Is the designed Printed Circuit Board (PCB) compact to be located inside the robot? Is it waterproof?

(6) Is power profiling results (considering flow condition) and assumed operation duration for the robot complaint with discharge time of the selected battery?

(7) As operating environment of these type of robots, is potable water in pipelines, is the components of the robot sealed in order not to be source of toxic substances? Considering the methodology, we proposed a design and prototype that is capable to carry a series of miniaturized sensors that need water samples for measurements in [31]. The sensors are often used to measure the concentration of target analyte(s) in water (for example PH [1]). Also, it can carry the sensors used for leak detection (e.g. acoustic sensors). In Fig. 2, the overall view of the different parts of the system and their interactions are shown. The sensing unit measures the concentration of the target analyte or pressure gradient (if acoustic sensors are used). The sensor measurements are processed by data processing unit. The control unit's task is to control the motion of the robot during operation. The actuation unit moves the robot inside the robot. The power unit provide the energy for robot components.

III. Two-parallel robot MI based Wireless Communication Mechanism

We first describe the concept of MI communication. Then propose two-parallel robot mechanism. These two parallel robot communicate based on MI communication in real time. Then the feasibility of the idea is analyzed based on simulation and real operation condition.

A. MI communication concept

To begin with, first, the problem of EM based setups are discussed. Based on Friis theory, the received power at receiver side, P_r ,to power at transmitter side, P_t, is calculated as:

$$\frac{P_r}{P_t} \approx G_t G_r (\frac{\lambda}{4\pi r})^2 = G_t G_r \frac{\pi}{4\mu\varepsilon\omega^2 r^2} \tag{1}$$

In Eq. (1), ω, and r are carrier frequency and the distance between transmitter and receiver, respectively. Also, ε is permeability of environment. Eq. (1) shows to to have high received signal power, lower frequencies should be used [25]. Relation between frequency and the wavelength is as:

$$\lambda = \frac{c}{f} \tag{2}$$

where λ, c, and f signal wavelength, speed of light, and signal frequency, respectively. So, the lower the signal frequency, the higher the wavelength. The antenna size of EM wireless communication increases as signal wavelength increases. For example, to properly detect a signal with 100MHz carrier frequency, an antenna of 0.75m is required [32] while limited space in pipeline makes it hard to implement such an antenna on robot. Another alternative wireless communication setup is MI communication in which sensor data can be encoded to a carrier signal and two coils, so-called primary and secondary coils transmit the data based on mutual induction [26]. The coils in this communication type act as antennas. The simplified representation of two coils is shown in Fig. 3. In Fig. 3, M is mutual induction, L_t and L_r are self inductions. R_t and R_r are electrical resistance of coils. Z_l is the load impedance of receiver coil. In Fig. 3, (c), the equavalent circuit is shown. Hence, the impedance in transmitter coil is calculated as:

$$Z_t = R_t + j\omega L_t; Z_t' = \frac{\omega^2 M^2}{R_r + j\omega L_r + Z_L} \tag{3}$$

and the impedance on receiver side is:

$$Z_r = R_r + j\omega L_r; Z_r' = \frac{\omega^2 M^2}{R_t + j\omega L_t} \tag{4}$$

Also, if the voltage U_s is on primary coil, the induced voltage on secondary coils, U_M is computed as:

$$U_M = -j\omega M \frac{U_s}{R_t + j\omega L_t} \tag{5}$$

More details are in [26]. The end result would be the relation between the received signal's power and the transmitted signal's power which is computed in [26] and is:

$$\frac{P_r}{P_t} = \frac{\omega^2 \mu^2 N_t N_r {a_t}^3 {a_r}^3 \sin^2\alpha}{8r^6} \frac{1}{4R_0(2R_0 + \frac{1}{2} l\omega\mu N_t)} \tag{6}$$

