The Design and Use of an Explosion Metrology System

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Abstract

Since the terrorist attacks on the World Trade Centre, western governments and their military advisors have been forced to re-evaluate engagement strategies, and reconsider the weaponry necessary to support such strategies. Bombs that provide the "biggest bang for the buck" are arguably inappropriate for tackling close-hand skirmishes, minimising civilian deaths and reducing infrastructural damage. As a result there is a need to develop explosive devices capable of delivering a targeted and metered explosion of sufficient potency to neutralise no more than the threat. The development of such devices requires knowledge of the threat, the design of an explosive capable of neutralising the threat and a means of assessing the efficacy of conditions created by the explosion to eliminate the threat. The assessment of the explosion and the environment it creates requires appropriate instrumentation. This paper describes the design and development of an explosion metrology system capable of sampling data from the target of an explosion. The work was commissioned by the Office of Naval Research ONR (London) and the Defense Threat Reduction Agency DTRA (Washington D.C.).

Introduction

As stated, the purpose of this work was to create an explosion metrology system comprising sensors, instrumentation hardware and software. At the start of the program there was no design specification, instead a loose description of requirements and desirables was agreed. No information regarding the nature of the target or the explosive materials were forthcoming, neither was a description of the test site; other than the fact that the explosion would take placed in a steel lined enclosure.

The absence of such data was due to the fact that some of the information was classified but more importantly (as was subsequently found) the data had been withheld so as not to prejudice or influence the design.

Working in such an information vacuum was liberating allowing the problem to be tackled from first principles. Early calculations predicted that the duration of an explosive event be in the order of 50ms. Temperature would rise quickly and blast forces would be considerable; however it was not possible to ascertain metrics for these quantities, target side, from the literature. It was then the true purpose, aim and worth of the project became clear.

Aim

The design aim was to create a wireless integrated system on chip, free from battery power; small and compact; resilient to the explosive environment; capable of sampling data at the appropriate rate and in the appropriate format. The system had to be packaged in a form-factor which would minimise the effect of the measuring system on the explosive event yet maximise the ability of the system to sample data.

This feature set flowed logically from the decision to create a tele-sensing node, which would initially reside in the target. During the explosion the node would be moved randomly by blast forces, yet communicating all the while. Controversially a decision was made not to over protect the device. This was done in the belief that protecting the device would result in a larger device, which would be more prone to blast forces and influence observations. This decision however had a significant impact on the system architecture, for the following reasons.

- Batteries were incompatible due to their size, weight, susceptibility to blast forces and heat.
- The sensor was expected to move randomly during the explosion, therefore how could the device sample and communicate data.

It was decided that an application specific circuit (ASIC) manufactured from a high operating temperature, silicon-on-insulator technology would provide resilience to thermal and mechanical shock. This ASIC, which became known as the XT01 transponder would offer simultaneous, wireless, real time communications over both a near and far field channel; the near field channel also being used to provide power and configuration data to the device.

This set of features allowed the sensor to be embedded in the target prior to the explosion. The device was powered using an interrogating device to set up the near-field (inductive channel). This channel was used to power the device, configure the device, run pre explosion checks and sample data from the from the XT01 transponder for as long as it remained within proximity of the reader.

Simultaneously, data was transmitted on a far-field channel, which continued to transmit data even when out of proximity to the interrogator, by virtue of stored power on the tag. A schematic of the operating principle is shown in Figure 1.

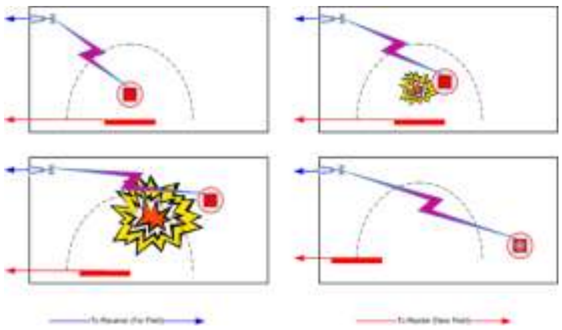

Figure 1: Explosion Metrology Operating Principle

Figure1, top left, shows the embedded sensor placed in the target. Near field communication is possible via the interrogator placed below the target (sensor), with far field transmission from the sensor to a receiver shown by the "flash". The dotted hemisphere marks the boundary of the near-field zone, the black rectangle the steel walls of the explosion chamber.

As shown the sensor moves with the blast forces. For a period of time data is received on both channels; as the sensor moves out of range of the interrogator, data transmission is maintained on the far-field channel. In Figure 1, bottom right, the explosion has ended, the sensor has come to rest out of reach of the interrogator and the far field channel persists until the power stored on the tag has been consumed.

Metrological Considerations

While explosion metrology could benefit from the measurement of a variety of parameters it was agreed that temperature measurement be the sole focus of this program. The determining factor was that considerable effort has been made to both theoretically model and experimentally measure temperature in explosive events.

