

Towards Tag Antenna Based Sensing – An RFID Displacement Sensor

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Abstract— Displacements can be used as indicators of structural health and are measured by commercially available sensors that need to be accurate and cost effective. In this paper, we examine a technique to utilize a UHF RFID tag antenna as a displacement sensor by mapping structural deformation to a change in RFID tag characteristics. We evaluate how changes in two different parameters, a) tag backscatter power and b) minimum reader transmit power required for RFID chip activation, can be mapped to structural deformation. The theoretical principles of sensor development are first discussed followed by a presentation of the results of experimentation. It is demonstrated that the sensor is sensitive to displacements for a dynamic range of 40 mm.

I. INTRODUCTION

Civil infrastructure development is cost intensive and the developed structures are designed for typically fifty years life span [28]. During the structure's life, it is subject to several physical loads and environmental effects. Fatigue damage, environmental corrosion and erosion are all factors that cause progressive damage and reduce the life and load bearing capacity of the structure. Failure to detect and correct these flaws can lead to catastrophic failures and loss of life and property.

Structural health monitoring schemes are frequently employed in major infrastructure projects today in addition to periodic visual inspections. Physical quantities such as the strains developed in critical load bearing members, free vibration responses, deflections, tilts and inclination changes can be mapped to the structural health of an infrastructure project. An assortment of sensors have been developed to monitor these quantities - strain gauges, single and multi-axis accelerometers, tiltmeters. Some of these sensors are connected to the monitoring equipment using lead wires and some are wireless. Wired sensors are cheaper, however the lead wires are costly and expensive to manage and maintain. Wireless sensors, on the other hand, are more expensive and tend to have a limited life due to battery power limitations.

While much of the research effort has been to quantify ([6], [15] and [26]) and improve the performance of RFID tags in high metal environments [22], we believe that the reduction in performance of RFID tags in high metal environments can in fact be exploited to develop sensor devices by calibrating the degradation in performance to a change in some physical

parameter - in this case displacement. The focus of this paper is thus to utilize the RFID tag antenna as a displacement sensor that presents the advantages of being wireless, cheap, passive and long lasting. This research effort would also leverage prior work in the area of low cost standardized RFID tag development [24]

In Section II we provide a brief introduction to related research efforts and in Section III, we introduce the concept of the RFID Displacement Sensor and the mechanism of displacement measurement by outlining the theoretical considerations behind the development of the RFID displacement sensor. In Section IV we describe the experimental setup and the details of the RFID tag used in the design of the sensor. In Section V a synopsis of the results of field trials conducted is presented and finally in Section VI we present the conclusions and lessons learned from the study.

II. RELATED WORK

Displacement is one of the most important parameters in structural health assessment and perhaps the most perceivable. It is, however difficult to measure and thus is often indirectly measured via bending strain measurements. The literature is replete with examples where strain gauges are utilized to monitor the health of a structure - for example Ko *et. al* [12] provide an excellent overview of the typical types of sensing devices used today and common areas of installation on the actual structure itself. Similarly, Li *et. al* [8] demonstrate the utility of fiber optic sensors in monitoring strains as well as other physical quantities in widely different civil infrastructure applications from bridges, foundations and dams to traffic flow monitoring on highways.

There are several methods to measure strain and strain gauges ([10] and [25]) and fiber optic sensors ([21]) are two of the most common types of sensors deployed in the field. Commercial electrical strain gauges can typically measure a maximum strain of 30000-50000 microstrain [19] while fiber optic strain gauges can measure a maximum of about 36000 microstrain [9]

These two types of strain gauges have their strengths and weaknesses. While fiber optic sensors are not prone to electromagnetic drift [3], they are expensive to deploy. The electric strain gauge while cheap, is prone to electromagnetic drift

and is difficult to deploy due to the cumbersome lead wiring. Furthermore deflections are measured approximately since relating strain to deflection requires the adoption of some type of bending model. In this paper, we present an approach that measures displacement directly rather than estimating the value from bending strain while using a wireless interface which also results in low deployment and maintenance costs. Hou, Yang and Huang [29] recognize the importance of measuring deflections in their paper and present a technique to monitor deflections using inclinometers. The typical displacement values obtained from their experiments are of the order of 1 mm in the case of an experimental steel beam and of the order of 4 mm to 20 mm in the case of the Taolaizhao Bridge. By placing inclinometers at regular intervals on the structure, they were able to construct the deflection profile and calculate the displacements at key points of the bridge deck.

Fletcher *et. al* [23] propose the use of a magneto-elastic amorphous metal ribbon as a relative position sensor. In this chip-less wireless sensing approach, changes in resonance frequency map to displacement.

