

Proximity Identification and Tracking for Mining Automation

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Abstract

A priority issue within coal mines is ensuring the safety of underground personnel. It is vitally important to have up-to-date information about: which districts personnel are working; if there is adequate provision of safety equipment and facilities, and whether the mine environment is hazardous. This paper canvasses recent developments in proximity identification and tracking technologies for mining automation. Recent developments in LF, HF and UHF passive tags, active tags (including LAMPS), micro-power generation and video tags are reviewed.

1 Introduction

Mining automation applications of automatic identification systems include: (a) tracking the coal or ore product from mine to port; (b) optimising the design of block caving mines by preseeding regions with tags and back-estimating the 3D material flow dynamics; (c) electronic barriers that screen incoming traffic in areas where automated equipment operate, and (d) routine personnel safety management in underground mines. This paper is motivated by safety in mines, it is equally relevant to the applications (a) – (c).

A recent survey of Queensland's longwall coal mines [1] has reaffirmed that needs exist for personnel and vehicle/mobile equipment tracking systems. A priority issue within longwall mines is ensuring the safety of underground personnel. It is vitally important to have up-to-date information about: which districts personnel are working; if there is adequate provision of safety equipment and facilities, and whether the mine environment is hazardous. This paper canvasses recent developments in proximity identification and tracking technologies for underground mines.

Location monitoring systems commonly employ two types of components: tags and readers. Typically tags are physically attached to personnel, vehicles, mobile equipment and materials. Readers monitor the presence of tags in the vicinity and are connected to communications infrastructure.

Tags fall into two categories: passive and active. Passive tags do not rely on a local battery or power supply. They can emit fixed coded signals when irradiated at appropriate frequencies. In contrast, active tags possess a connection to a power supply, such as a battery, which enables sensor monitoring to be supported.

This paper is organised as follows. A survey of passive tag systems is presented in Section 2. Section 3 reviews active tag systems, including the Location and Monitoring for Personnel Safety (LAMPS) system (see [2] and <http://www.mining-automation.com>) which is pictured in Fig. 1. Some self-powered or microgeneration technologies which are possible candidates for powering active tags are discussed in Section 4. Section 5 describes some recent developments employing visual tags and video cameras.



Fig. 1. The LAMPS tag, cover and cap-lamp battery assembly.

2 Review of Passive Tag Developments

The advantages of passive tags are: an absence of battery maintenance issues and a reduction in the tag installation costs. The disadvantages of passive tags are the comparatively reduced operating range and the inability to perform sensor data monitoring. Four categories of systems are discussed: low frequency (LF), high

frequency (HF), ultra-high frequency (UHF) and microwave tags.

