Inductively Coupled Telemetry and Actuation

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INTRODUCTION

The transmission of both power and data between a transmitter and receiver, using a single carrier communicating in the near field, by means of a weak transformer action, is not new, Stockman (1). The ability to transmit power as well as data enables remote electronic circuits to be powered via the coupled carrier frequency and hence remove the need for a battery cell or generator.

The realisation of integrated circuits (tags), powered by the inductively coupled field, enabling bi-direction data communication, has led to the burgeoning market of radio frequency identification, RFID. RFID systems are used to track objects which have been tagged, be they criminals, animals or assets in a supply chain etc. Tracking of an object requires the means to electronically communicate with the tag and store the unique identifier code associated with each tag. In practice this is achieved using a scanning device called a reader and the use of a database.

While useful, current RFID systems have a number of limitations the most important being the fact that they are functionally passive, i.e. they provide access to identification codes and other data etc. but are not active in terms of sensing or interacting with the tag environment. This paper describes the development of an RFID technology which allows the tag to both sense it's environment and affect change within that environment by means of actuation.

A generic inductively coupled system is shown in Figure 1. The system has two subsystems, local reader and the remote sensing and actuating tag. The reader is connected to a PC, allowing real-time control of the tag sampling regime, display and storage of the data telemetered from the sensors connected to the tag as well as access to a distributed database.

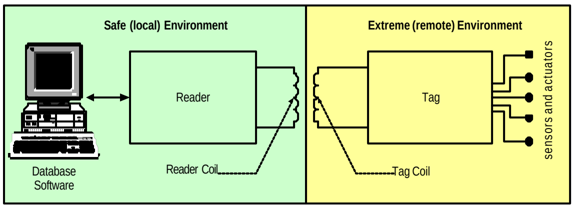

Figure 1: Generic Inductively Coupled System

The tag and reader are wirelessly connected via the mutual inductance of the tag and reader coils. In operation the reader energises the remote tag by means of a time varying electromagnetic radio frequency carrier. Control data is transmitted to the tag by conventional modulation of this carrier, the sampled data being communicated back to the reader by modulating the carrier signal; a process known as load or back-scatter modulation.

THEORY OF OPERATION

A typical equivalent circuit diagram for inductively coupled circuits is shown in Figure 2.

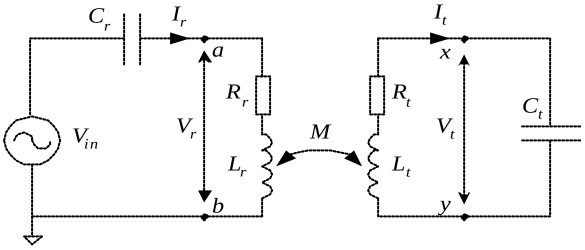

Figure 2: Typical Inductively Coupled Circuit

As can be seen from Figure 2 the configuration is essentially a transformer circuit with a mutual inductance *M* linking the reader and tag circuits. From this circuit it is possible to derive two Thevenin circuits which clearly show how the system operates.

The Thevenin reader circuit, Figure 3, comprises the reader source V_{in}, reader capacitance C_r and effective reader load impedance Z'_r, i.e., the impedance looking into the reader coil nodes *a*, *b* and including the mutual impedance of the tag.

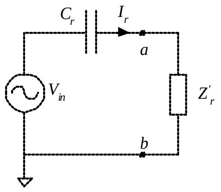

Figure 3: Reader Thevenin Circuit

From this circuit we can derive the following reader quantities. Note, M is the mutual inductance between the two circuits.