There have been research efforts to utilize RFID as a data communication medium in sensing. For example, Smith *et. al* [2] present a passive RFID UHF frontend to an electric strain gauge. Their approach is based on the WISP Platform [5] where a micro-controller interfaces with different sensor systems.

In closely related research, Johan [13] *et. al* also demonstrate a technique to relate moisture detection to RFID tag-detuning. In this paper we present the principle of antenna based sensing where changes in physical quantities are calibrated to a change in RFID tag antenna characteristics. Using RFID tags as sensors allows for a low cost measurement method with infinite lifetime due to their passive nature. Furthermore the integration of a low cost RFID tag microchip enables the unique identification of the sensor via the globally unique tag identifier. In the case of the displacement sensor presented in this paper, we are using the property that metal in close proximity to an RFID tag changes its response to reader interrogation. While, the degradation of tag read performance in the presence of metal has been studied by several researchers ([6], [15] and [26]), in this paper, we attempt to utilize the degradation of performance of RFID in the presence of metal to our advantage as a mechanism to directly quantify displacement.

III. RFID DEFLECTION SENSOR PRINCIPLE

Our sensor system is composed of a conventional RFID reader, a RFID UHF tag and a metallic backplane attached to the structural member to be monitored. The RFID reader is placed at a convenient location from the beam and the RFID tag is placed in proximity to the metal plate facing the RFID reader (cf. Fig.1 and Fig.2). The sensing principle involves relating a degradation of RFID tag performance in the presence of metal to the displacement of a structural beam subjected to loading. Degradation is measured by monitoring the tag backscatter signal strength and the minimum reader transmit power to turn on the tag. An increase in displacement

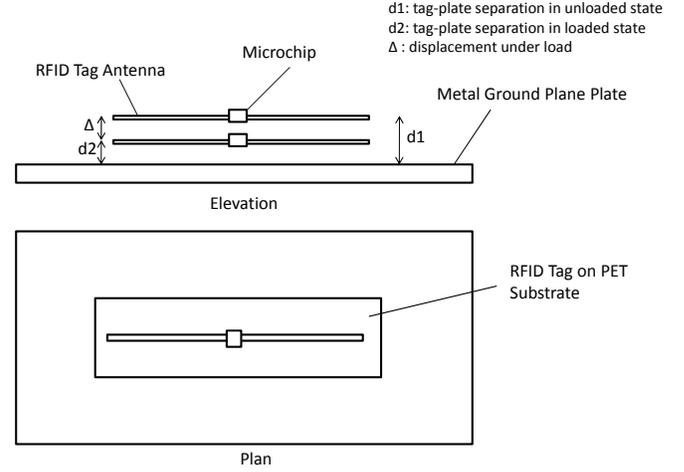


Fig. 1. RFID Displacement Sensor Schematic

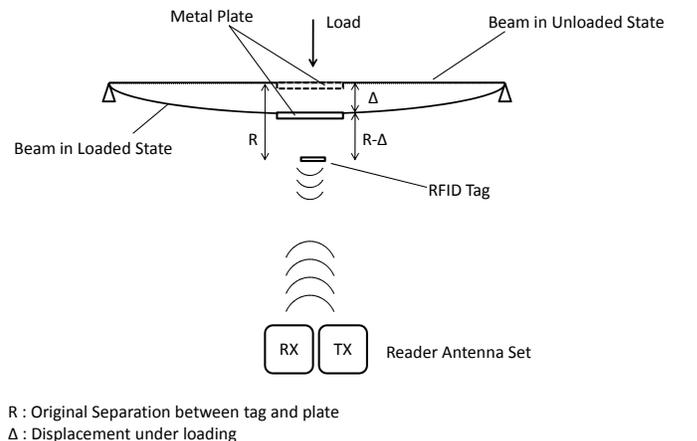
corresponds to a decrease in separation between the RFID tag and a metallic plane. This reflects in changes in tag antenna characteristics in particular tag antenna impedance, radiation pattern and radiation efficiency.