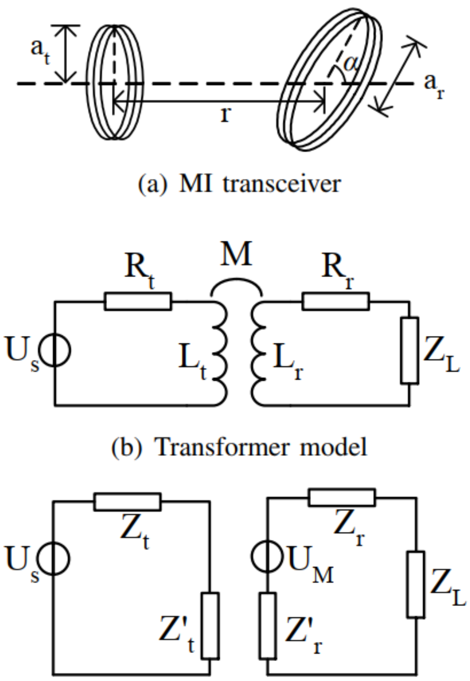

Fig. 3. MI communication channel model [26].

TABLE I
Parameters in MI communication modeling, Eq. 1

Parameter	Description
N_t	Number of turns in primary coil
N_r	Number of turns in secondary coil
a_t	Primary coil radius
a_r	Secondary coil radius
ω	Signal frequency
r	Distance between primary and secondary coils
μ	Permeability of the environment
R_0	Electrical resistance per unit length
α	Angle between the vertical axis and the coil axis

Parameters in Eq. (6) are described in Table. I. Eq. (6) states that higher frequencies result in higher received signal power to transmitted signal power. To the best of our knowledge, there is no precedent work where MI communication is implemented for robotic application where transmitter is moving inside pipeline and it has communication with BS. We propose a scenario that implement MI communication for in-pipe robots and provide its feasibility with simulation.

B. Two-parallel Robots

In this scenario, two robots are considered. One robot is moving inside pipeline and the other robot is moving above ground. We call the robot inside pipeline U-robot and the robot moving above ground A-robot (Fig. 4). The robots are moving in parallel. One coil is located on U-robot in which transmits the sensor(s) measurements and the other coil is located on A-robot which receives data. The coils on U-robot and A-robot are also parallel. In this way, it is possible to have real time

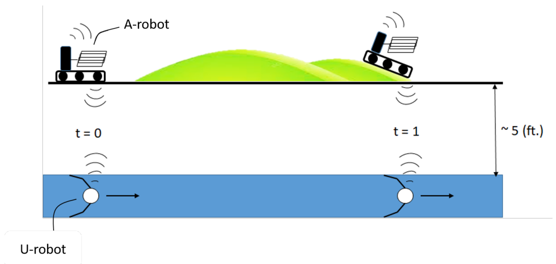

Fig. 4. Concept of two-parallel robots based on MI communication.

TABLE II
PARAMETERS IN MI COMMUNICATION MODELING, EQ. 1

Parameter	Description
Col diameter [cm]	11.43
Wire Diameter [mm]	1
Pipe depth[m]	1.4
Soil condition	Dry
Carrier frequency [Hz]	10^6
Input power to primary coil [W]	1
Output power from secondary coil [μW]	66

communication between BS and the robot underground during operation.

C. MI communication modeling

To analyze the scenario feasibility, we model MI communication based wireless communication in real conditions with simulation. In the simulation, two coils are considered in the 5ft away from each other in z-axis (Fig. 5). The coil size is considered based on the robot size and geometry in [31]. A signal of power 1W is passed in the first coil and the received power at the secondary coil is calculated to find out if the received signal power is strong enough to be properly realized. Parameters are listed in Table II. With tuning parameters of the circuit (i.e. the capacitors and resistors) the resonated magnetic field was manipulated to be maximum in the 5 feet. In Fig. 5, the magnetic field in z-axis is shown. As can be seen in the Fig. 5, if $125\mu T$ magnetic field is induced in the primary coil, around $4\mu T$ is induced in the secondary coil. Also, we