Reader Load Impedance

$$Z'_r = \left(R_r + sL_r\right) - \frac{s^2 M^2}{Z_t} \qquad (1)$$

Reader Load Voltage

$$V_{ab} = V_{in} \frac{\left\{ Z_t \left(R_r + sL_r\right) - s^2 M^2 \right\}}{\left\{ Z_t Z_r - s^2 M^2 \right\}} \qquad (2)$$

Reader Current

$$I_r = V_{in} \frac{Z_t}{\left\{ Z_t Z_r - s^2 M^2 \right\}}$$

(3)

Reader Load Power

$$P_{Z'_r} = \frac{V_{in}{}^2 \; Z_t \left\{ Z_t \left(R_r + sL_r\right) - s^2 M^2 \right\}}{\left\{ Z_t Z_r - s^2 M^2 \right\}^2} \qquad (4)$$

Similarly a Thevenin tag circuit, Figure 4, may be constructed comprising an induced tag (source) voltage V'_{in}, tag load capacitance C_t and effective source impedance Z'_t, i.e., looking into the tag coil nodes *x, y* and including the mutual effects of the reader

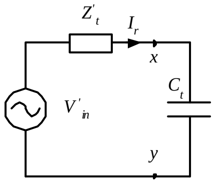

Figure 4: Tag Thevenin Circuit

Parameters of interest are as follows:

Tag Source Voltage

$$V'_{in} = V_{in} \frac{sM}{Z_r} \qquad (5)$$

Tag Source Impedance

$$Z'_t = \left(R_t + sL_t\right) - \frac{s^2 M^2}{Z_r} \qquad (6)$$

Tag Load Impedance

$$\frac{1}{sC_t} \qquad (7)$$

Tag Load Voltage

$$V_{xy} = \frac{V_{in}}{C_t} \frac{M}{\left\{ Z_t Z_r - s^2 M^2 \right\}} \qquad (8)$$

Tag Current

$$I_t = V_{in} \frac{sM}{\left\{ Z_t Z_r - s^2 M^2 \right\}} = I_r \frac{sM}{Z_t} \qquad (9)$$

Tag Power

$$P_{\frac{1}{sC_t}} = \frac{V_{in}{}^2}{C_t} \frac{s \; M^2}{\left\{ Z_t Z_r - s^2 M^2 \right\}^2} \qquad (10)$$

In the preceding expressions, $Z_r = R_r + sL_r + \frac{1}{sC_r}$ is the series impedance of the reader circuit with no tag present, i.e. M = 0. Similarly $Z_t = R_t + sL_t + \frac{1}{sC_t}$ is the series impedance of the tag circuit with no reader present.

Mutual Inductance

The analysis presented above shows that the performance of any inductively coupled system is limited by the mutual inductance M. In practical applications, M can be affected in a variety of ways, however to further our analysis, we shall consider the case of two co-axial coils in air. The expression for the mutual inductance between a reader and tag coil of radius *r* and *t* meters and turns N_r and N_t respectively, a distance *x* apart, is provided in equation 11, Lee (2).

$$M = \frac{m_0 p \, N_t N_r (rt)^2}{2(r^2 + x^2)^{\frac{3}{2}}} \qquad (11)$$

As a result of the mutual inductance between the reader and tag coils, the reader source voltage V_{in} produces a reader current I_r, stimulating an electromagnetic field which in turn induces a voltage in the tag V'_{in} (Faraday’s Law). The tag voltage gives rise to a tag current which in turn induces a voltage in the reader opposing the reader applied voltage V_{in} and as a result the reader impedance may be considered to have been increased by the presence of the coupled tag impedance. The induced tag voltage is dependent on the mutual inductance *M* between the reader and tag coils, (as would be expected), but is also proportional to the reader frequency *w* (through the Laplacian operator *s*) and inversely proportional to the reader impedance Z_r. In addition, the tag current is also directly proportional to V_{in}, *w* and *M*, while being inversely proportional to tag impedance Z_t, Z_r, w^2 and M^2. This suggests that the tag voltage, current and hence available power can be maximised in a variety of ways; of paramount importance if the tag is to support both sensing or actuation features.

Figure 5 shows how the mutual inductance of air wound coils changes as a function of inter-coil separation.

While the absolute value of M can be tuned (to a degree) by varying the coil dimensions, number of turns etc., for any given reader and tag coil configuration there will be an upper limit for M which cannot be exceeded. This ensures that for each application power transfer must be optimised.