In the following two subsections, we derive the relevant theoretical expressions quantifying the change in the two performance metrics – the reader transmit threshold power and the tag backscatter power and how they relate to structural displacement. The power measurements recorded at the reader transmit antenna and receive antenna are outlined in Fig.3(a) and Fig.3(b)

A. Calibration of Strain to Transmitted Power required to power up the chip on the RFID tag

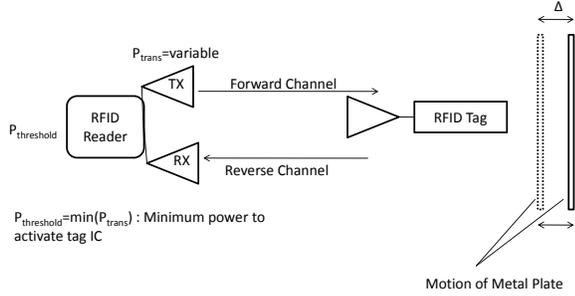
The reader transmitting antenna transmits a power of P_{trans} and this results in a power density W_{trans} [4] of

$$W_{trans}(\theta_{trans}, \phi_{trans}) = \frac{P_{trans} G_{reader}(\theta_{trans}, \phi_{trans})}{4\pi d^2} \quad (1)$$

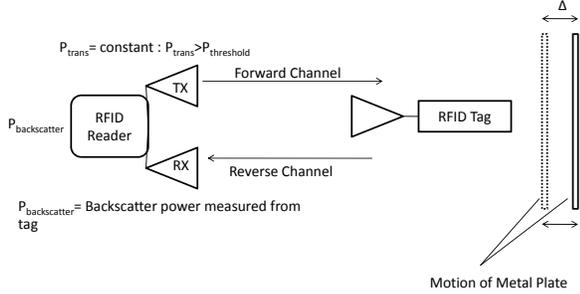


R : Original Separation between tag and plate
 Δ : Displacement under loading

Fig. 2. RFID Displacement Sensor Setup



(a) Measurement of Threshold Reader Transmit Power



(b) Measurement of Tag Backscatter Power

Fig. 3. (a) and (b)

where $G_{reader}(\theta_{trans}, \phi_{trans})$ is the directional gain of the reader transmitting antenna and d is the distance of the tag from the reader transmitting antenna. The RFID tag antenna intercepts power given by the expression

$$P_{tag} = \frac{W_{trans} G_{tag}(\hat{\theta}_{trans}, \hat{\phi}_{trans}) \lambda^2 |\hat{\rho}_{trans} \hat{\rho}_{tag}|^2}{4\pi} \quad (2)$$

where W_{trans} is the transmitted power density in Eq. 1, and $\hat{\theta}_{trans}$ and $\hat{\phi}_{trans}$ are polar measures in the tag's coordinate system.

$|\hat{\rho}_{trans} \hat{\rho}_{tag}|^2$ is the polarization loss factor and λ is the wavelength of reader operations.

The amount of this power that is received by the RFID chip P_{chip} depends upon the power reflection coefficient Γ_{tag} and is given by [4]

$$P_{chip} = (1 - |\Gamma_{tag}|^2) P_{tag} \quad (3)$$

where Γ_{tag} is given by

$$\Gamma_{tag} = \frac{Z_c - Z_a^*}{Z_c + Z_a} \quad (4)$$

where Z_c is the RFID IC impedance and Z_a is the RFID tag antenna impedance.

For ease of representation we now drop the polar coordinate angular notation and manipulate equations 1, 2 and 3 to give

$$P_{chip} = (1 - |\Gamma_{tag}|^2) G_{tag} G_{reader} P_{trans} |\hat{\rho}_{trans} \hat{\rho}_{tag}|^2 \left(\frac{\lambda}{4\pi d}\right)^2 \quad (5)$$

This implies that

$$P_{chip} \propto (1 - |\Gamma_{tag}|^2) G_{tag} P_{trans} \quad (6)$$

all other factors being equal. The increasing proximity of the metal due to increased displacement, changes the antenna impedance. The microchip and tag antenna impedance are no longer matched. This is manifested as a increase in the reflection coefficient Γ_{tag} resulting in a reduction in power available to the chip. The tag antenna gain G_{tag} , radiation pattern and efficiency, is also affected. Thus Γ_{tag} and G_{tag} are both non linear functions of Δ - the midpoint displacement of the beam and Eq. 6 can be expressed as

$$P_{threshold} \propto (1 - |\Gamma_{tag}(\Delta)|^2) G_{tag}(\Delta) P_{trans} \quad (7)$$

Since RFID systems are forward channel limited¹ and the minimum chip sensitivity P_{chip_min} is constant, we can measure the combination of $(1 - |\Gamma_{tag}|^2) G_{tag}$ by varying the transmitted power at the reader until the tag no longer replies. The minimum transmit power at the reader $P_{trans} = P_{threshold}$ required to power the tag can thus in theory be related to the displacement. It is important to note here that the mathematical expressions we have used here stem from the Friis Transmission Law in Free Space. We have not considered the effect of fading and scattering in the above derivation. Furthermore the exact dependency of Γ_{tag} and G_{tag} on Δ is unknown and will be experimentally determined in Section V.