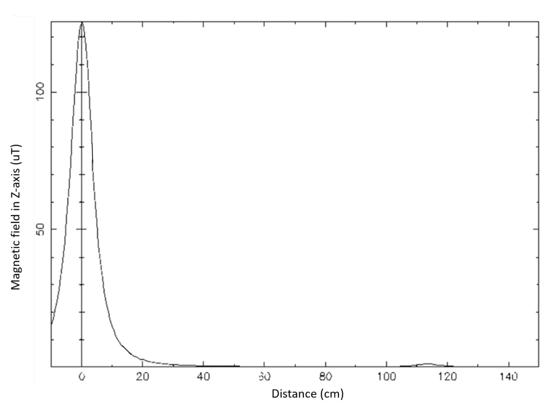

Fig. 5. Magnetic field strength in z-axis based on the coils distance.

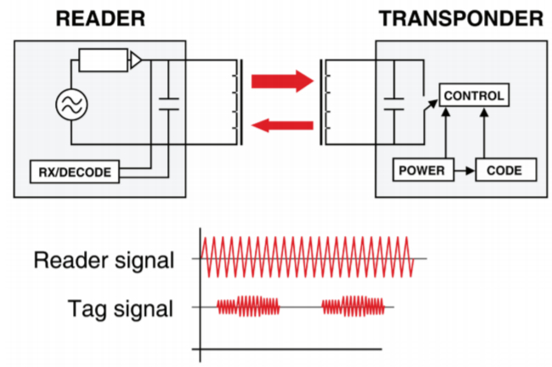

Fig. 6. A Full Duplex (FDX) RFID concept [33].

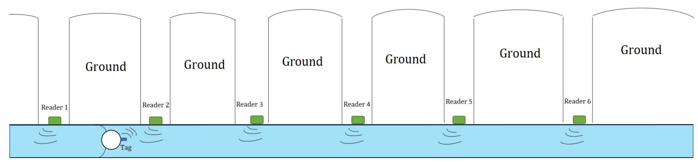

Fig. 7. RFID based wireless communication scenario in our robotic application.

considered 1W power on the primary coil (the coil on U-robot) and received 66μW on secondary coil which can be detected with lock in amplifier. So, MI communication can be a solution for underground communication. But there are challenges for this type of communication. We considered two coils parallel in our simulation ($\alpha = 0$) in Eq. 2. But in reality, when two robots are moving in parallel, A-robot terrain is not absolute flat which makes the coils become in-parallel and the communication link reliability decreases.

IV. RFID BASED COMMUNICATION

In this section, we propose another scenario for communication based on RFID. A transponder (tag) and reader communicate with each other when RFID reader reaches close to RFID tag. The communication can be in one way (Half-Duplex (HDX)) where data can be transmitted from tag to reader or two-way where data can be transmitted from reader to tag and vice versa (Full-Duplex(FDX)) [33]. In Fig. 6, a FDX RFID communication setup is shown. In our proposed scenario, the readers in which read the tag information are sent above pipe through access points like fire hydrants. The tag is located on the robot and moves with it. The sensor measurements is put on the payload of tag memory. The robot is moving inside the pipe line. Whenever the robot reaches the range of the RFID reader, the sensor measurements are transmitted (Fig. 7). A number of readers can be located on the pipe in different point of the network to have more data transmission locations during operation. To test the performance of the proposed RFIID based wireless communication, we did an experiment. As mentioned, the water environment causes signal attenuation. To test, if the proposed RFID module, penetrates water. An RFID tag, RF430FRL152H evaluation module, is placed in a water resistant bag and immersed in water and ST25R3911B