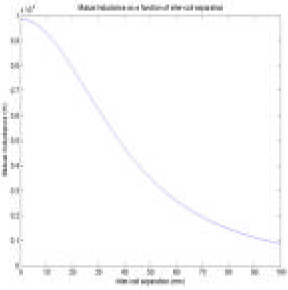

Figure 5: Shows the mutual inductance between a reader and tag coil each having 5 turns and a radius of 5cm, varying as a function of inter-coil separation.

MAXIMISING POWER TRANSFER

Given a sinusoidal reader voltage of fixed amplitude and frequency, the power inductively coupled to a remote tag may be maximised (for any given mutual inductance M) by tuning the reader and tag circuits to resonate at the same frequency, as well as constructing coil arrangements to maximise the mutual inductance between them.

If the coupling between the reader and tag coils is small enough, each may be considered independently, i.e. one may be assumed to resonate as if the other circuit was absent. Furthermore if the reader and tag circuits are tuned to a common angular frequency then Z_r and Z_t simplify to R_r and R_t and the tag current can be shown to be

$$I_t = V_{in}\frac{wM}{\{R_tR_r - w^2M^2\}} \qquad (12)$$

which reaches a maximum value when

$$wM = \sqrt{R_tR_r} \qquad (13)$$

Equation 13 shows the coupling necessary for maximising the tag current, subject to the assumption previously described. This value of wM provides optimum coupling to the tag. For values of coupling less than this both the reader and tag current responses mimic a single peaked resonance curve. This is to be expected, because as the coupling decreases the tag and reader become increasingly isolated from one another, i.e. the reader circuit tends to a series resonant RLC circuit driven by the source voltage V_{in} while the tag circuit resolves into a series resonant RLC circuit driven by a diminishing source voltage V'_{in}. As the coupling is increased to the optimum value, the tag and reader circuits begin to affect each other. The coupled impedance reduces the peak in the reader current frequency response and small peaks appear either side of the resonant frequency, simultaneously the tag current reaches its absolute maximum value. Increasing the coupling yet further results in a fall in the reader current at the common resonant frequency, with “humps” developing on either side. The tag current also exhibits the same effect, with the frequency difference between the humps increasing until maximum coupling is reached. The current versus frequency responses for the reader and tag currents are shown in Figures 6 and 7.

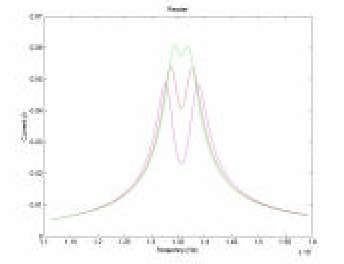

Figure 6:Reader and Tag Currents vs Frequency.

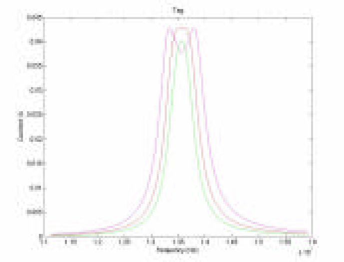

Figure 7:Reader and Tag Currents vs Frequency.

TRANSMITTING DATA

The communication of data between the reader and tag is achieved by modulating a carrier frequency with a defined and encoded protocol.

Reader to Tag Data Transmission. Equation 5 describes the relationship between the induced tag source voltage V'_{in} and the reader source voltage V_{in}. Evidently any modulation of the reader source voltage will be transferred to the tag. Any modulation technique may be used to convey data from the reader to the tag. However, demodulation of the signal at the tag may not be straight forward due to changes in the impedance of the tag, equations 6 and 7. The demodulation problem is particularly pronounced in applications where the coils are moving relative to each other, i.e. the degree of coupling is continually changing, as in piston telemetry. In addition, some modulation techniques, particularly amplitude modulation, can result in a reduced power range due to a time averaged drop in the received power.