B. Calibration of Strain with Backscatter Power Strength

RFID tag-reader communication relies on the tag modulating a signal response which is intercepted by the reader. The tag IC is assumed to have two impedance states Z_1 and Z_2 . The tag antenna is typically well matched to state Z_1 resulting in a reflection coefficient Γ_1 close to zero where as state Z_2 is typically a shorted state where there is great impedance mismatch between the tag antenna and IC impedance resulting in a higher reflection coefficient Γ_2 . This differential power reflected from the tag is what results in a signal modulation which the reader can interpret as the tag response. Note that there are other ways to choose Z_1 and Z_2 and thus Γ_1 and Γ_2 as outlined by Karthaus et al. in [14]. We now present the relevant mathematical expressions required for the derivation of change in backscatter power received at the reader as a function of the structural displacement. Note that these mathematical models are idealized for a tag-reader system in *free space* and we have assumed that there is no fading and scattering effects. The differential power backscattered by the tag is directly proportional to the impedance matching between the tag antenna and chip, given by the power wave reflection coefficients $\Gamma_{1,2}$ [20]. Thus the differential tag radar cross section (RCS), which is directly related to the backscatter power can be given by [20]

$$\Delta\sigma = \frac{\lambda^2 G_{tag}^2 |\Gamma_1 - \Gamma_2|^2}{4\pi} \quad (8)$$

¹Radiofrequency regulations limit the transmit power by the reader antenna ($P_{trans} G_{trans}$) to 36 dBm in North America. The sensitivity of RFID readers is of the order of -70 dBm for backscatter power detection. Since most RFID tag microchips require -10 dBm [11] or better, the forward channel from reader to tag is the limiting factor in RFID communication.

where G_{tag} is the tag antenna gain, λ is the wavelength of reader operations, $\Gamma_{i=1,2}$ is the power wave reflection coefficient for chip impedance state i . Alternatively, in terms of the power received at the reader, the RCS is given by: [20]

$$\Delta\sigma = \frac{\Delta(P_{received})(4\pi)^3 d^4}{P_{trans} G_{reader}^2 \lambda^2} \quad (9)$$

where $P_{received}$ is the power received at the reader from the tag, P_{trans} is the power transmitted by the reader, G_{reader} is the reader gain, and d is the distance to the tag.

Equating Eqn. 8 and Eqn. 9 the following result is obtained

$$\Delta P_{received} = \frac{\lambda^4 G_{reader}^2 G_{tag}^2 P_{reader} |\Gamma_1 - \Gamma_2|^2}{(4d\pi)^4} \quad (10)$$

Now we note that both G_{tag} as well as Γ_1 and Γ_2 are functions of Δ . Thus the above equation may be expressed as

$$\Delta P_{backscatter} = \frac{\lambda^4 G_{reader}^2 G_{tag}(\Delta)^2 P_{reader} |\Gamma_1(\Delta) - \Gamma_2(\Delta)|^2}{(4d\pi)^4} \quad (11)$$

It is thus possible to observe that change in backscatter power can be related to a non-linear function of displacement Δ . The exact nature of this relationship is discussed in Section V.

IV. EXPERIMENTAL METHOD

Mufti *et. al* [1] and Zhu *et. al* [30] demonstrate that typical deflections expected in structural members are of the order of 1 mm to 20mm. In our experimental setup, the beam is loaded with a central point load so as to induce midpoint deflections from 0 cm to 5 cm in steps of 2.5 mm (c.f Fig 2). The two quantities of interest — tag backscatter power and threshold transmitted power, are measured. The following sections describe the RFID tag used and the experimental setup in greater detail.

A. RFID tag used in experimentation

The Impinj Banjo UHF RFID tag [18] is used in the experiment (cf. Fig. 4). The tag has form factor of 80 mm x 80 mm and is constructed from conductive silver ink printed on a PET substrate. The embedded IC is the Impinj Monza [16] which implements the EPC Global Generation 2 UHF Protocol [7].

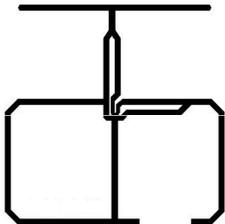


Fig. 4. Impinj Banjo UHF RFID Tag [18]

B. Experimental Setup

In this experiment, a simply supported beam constructed from wood (with Modulus of Elasticity $E=10$ GPa) is considered. The metallic plate component of the RFID sensor (Section III) is attached to the center of the beam, right under the point load. The load can thus be adjusted so as to achieve the desired deflection Δ . The reader transmission and receiving antenna is located at a sufficiently large distance below the beam. The apparatus is illustrated in Fig. 2. The experiments were not conducted in an anechoic chamber, but rather were conducted in a spacious room with few obstructions. Particular attention was paid to avoid the presence of metallic objects in very close proximity to the apparatus. Furthermore, we believed that choosing the experimental environment in this manner represented a good compromise between capturing true field conditions and losing precision due to excessive multi-path effects.