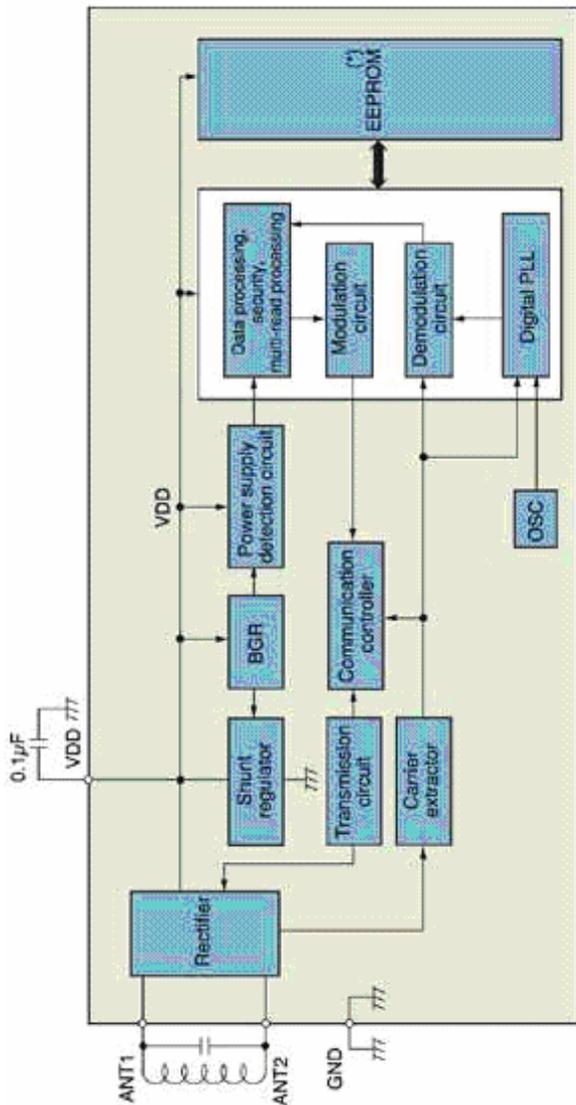


Fig. 2. Block diagram of a *Toshiba* 125 KHz tag circuit (see www.semicon.toshiba.co.jp/eng/solution/ic/rfid3.html).

2.1 LF Tag systems

The LF tags use unlicensed spectrum; the frequency of 125 KHz was the first to be employed for radio frequency identification (RFID) within industrial applications. The majority of 125 KHz tag systems are passive in the sense they do not possess an integrated battery. The energy coupling to the tag is similar to that in a transformer. Namely the reader generates a magnetic field, which is inductively coupled to a coil within a nearby tag. The induced voltage in the tag coil powers the data transmission back to the reader.

Common applications of 125 KHz tags are smart cards, personnel access control cards, locks and car immobilization. A block diagram of a *Toshiba* 125 kHz

smart card tag integrated circuit is shown in Fig. 2 (see www.semicon.toshiba.co.jp/eng/solution/ic/rfid3.html).

The coil and capacitor are not part of the integrated circuit. Briefly, the voltage induced on the external coil is rectified and provides power for the code stored within the EEPROM to be communicated back to the reader. The *Toshiba* tag communicates using binary phase shift keying (BPSK) on a carrier frequency that is half the reader transmitter frequency, using a half duplex serial protocol. The tag memory capacity can vary between 1 Kbits to 4 Kbits EEPROM. The maximum 125 KHz tag read rate is about 10 tags/s.

The maximum 125 KHz tag to reader range is typically 50 mm and in some cases up to 100 mm. Some manufacturers produce 125 KHz tags embedded within PVC credit cards suitable for accommodating magnetic strips and compatible with offset printers.

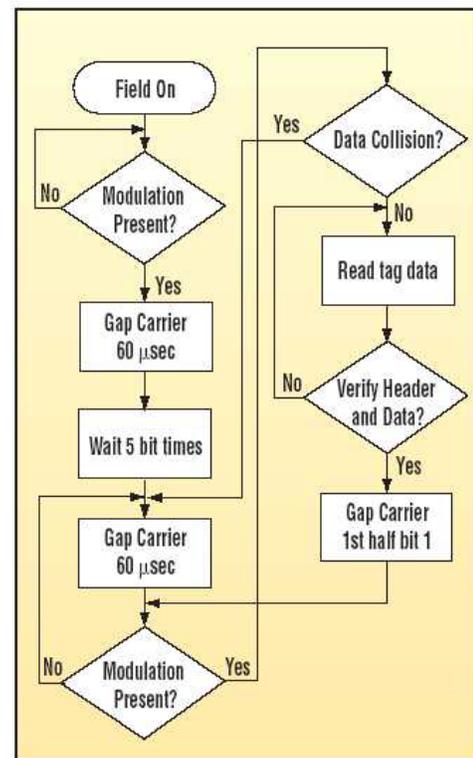


Fig. 3. Anti-collision algorithm for a *Microchip Technology* 125 MHz tag [3].

Reading one tag at a time is appropriate in personnel access and security applications involving card-swipe style readers. In applications where a large volume of tags are in the field of the reader, a collision avoidance feature is required, so that the individual tag transmissions don't jam each other. The collision avoidance algorithm employed within a *Microchip Technology Inc.* 125 MHz tag integrated circuit [3] is shown in Fig. 3. Briefly, collision avoidance involves each tag waiting for an absence of transmitted signals prior to transmitting. Indeed the LAMPS tags [2] employ a similar collision avoidance technique.