In terms of experimental instrumentation, explosion metrology usually deploys modified thermocouples. These thermocouples are standard in all respects bar the thickness of the wire used to fabricate them; typically 0.25 mm or less. The wire is thin in order to reduce the thermal inertia of the sensor and prevent the skewing of results, however the thinness of the wire means that welded junctions are hard to manufacture and the resulting sensor is very fragile. As a result, such sensors are mounted (protected) on ceramic stems. Once again ceramic is used so as not to skew the measurement, but it is sub-optimum in the explosive environment due to its' brittle nature.

For these reasons, together with the fact that a thermocouple requires a set-point reference, thermocouples were discounted. Platinum resistance thermometers were also considered, but they exhibit many of the problems of associated with thermocouples namely.

- Very thin platinum wires are necessary to reduce thermal inertia and not skew results.
- Thin platinum wires are fragile.

As a result, the use of diodes as temperature sensors was assessed. It was found by experimental means that a diode was capable of acting as a repeatable very fast acting temperature sensor, providing a constant current was applied to it; when compared to a standard thermocouple and a platinum resistance thermocouple, Table 1.

Sensor	Slew rate mVs^{-1}
Platinum Resistance Thermometer	221
Type K Thermocouple	2203
Diode IN4148	152
Diode GHT (high temperature diode)	2104

Table 1: Sensor Slew Rates

Feature Set and Architecture

The design of the XT01 had to strike a compromise between the sample rate of the sensor and the operating range of the near field. An operating frequency of 13.56 Mhz was chosen to support a 200 kbits^{-1}data transfer rate.

The XT01 has an on-board Analogue to Digital Converter (ADC), used to sample the voltage on an external pin. The ADC can operate as a standard analogue to digital converteror as a mixed mode comparator; these modes are described below.

ADC Mode

This is a successive approximation Analogue to Digital Converter. On request, the ADC takes a sample of the input voltage; it then approximates each of the 8 bits in succession, starting at the MSB working its way to the LSB. The maximum sample rate for 8-bit conversion is 15ksps. A block diagram is shown in Figure 2.

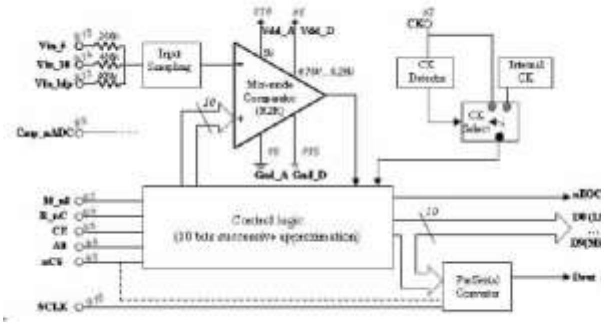

Figure 2: Analogue to Digital Convertor

ADC Comparator Mode

The comparator mixed mode operation compares the analogue input voltage with a digital reference voltage; the comparison does not require a clock. The response time of the mixed mode comparator is 3.3us, imposing a maximum sample rate of 300ksps.

The mixed mode comparator is essentially the ADC with the successive approximation logic disabled. Once the control line for the ADC has been set to comparator mode, it constantly compares a digital value placed on the bi-directional bus with the voltage placed on its analogue input. The output of the comparator goes low when the value placed on the bi-direction port is higher than the voltage on its analogue input. The circuit has a 5us response time when there is a change on either the analogue or digital inputs. This limits the sample rate to 200ksps. The IO signals required to realise comparator mode is shown in Figure 3.

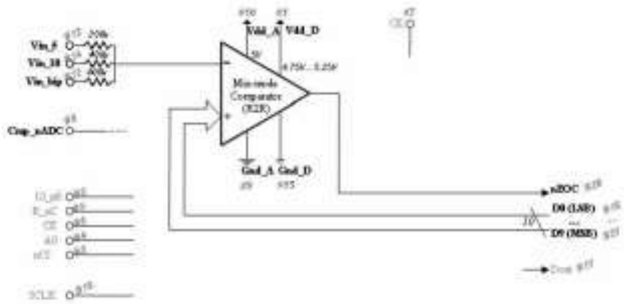

Figure 3: ADC Comparator Mode

The ADC when driven by the onboard digital core is capable of sampling data in a variety of ways. A full description of the device operation and the various functional modes it supports can be found in the data sheet [1]. However, the two modes used most extensively during the explosion testing are described below.

Peak Detect Mode

Starting at a given threshold, the ADC tracks the highest value reached. The tracking increment and sample time can be configured by the user. Each time the threshold is exceeded, the system outputs a pulse, Figure 4.

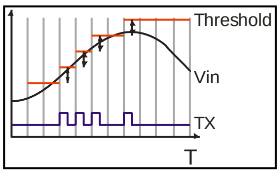

Figure 4: Peak Detect Mode

The peak value can be calculated using equation 1.

$$v = v_0 + n \cdot v_i \qquad \textbf{Equation 1}$$

Where v is the value at time t, v_0 the trigger threshold, v_i the quantised increment and n the number of pulses since the triggered threshold.