C. Reader Measurement Equipment

The Voyantic Lite Measurement Equipment is used in the experiment [27]. This measurement apparatus has several advantageous features including the ability to conduct a frequency sweep, being accurate and precise and being able to maintain stable transmit power levels. The reader antenna is linearly polarized. We expect high sensitivity of measurement with this equipment and utilize it to test our hypothesis. Two measurement tests were conducted with the Voyantic Equipment:

- Frequency Sweep: The threshold reader transmit power as a function of frequency was plotted for midspan displacement from 0 mm to 50 mm in steps of 2.5 mm. For each displacement level, the frequency sweep was conducted from 800-1000 MHz in steps of 5 MHz. Each sweep was conducted 5 times and the mean and standard deviation was computed to gain an understanding of the test precision.
- Backscatter Power Sweep: The tag backscatter power strength as a function of reader transmit power was plotted for midspan displacement from 0 mm to 50 mm in steps of 2.5 mm. For each displacement level, the transmit power was varied from 0 dBm to 30 dBm. Each test was conducted 5 times and the mean and standard deviation was captured to gain an understanding of the test precision. For the purposes of this test, the operating frequency was set to 915 MHz.

V. RESULTS

We now discuss the feasibility of the proposed theory, keeping in mind the variations caused by changing the experimental environment and equipment.

A. The use of Threshold Transmitted Power as an indicator of Bending Displacement

The chip on the RFID tag requires a minimum amount of power to turn on and respond to reader interrogation. In the absence of a metallic backplane, the tag antenna impedance

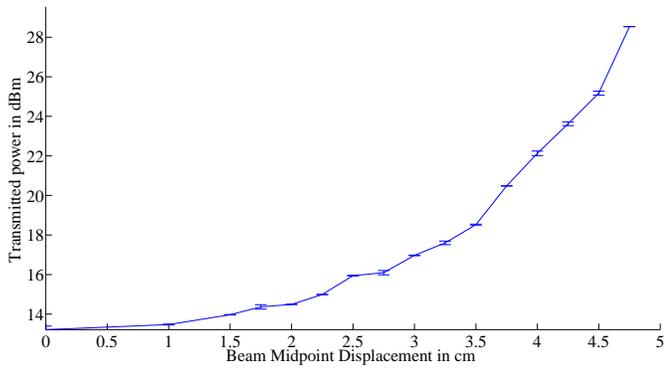


Fig. 5. Threshold Transmitted Power as a function of beam deflection at 915 MHz reader operating frequency

is matched to the chip impedance so as to minimize the amount of transmitted power required to activate the chip. An increase in displacement corresponds to a decrease in separation between the RFID tag and a metallic plane. This reflects in changes in tag antenna characteristics in particular increase in tag antenna - tag IC impedance mismatch, increased directivity of the antenna radiation pattern and reduced radiation efficiency. Thus it is expected that as the separation between the tag and the plane decreases, the transmitted (threshold) power required to turn the chip on would increase. As observed in Fig. 5 this hypothesis is verified for a constant reader operating frequency of 915 MHz. The threshold power changes are significant for deflections greater than 2.5 cm or tag-plate separations of less than 4 cm (we have set the value of R , the tag-plate separation distance under zero load, in Fig. 2 to be 6.5cm). Thus the hypothesis of developing a displacement sensor by calibrating threshold transmitted power to beam deflection is certainly feasible. It is also interesting to measure the variation of threshold transmitted power required to power up the RFID microchip as a function of reader operating frequency. RFID UHF operating frequencies vary between 868 MHz in Europe to 960 MHz in Japan. Plotting this variation enables us to determine the potential of deploying the RFID based displacement sensor on a global scale. Fig. 6 plots the variation of threshold transmitted power as a function of operating frequency for different tag-plate separation levels. It may be noted that although the absolute values of threshold transmitted power vary with frequency, the trends remain the same. Thus with some calibration effort, it would be possible to utilize this sensor globally.