Tag to Reader Data Transmission. The effective load impedance of the reader Z'_r , equation 1, shows how data can be modulated from the tag to the reader, i.e. a change in tag impedance will manifest itself in the reader circuit by virtue of the mutual inductance. For passive tags this process is called backscatter modulation. Figure 8 presents a circuit which back-scatters data from the tag to the reader by means of a resonant circuit and de-tuning capacitor. In this case the RF field linking the tag and reader behaves as a weak transformer. Note that the modulation of the tag impedance will also modulate the power to the tag and as such the modulating impedance must be optimised to achieve the desired performance.

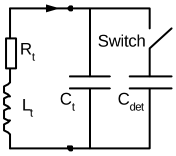

Figure 8: Conceptual Tag Circuit

To detect the backscattered data a reader must peak detect data signals of >60dB down. To recover such low signal levels and maximise read-range (inter-coil separation), the reader and tag circuits are usually made resonant, with tag reactance (inductive or capacitive) being modulated. Resonance boosts the interaction between tag and reader and is key to increasing both the power available at the tag and the loading effect of the tag on the reader.

DESIGNING AND USING “SUPER” RFID SYSTEMS

As described, the virtue of a passive RFID system is the fact that no batteries or crystal oscillators are required. This offers the prospect of sensing and actuation in extreme, hazardous or difficult to access environments where batteries and crystal oscillators are impractical or incompatible. However, most practical applications conspire to affect the mutual inductance and hence limit performance. As a result of this a modelling tool was developed in order to investigate performance as a function of system parametrics. The graphs of Figures 9 and 10 model the performance of a coupled reader and tag coil respectively.

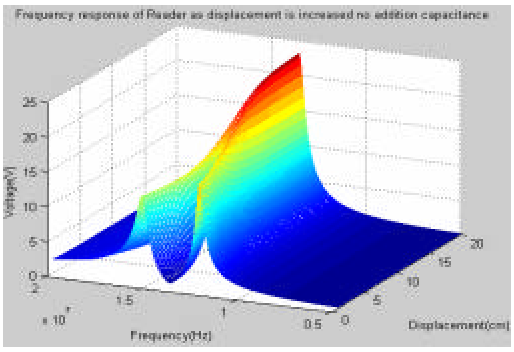

Figure 9: Reader Coil Performance

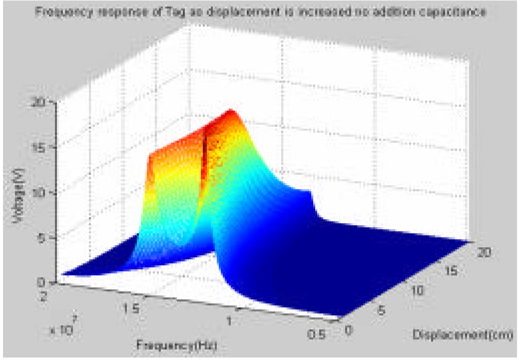

Figure 10: Tag Coil Performance

It has been found that the model agrees closely with experiment and the system is being developed to create a integrated design environment for “super” RFID systems.

While modelling is useful, ultimately, it is necessary to build electronic systems suitable for the target application. Achieving the appropriate level of performance from an inductively coupled telemetry and actuation system, particularly in an extreme environment is an exacting task.

Without a battery all aspects of the system must be optimised. The circuit must be made to operate at the lowest power levels to increase read range. This has implications on processor, memory and analogue to digital conversion clock speeds, which in turn limits both sampling and communications bandwidth. Furthermore, the incident e.m. radio wave, while coupling the necessary power to the tag, also bathes the tag’s power, signal and data-lines in RF which can affect tag performance. For Some applications the physical size of the electronics is key, as too is the upper temperature rating. To date all of the system tested have been constructed from discrete components; future work will realise an integrated system-on-chip fabricated in a high temperature silicon-on-insulator technology and offer a microcontroller core and necessary peripheral circuits.