A LF tag system that is widely used for marathon, fun-run, triathlon and other sports events timing is the *ChampionChip* see <http://www.championchip.com/>. The packaged *ChampionChip* tags retail for about AUD \$50 each and the cost of a 4 m wide section of reader mats and equipment is about AUD \$30000; consequently the systems are typically rented by the sports event organisers. A 4 m wide timing mat can capture about 1500 athletes per minute. The tags contain a *Texas Instrument* integrated circuit which employs a 7-digit identification code and has a range of about 20 cm. The energising and reading process takes approximately 60 ms.

A LF tag system for underground mine personnel management is the *eProx* system developed by *MineCom* (see <http://www.minecom.com/>). *MineCom* have packaged 125 KHz tags manufactured by *HID Corporation* (see <http://www.hidcorp.com/>) within rugged waterproof enclosures suitable for mining environments.

2.2 HF Tag systems

The operating range of HF tags tend to exceed that of 125 MHz tags. In general the tags need to be located within the near field (approximately within 1 diameter) of the reader transmission antenna. Typically the available range spans 0.1 m to 1.5 m depending on the reader's transmit output power and the sophistication of the receiver circuitry.

Compared to LF tags, HF tag construction is thinner because less turns are required on the external coil. This can result in a small cost reduction. An advantage of operating at 13.56 MHz is that the radio field is not absorbed by water or organic tissue. Thus the available range is not affected by people in the intervening path. Another relative advantage is that the higher frequency supports a higher data rate, that is, it takes less time to read the same tag identification information.

Typically 13.56 MHz readers have transmit powers of about 1 W and antenna gains of up to -30 dBi. The tag memory size can vary between 64 bits and 10 Kbytes. The combination of multiple multiplexed reader antennas and anti-collision protocols can support reading rates of 10 to 30 tags per second. Popular applications of 13.56 MHz tags include library, carton and shipping labels.

The previously mentioned LF and HF tags rely on inductive coupling, whereas the UHF tags employ electromagnetic coupling. This offers a potential range advantage over and 125 KHz and 13.56 MHz systems. The achievable range is limited however by the prevailing regulations. For example, in Europe the maximum allowable UHF reader output power of about 0.5 W constrains the range to about 0.7 m. In Japan the UHF tags cannot even be used. In the USA, the maximum effective radiated power (ERP) over the unlicensed 902 -

928 MHz band is about 4 W, for which some tag manufacturers claim a read range of 6 - 8 m. This compares with manufacturer quoted ranges of beyond 20 m in the case of a 30 W ERP site licence in the USA.

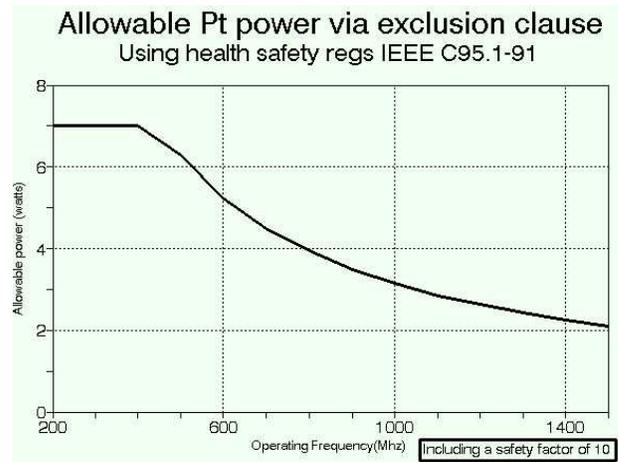


Fig. 4. Transmitter power allowed by *IEEE C95.1-95*, extracted from : "Range versus power and frequency from passive electric tags", Mike Marsh, *Trolley Scan Pty Ltd*, <http://trolleyscan.co.za/technic3.html>.

The amount of transmitted power is governed both by spectrum licensing regulations and by health and safety requirements. In the USA, they have approved the standard: *IEEE C95.1-1991-IEEE Standard for safety Levels with respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 KHz to 300 GHz*. Based on *IEEE C95.1-1995*, ensuring a safety factor of at least 10 times, the maximum allowable transmitter power varies from about 7 W at 200 MHz down to about 4 W at 900 MHz as shown in Fig. 4. This suggests that if the range of 800 - 900 MHz tags are inadequate, then either passive tags operating in the region 100 MHz to 500 MHz or active tags require consideration.