B. The use of Backscatter Power as an indicator of Bending Displacement

Fig. 7 illustrates the variation of the tag backscatter power measured at the reader as a function of the midspan deflection of the beam for two different reader transmitted power levels for the Voyantic System. As the metal plate comes closer to the tag due to increasing deflection of the beam, more transmitted power is lost due to increasing loss in tag antenna

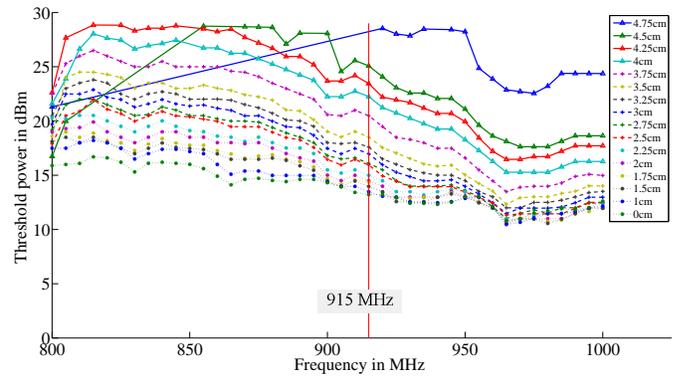


Fig. 6. Threshold Transmitted Power as a function of reader frequency of operation for different beam deflection levels

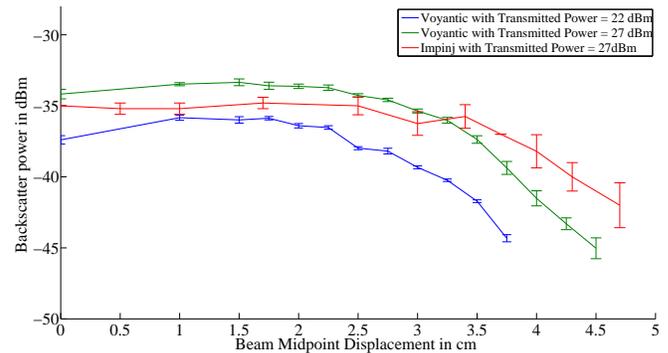


Fig. 7. Backscatter Power at receiving antenna as a function of mid span displacement developed in the beam

efficiency, impedance mismatch and destructive interference due to reflection off the metal plate. The chip thus receives less power and this manifests in lesser power being scattered back by the tag. Thus the tag backscattered power intercepted by the reader receiving antenna decreases with increasing deflection of the beam. The curve is found to be uniformly decreasing and it is thus possible to uniquely predict the deflection value by measuring the backscatter power at the receiving antenna. From Fig. 8 we note that the threshold transmitted power required to turn the RFID chip on, increases as the metal plate comes closer to the tag, for a large displacement of 4.75cm, this value is as high as 27 dBm. Thus in order to exploit the entire dynamic range of the sensor as seen in Fig. 7, it is recommended that the transmitted power setting be set to at least 27 dBm. We also present measurements at a lower transmitted power setting of 22 dBm. As observed from Fig. 7, the dynamic range of the sensor is significantly reduced because 22 dBm is below the transmitted power for very large displacements.

C. The effect of Reader Location

It is important to measure how sensitive the experiment is to the exact positioning of the RFID reader. Assuming the reader is positioned at about 1m from the tag for a fixed operating frequency of 915 MHz, for a position fluctuation of 10 cm

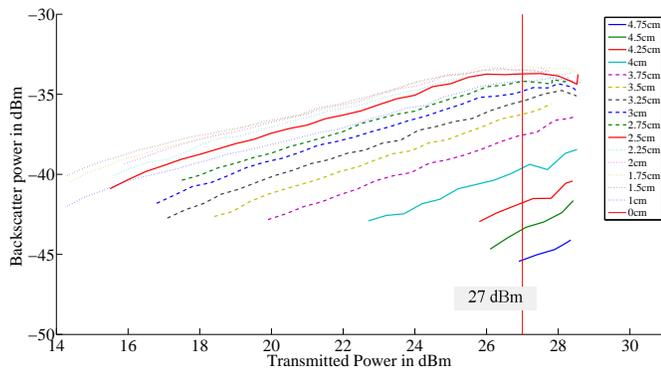


Fig. 8. Backscatter Power as a function of Transmitted Power for different deflection levels