Many of the problems associated with such inductively coupled circuits are remedied by good circuit design. Maximising performance however is simply *(sic)* a matter of maximising the mutual inductance. Since every application is different a wealth of “know how” has been gained. This has been achieved through a regime of practical experiment, involving iterative experiments with coil sizes, number of windings, wire thickness etc. For example, the work of Grover (3) does not provide answers to the problem of the mutual inductance between two co-axial, concentric coils, one attached to an aluminium piston with both contained within a steel bore and threaded by a titanium connecting rod as found in Formula 1 piston telemetry.

Tele-Sensing Applications

Figure 11 shows a photograph of an inductively coupled temperature telesensing system.

Figure 11: Inductively Coupled Telesensing System

All aspects of the system are clearly visible, the powered tag is sitting on a perspex disc and supports a type K thermocouple. The reader coil is concentric to the perspex disc and connects to the reader electronic system (black box), which in turn is connected via the universal serial bus (USB) to the personal computer. A close up of the tag (minus the thermocouple) is shown in Figure 12.

Figure 12: Telesensing Tag

The telesensing tag of Figure 12 makes use of a printed circuit board antenna. Such antennas are cheap and offer satisfactory performance. The tag is designed for use at a carrier frequency of 13.56 MHz and is capable of supporting two independent sensing channels plus the usual identification codes.

A number of applications in addition to piston telemetry have been tackled, such as pH measurement and the temperature measurement of both the work-piece and friction probe associated with friction stir welding.

Tele-Actuation Applications

In addition to sensing, a facility to enable the tag to actuate has been achieved. This allows the tag to perform operations such as locking. A number of locking applications have been tackled, the most interesting being the ability to lock a container. In this application a tag with the integrated electronic locking means is embedded into the container. The lock is then controlled by the reader, via the tag. This solution reverses the conventional security paradigm by enabling contactless locking from within. Figure 13 shows a medical sample pot retro-fitted with such a lock. In use the pot can only be opened when placed within the electromagnetic field of a reader and subject to a secret access code. This allows the opening of pots to be controlled in terms of location, time and personnel.

Figure 13: Inductively Locked Pot

Figure 14 shows a lock designed to be retro-fitted to a sea-going container. In this application the reader must be portable, and in use linked wirelessly to the controlling database.

Figure 14: Inductively Locked Container Lock

Other applications for locking containers or securing loads have also been designed and tested. It is evident that the technology can aid organisations enforce chain of custody procedures, prevent the adulteration of food goods in transit, provide an effect method for anti-tampering and prevent opportunist theft.

It is envisaged that the locking system compliments standard RFID. This is due to the fact that the locked containers have the inductively coupled lock embedded into the fabric of the container ensuring that the identifier cannot be removed. The detatchment of the tag from an object is a known weakness of tagging technologies, however the cost of such an event is significantly reduced if the tagged objects are secured within a locked container. In addition the box may be scanned to control access, identify the container and the contents.

FUTURE WORK

While the inductively coupled sensor and actuation systems described have individual merit, future work will concentrate on integrating the two technologies. Coupling the sensing and actuation capabilities together is technologically feasible and offers the prospect of containers which can be locked and interrogated to establish if there has been a change in the contents, for example.

As described previously, it is necessary to realise an integrated circuit solution offering both sensing and actuation facilities. Prefereably this integrated circuit will be fabricated in a technology offering temperature and radiation resilience so as to enable sensing and locking over the widest possible range of environmental conditions in order to service the largest application base.

CONCLUSION

The authors have demonstrated, through use, a technology offering remote sensing and actuation from a variety of applications, using a batteryless inductively coupled method. This technology builds upon and extends the capabilities of radio frequency identification, RFID.

1. Stockman H. 1948.Proc. IRE, 1196-1204

2. Lee Y. 2003. “Antenna Circuit Design Application Note AN710”. Microchip technologies 2003., 1-4

3. Grover F.W. 1946. “Inductance Calculations, Working Formulas and Tables”. D.Van Nostrand Company Inc.