Threshold Bit Mode

Providing the sampled voltage is greater than a predefined threshold, the system emits pulses at a predetermined frequency, as shown in Figure 5.

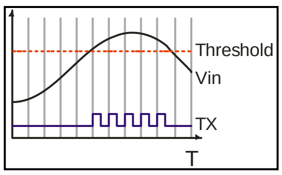

Figure 5: Threshold Bit Mode

This mode was used to test the health of the system when subject to an explosive event. For example, if the threshold temperature is set below ambient the XT01 transmits a continuous beacon at a predetermined frequency set by the user.

Implementation

The original idea for the system is presented in Figure 6.

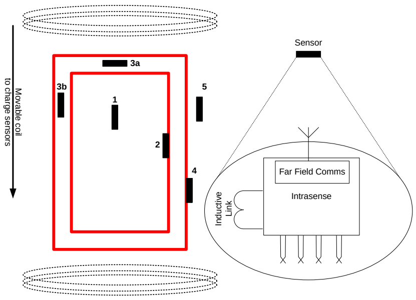

Figure 6: Original Concept

In Figure 6 a dual walled container shows the opportunities for locating and mounting the sensor. In use, the sensor was to be energised by moving the primary coil of the reader over the container. This aspect was dropped in favour of a static reader upon which the target would sit, so as to energise and configure the embedded sensor.Figure 8 shows the realisation of the embedded sensor.

Figure 7: XT01 Tag

It is clear from Figure 7 that the tag device was not protected in any significant way. The impact of this on system performance is explained in the next section.

XT01 Field Testing

The XT01 was field tested at the South West Research Institute (SwRI) at San Antonio Texas. As well as providing the facilities for conducting test explosions, colleagues at the Ballistic Division were commissioned to independently correlate explosion metrology results using the XT01 with standard instrumentation.

The explosions were conducted in a purpose built bunker on the ballistics range at SwRI, Figure 8.

Figure 8: SwRI Ballistics Bunker

Inside the bunker a steel scaled model of a room was constructed, Figure 9. This was where the XT01 was tested.

Figure 9: XT01 Testing

Figure 9 shows all of the Instrumentation components with the exception of the controlling computer. The tag is clearly seen in the plastic container (target) sat on top of the reader coil, in front of the door.

The reader coil is attached to the reader electronics by means of the red connectors. The far field antenna is visible, attached to the steel rod support on top of the house. The co-axial cable of the far-field antenna runs to a receiver box on top of the house. Signals were routed from the receiver, and to and from the reader through a hole on the steel bunker, right of Figure.

Figure 10 shows a tag after it had been subject to an explosive event. It is clear that the near field coil has been destroyed, however the Tag printed circuit board PCB has survived largely intact.

Figure 10: Destroyed XT01 Tag

Close scrutiny of the tag in Figure 10 reveals that the XT01 transponder integrated circuit has been blown clean off the substrate. The device in question was found in the desert scrub, in proximity to the bunker, Figure 11.

Figure 11: Detached XT01 in Desert Scrub

This device was subsequently returned to base where it was mounted on a new tag PCB and tested. It was found to work perfectly.

Results

A number of explosive tests were performed, however, while the XT01 tag provided data from all tests, data using the fine thermocouple approach was not as successful, with only one set of thermocouple data being recorded from five attempts. The results of this test were verified by SwRI and are shown in Figure 12.

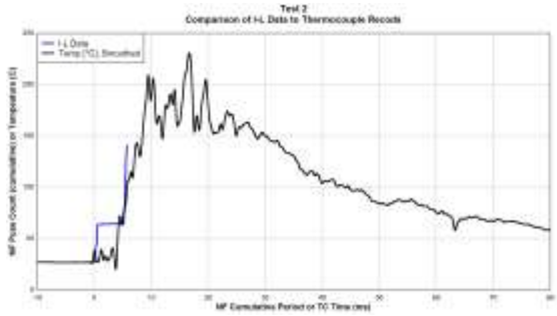

Figure 12: XT01 and Thermocouple Data

From Figure 12, it is clear that the XT01 (blue trace) has a better reaction time to the explosive event, when compared with the thermocouple. Also the blue trace shows a plateau in the first 5 ms of the explosion. This data was sampled using the peak detect mode and as such it is possible that the temperature instead of remaining constant across the plateau, could have dropped. Our sponsors believed this result to be significant.

Conclusions

This work concludes that:

1. An alternative technology for explosion metrology instrumentation has been developed.
2. The technology appears to be more robust than the instrumentation currently used.
3. The instrumentation is capable of sampling data from the target of an explosion.
4. The instrumentation is capable of sampling data during the first 5 to 10 ms of an explosion.
5. The resilience of the XT01 to an explosive environment has been ascertained and therefore should be satisfactory for other extreme environments.

References

[1] Instrumentel Ltd., "XT01 Data Sheet", www.instrumentel.com