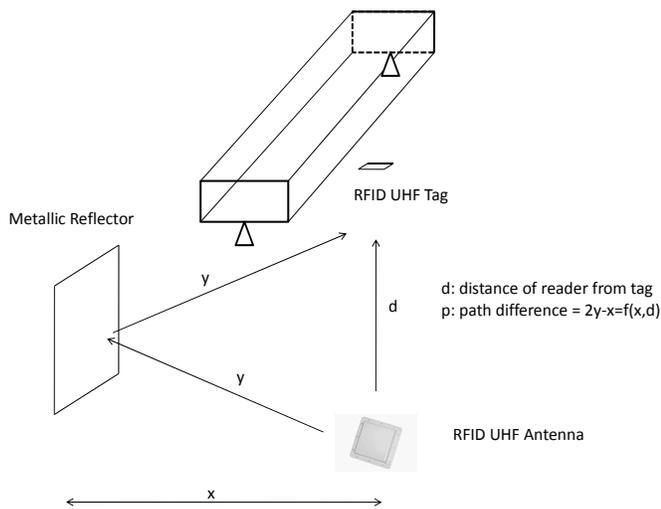


Fig. 9. Experimental Setup to account for Multipath

(-5 cm to +5 cm) we observe, from the Friis Transmission equation in free space, a change in power received by the tag of 0.5 dB which although sizable does not significantly affect the backscatter power measurements. Also a error in placement of 10 cm is exaggeratedly large and position errors would in reality be a lot smaller. Thus the measurement setup is relatively insensitive to vertical reader-tag position misalignment. The effect of effect of sensitivity to misalignment for other reader-tag positions have not been explored in this paper, although we do acknowledge that this is an important issue to be investigated.

D. The effect of Multipath on Experimental Results

RFID power measurements are highly susceptible to the effects of fading caused by metallic reflecting surfaces in close proximity to the tag. Electromagnetic radiation reflecting off metallic surfaces close to the tag could interfere either constructively or destructively with radiation arriving at the tag directly from the reader. This modifies the amount of power received by the tag for operations and could affect the calibration. Capturing the effect of multipath is important,

because our sensor works on the principle of establishing a 1:1 correspondance between backscatter power and displacement. The offset induced by constructive or destructive interference as a result of multipath could lead to erroneous results if not accounted for.

Attempts were made to investigate the multipath by placing a metallic reflecting surface at varying distances from the experimental setup as shown in Fig. 9. For a tag-reader separation d of 1m, the distance x was set so that the path difference p is 1 and 0.5 wavelengths corresponding to constructive and destructive interference conditions.

Fig. 10 graphs the variation of backscatter power as a function of transmitted power, at a plate-tag separation of 2.25 cm which corresponds to a reasonably heavily loaded condition. We observe from Fig. 10 that the backscatter power reflected by the tag is consistently more for the constructive interference case. This is as expected - the presence of greater power at the chip due to constructive interference manifests in an increase in backscatter power being reflected. Similarly, destructive interference causes a decrease in the power intercepted by the chip which manifests in lesser power being backscattered from the tag. This implies that the RFID displacement sensor would require to be calibrated for the enviroment it is located in to avoid errors from creeping into the measurements. As future work, we are considering relativistic backscatter power measurements as a method of compensation. Here differential backscatter power is measured relative to a second RFID tag in close proximity to the RFID tag displacement sensor, but which is unaffected by the metal plate. Such a technique should to some extent eliminate the effect of random fluctuations in the environment due to the metallic objects.

E. The effect of reader equipment

The experiments discussed in the previous section are conducted using the Voyantic Lite measurement equipment [27]. It is important to assess the repeatability of the measurements using lower cost off-the shelf RFID reader equipment such as the Impinj Reader equipment [17]. We note that the Impinj equipment antenna is circularly polarized. It is

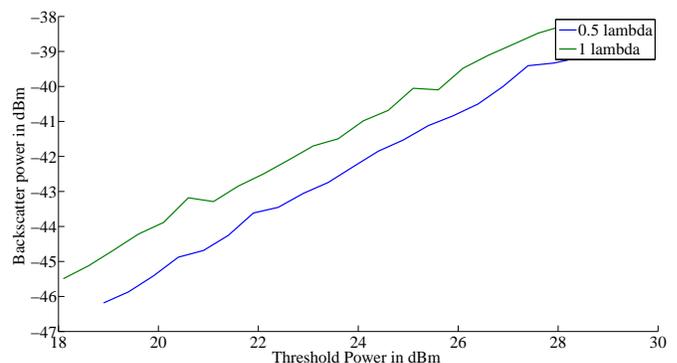


Fig. 10. Constructive and Destructive Inteferece from metallic reflecting surface in close proximity to the apparatus under medium-heavy loading conditions