Compared to the LF and HF tags, UHF tags offer an increased bandwidth. The tag coil size is also smaller at higher frequencies, resulting in reduced tag cost. The 800 - 900 MHz band does not penetrate water and organic material as well. During the last quarter of 2002, *Gillette* announced that they had ordered 500 million UHF transponders. This is the first time that a manufacturer of high volume low cost products has opted for passive tags instead of barcode labels. It has been suggested that in the future all supermarket items could be equipped with such tags so that items will no longer need to be scanned individually.

2.3.1 Evaluation of the *TrolleyScan* System

A passive tag evaluation system has been purchased from *TrolleyScan*, see <http://trolleyscan.cm/> and <http://trolleyscan.co.za/>. The approximate prices of the *TrolleyScan* tags are: USD \$10 each for quantities of less

than 1000, USD \$7 each for quantities of greater than 1000 and USD \$5 for quantities of greater than 10000. The reader output power can be varied in the range 4 - 7 W. The nominal tag reading range is 7 m. The claimed read rate is about 100 tags within 4.5 s. On first inspection, the *TrolleyScan* system could be a candidate for mine location tracking because ranges of 4 to 6 m and reading rates of 100 tags/4.5 s are claimed. However the tags need to be oriented in the same plane as the reader receive and reader transmit antennas.

Some experiments were conducted by the author in which 20 *TrolleyScan* tags and two aluminium yagi reader antennas were oriented vertically. The observed tag to reader antenna range was about 3 to 4 m. However, when the tags were oriented horizontally, they failed to be detected at the 3 to 4 m range. Suppose that tags are attached to hard hats. In underground mine vehicles, passengers seated at the front face forward whereas those seated at the rear face the sides. Therefore systems are desired which can handle arbitrarily oriented tags.

Duplicate brass yagi antennas were manufactured and Minicircuits splitter/combiners were employed to connect pairs of antennas together. It was found that the Minicircuits splitter/combiner insertion loss was about 4 dB. The *TrolleyScan* frequency synthesizer output was modified to provide about a few dB of extra gain and a separate power amplifier was installed for a second antenna. Some experiments were conducted using a pair of reader transmit antennas (vertical and horizontal) and a pair of reader receiver antennas (vertical and horizontal), together with arbitrarily 20 oriented tags. It was observed that the maximum range was less than 2 m. Similar results were obtained with the use of patch antennas instead of Yagis. The experiments have demonstrated that accommodating arbitrarily oriented tags results in an unsatisfactory range. The range cannot be extended by increasing the output power beyond about 4 W from Fig. 4.

The *TrolleyScan* tags require a minimum 1 mW (ie 0 dBm) input signal power level to work. In contrast, the receiver sensitivity of active tag receivers is typically in the region -80 dBm to -100 dBm and so active tags can offer a significantly greater range.

2.4 Microwave Tag Systems

Although some 2.45 GHz RFID technology is emerging, the regulatory issues are still in process. Currently, microwave frequency tags share unlicensed spectrum with other applications such as wireless local area networks, which can result in interference problems. The even higher frequency promises increased bandwidths and supports larger amounts of data. However, as mentioned in Section 2.2, the safe transmitter power level prescribed by *IEEE C95.1-1995* standard, falls rapidly with increasing frequency, which will probably limit the

operating range of such systems to around 1 m.

3 Review of Active Tag Developments

Short-range passive tag systems such as *MineCom's eProx* allow personnel to manually swipe their tags at a reader stationed at a mine entry/exit. In underground mines however, requirements additionally exist for automatically tracking pedestrians and vehicle passengers [1, 2].

Two categories of active tags are discussed: intrinsically safe (IS) tags and non-IS tags. A recently developed IS tag known as LAMPS [2] is described in Sections 3.1 and an example of a non-IS system is described in Section 3.2.

3.1 The LAMPS System

The recent survey of Queensland's longwall mines [1] reaffirms the needs for underground mine location monitoring. Further, the paper [2] contrasts the gap between existing technologies and the requirements for location and managing mine emergency incidents.

The LAMPS system has been developed in two phases and is supported by *Australian Coal Association Research Program (ACARP)*, see <http://www.acarp.com.au/>. The first phase project is known as *ACARP C7037 Location and Monitoring for Personal Safety*. The second project phase is known as and *ACARP C9016 LAMPS Further Development*. A summary of the LAMPS developments are presented in the two sections that follow.