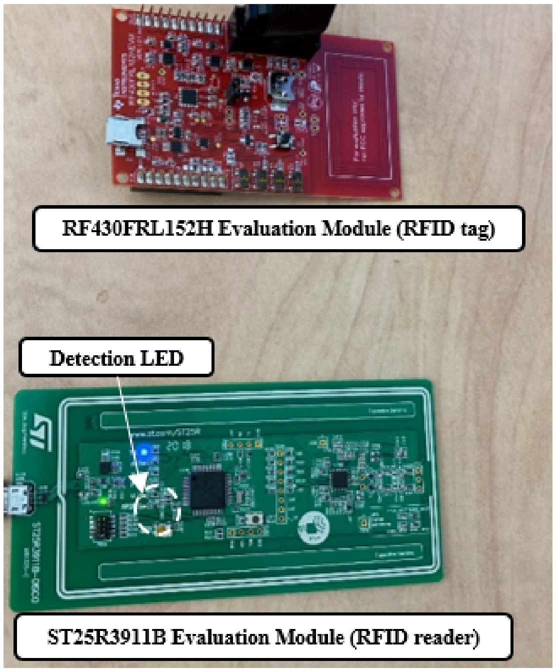

Fig. 8. RFID tag and reader

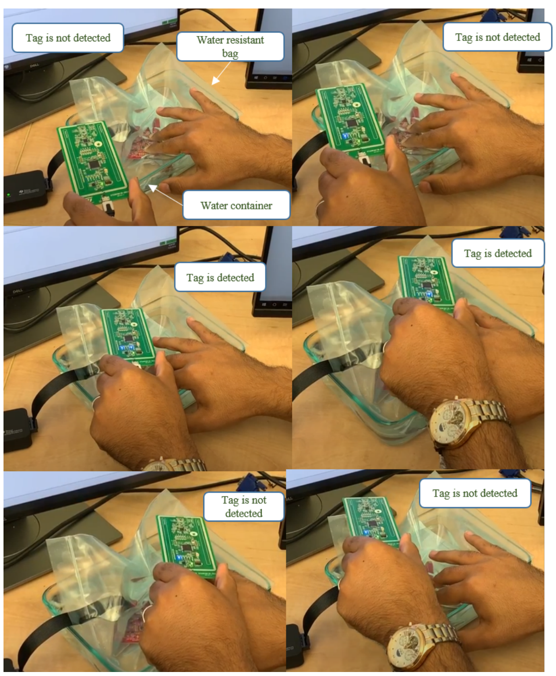

Fig. 9. RFID performance experiment.

evaluation module is considered a RFID reader (Fig. 8). The system works in 13.56MHz and ISO15693. The reader is slowly closing the tag and upon detecting the tag, a light turns on on the reader. The communication setup can penetrate water. Also, The read range that we measured was around 10cm (Fig. 9). The small read range help prevent the overlap between adjacent readers [34]. Also if the readers are placed in special configurations of pipeline like bends and T-junctions to direct the robot in new direction, precise localization of the robot can be achieved.

V. Conclusion

In this research, a review over in-pipe robots are done. The requirements of an in-pipe robot is presented an end-to-end methodology is introduced to design and fabricate such robots. The wireless underground communication is not well addressed for in-pipe robots. In this paper, We focus on the wireless communication part and introduce two proposals for robotic underground wireless communication. In the first scenario, two parallel robot based on Magnetic Induction (MI) communicate with each other. A simulation is done based on the real conditions of the robot operation. Based on the simulation result, the read range is computed 1.4m which matches the depth the pipelines are is MI communication can be a solution for wireless underground communication while there are challenges with this method. Also, we suggest another solution based on Radio Frequency Identification (RFID) in which the reader are placed on the pipe and communication is established when tag on the robot reaches the range of the reader. Then we set an experiment to analyze the feasibility of the communication setup in water. The setup working in 13.56MHz and ISO 15693 standard successfully penetrates water and the read range was measured 10cm. The small read range helps prevent overlap between adjacent readers. So, the RFID method we introduced can be solution for wireless underground communication.

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