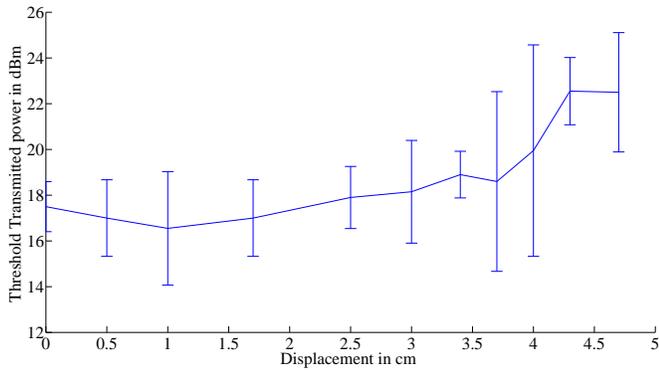


Fig. 11. Threshold Transmitted power vs. deflection using the Impinj RFID reader

encouraging to note that the backscatter power vs. deflection curve obtained with the Impinj equipment follows exactly the same trend as the one with the Voyantic Equipment as seen in Fig. 7 indicating that the sensing mechanism, proposed in our paper, would work even for commercial UHF RFID reader equipment. Similarly, the threshold transmitted power vs. deflection curve obtained in Fig. 11 follows the same trend as the one in Fig. 7 which indicates that both methods to measure displacement could be used with off-the-shelf reader equipment albeit with less precision than the Voyantic System. The Impinj reader operates as per FCC rules and frequency hops in the 52 channels between 902 and 928 MHz. Chip impedance is a function of reader operating frequency and if the chip impedance were to change significantly in this frequency band, we would expect to see this manifest as a larger standard deviation in the measurement results. Variation in backscatter power is considered as an example. Fig 12 demonstrates that there is no significant trend associated with variation in backscatter power with operating frequency channel. We also note here that while the Voyantic equipment has been designed for accurate power measurements from a single tag, the Impinj equipment is optimized for tag ID reads. We can thus attribute the larger standard deviations for measurements with the Impinj equipment to less accurate on-board electronics.

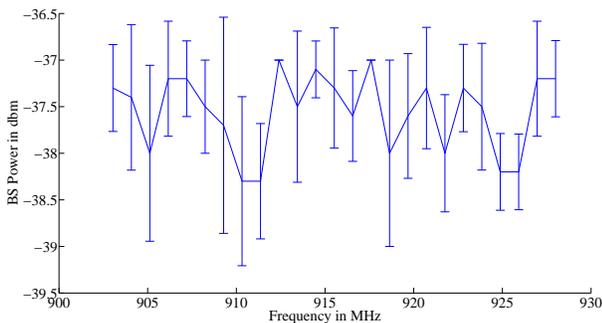


Fig. 12. Variation of Backscatter Power with reader operating frequency channel

VI. CONCLUSIONS

In this paper, we propose the principle of RFID tag antenna based sensing where we relate changes in tag characteristics to a change in some physical quantity as opposed to using the RFID tag IC as a wireless interface to a sensor. We believe that using the tag antenna as a sensor provides a cheap, long lasting and wireless alternative to some of the sensing devices commercially available in the market. The focus of this paper is to validate this principle by designing a tag antenna based displacement sensor.

The experimental setup consisted of a simply supported beam, a metal plane and an RFID UHF tag. As the midspan displacement increased, the separation between the tag and the metal plane decreased. Attempts were made to relate displacement to changes in threshold reader transmit power and tag backscatter power caused by deteriorating tag performance in the presence of metal. Through experiments, we observed that the displacement can indeed be mapped to these quantities and is accurate to a few mm over a dynamic range of 40 mm.

We attempted to approximate field conditions where it is possible to have the presence of metallic reflecting surfaces. The effect of constructive and destructive interference due to multipath was quantified and it was concluded that the effect of fixed metallic reflecting surfaces could be accounted for by performing a recalibration in the environment of sensor deployment. We acknowledge that accounting for the effect of moving or randomly appearing metallic reflecting surfaces is a challenging problem, but do not attempt to provide a solution in this paper. We also noted that the measurement apparatus is relatively insensitive to reader-tag vertical misalignment.

We investigated the effect of different reader equipment. The sensitive Voyantic equipment was used to validate our hypothesis and the practicality of the sensor was tested using the off-the-shelf RFID reader equipment. We observed that displacement could be related unequivocally to backscatter power as well as threshold transmitted power in both cases.

Although the focus of this paper was to demonstrate the utility of an RFID tag-antenna based displacement sensor, it is possible to extend the concept to measure changes in any physical phenomenon which give rise to changes in RFID tag antenna impedance and power characteristics. We believe that RFID tag-antenna based sensing does have the potential to provide a low-cost, long lasting and reasonably accurate alternative to expensive commercial sensors.

Future work includes attempting to design a custom RFID tag with form factor and dielectric substrate selected so as to optimize the dynamic measurement range for good accuracy and precision as well as to propose tag sensor designs that measure other physical phenomena like touch, light sensitivity, strain, temperature etc accurately.

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