3.1.1 LAMPS Phase 1 Developments

Some recommendations concerned with managing the risk in the mine emergency response followed from an accident at an underground *bord and pillar* coal mine at Moura in 1994 [2]. An escape and rescue model was proposed in which there are three rescue phases: self rescue; aided rescue and mine recovery. Underground staff need to be made aware of safe exit paths for self escape. In the aided rescue phase, the emergency management team need to know where people are trapped in a mine by a physical impediment or injury. Finally, in the mine recovery phase, data about prevailing conditions is desired to minimise risk to workers while attempting to stabilise the situation. The following two requirements also emerged: if the mine power system fails the communication system should remain active for up to a week and the system should be able to survive a section taken out because systems with a single high capacity backbone are vulnerable [2].

Managing mine emergency incidents requires systems that are standalone, survive failures and support self-rescue, aided rescue and mine recovery. The review of

mine communications systems presented in [2] indicate that existing and emerging technologies cannot meet the afore-mentioned requirements in support of managing emergencies. A key deficiency of conventional mine communications systems is survivability. That is to say, conventional systems are vulnerable whenever there is a risk of severing a communications or power cable. The LAMPS concept was developed to address this limitation.

The LAMPS system was aimed at bord and pillar mines such as Moura. The original concept involved installing readers at intersections of roadways and cut-throughs within bord and pillar mines which are spaced at about 50 m intervals. Active tags are worn by underground personnel and automatically report to any readers in their vicinity. In the case of the *Moura No. 2 Underground Mine*, Panel 510 has from 5 to 6 roadways along its length. These bord and pillar panels offer a good deal of opportunity for redundant communication paths. Indeed, the results of simulation studies for a bord and pillar panel shown in Fig. 5 demonstrates that with a 10% failure rate, a mesh interconnected system such as LAMPS would provide about 80% communications availability, whereas conventional leaky feeder installation would provide less than 10% availability.

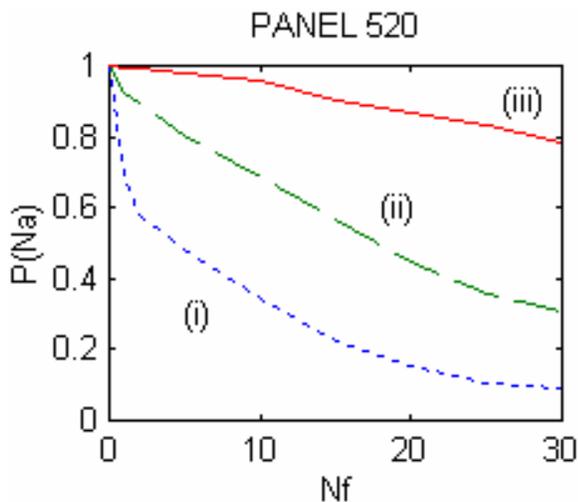


Fig. 5. Probability of cell availability for Moura No. 2 Underground Panel 520: (i) Single cable, (ii) Branched cable (iii) RF network.

The first phase LAMPS developments were designed to target the above-mentioned bord and pillar mine requirements. It is based on a network of readers communicating over radio via a large number of redundant line-of-sight pathways within underground mines. Each reader possesses a unique identification number, which is recorded against locations in a mine. The network accommodates arbitrary growth and failure as readers are either added or removed from the mine. Tags designed for underground personnel and equipment also possess unique identification numbers and automatically communicate with the nearest readers in the network. The set of nearest-reader data constitutes the

location information, which is communicated to and monitored by tracking software. The tracking software enables emergency messages to be sent to the tags.

The phase 1 tags nominally report at approximately 100 second intervals. The phase 1 tag RF output power is about 10 mW at 433.9 MHz (which compares with about 0.7 W for mobile phones) and so is most unlikely to be hazardous to personnel. Note that a maximum output power of 20 mW is permitted for the 433.05 MHz to 434.79 MHz frequency band by the Low Interference Potential Devices (LIPD) Class Licence specified by the *Australian Communications Authority*.

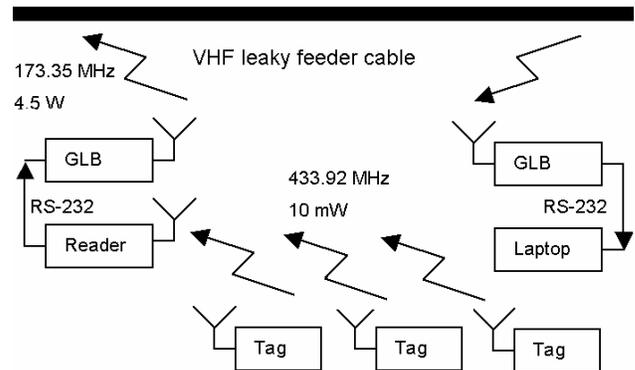


Fig. 6. Configuration of test equipment deployed at the Enterprise Mine at Mt Isa.

A demonstration of the phase 1 LAMPS system was carried out at the *Enterprise Mine* at Mt Isa. The configuration of the test equipment deployed underground is shown in Fig. 6. The LAMPS readers were connected to the existing mine leaky feeder system via GLB modems. These modems are used for convenience and are not necessarily employed in a mine installation. Two tests were conducted. Firstly, seven LAMPS tags were distributed on the floor within about 30 m from a LAMPS reader mounted on pipe-work near the back (roof). A GLB modem (model ST150DD11C) served to transmit the reader data to the nearby leaky feeder cable via a quarter wave whip antenna. The time-stamped data was successfully observed on laptop computer connected to another GLB modem having a whip antenna, in a vehicle travelling along the drives in regions where leaky feeder communications were available. Secondly, seven LAMPS tags were deposited in the back of a vehicle which was driven at nominal speed past the overhead LAMPS reader. The time-stamped data was successfully observed on a stationary laptop connected to a GLB modem plugged into the leaky feeder system basestation, some 2.5 km from the reader. This test was repeated several times. The tests have demonstrated that the LAMPS tag and reader power budget and radio frequency are satisfactory for underground personnel location monitoring via Mt Isa's existing leaky feeder cable system.

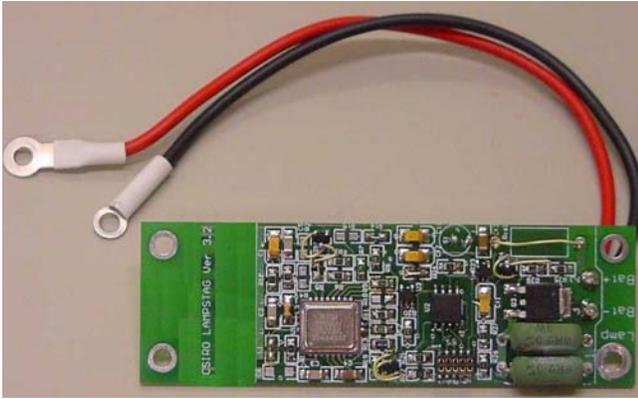


Fig. 7. The LAMPS tag module.

3.1.2 LAMPS Phase 2 Developments

The objective of the second phase LAMPS project is to migrate the developed phase 1 technology to intrinsically safe commercial versions for installation in coal mines. *MineCom* requested that the LAMPS tags had a receiver enabled between transmissions and a capability to modulate the cap-lamp light intensity and so warn personnel of emergency or hazardous conditions. *MineCom* has received orders to supply LAMPS to underground longwall coal mines in which the requirements include: installing pairs of readers at strategic locations; tracking personnel in vehicles travelling at nominally 10 km/hr; providing reports summarising the personnel that travelled underground for selected shifts/days/weeks and for selected mines; and interfacing to the existing mine local area network (LAN) and Microsoft SQL Server.

The LAMPS design was evolved in response to the above-mentioned commercial requirements. In particular an IS tag was produced which possesses a receive function and modulated the cap-lamp light intensity on command. The IS assessment was undertaken by the safety in mines testing and research station (SIMTARS), see <http://www.nrm.qld.gov.au/simtars/>. A certificate of conformity to AUS/NZ/IEC 60079-0 and 60079-11 is available at <http://www.mining-automation.com>. The LAMPS tag is shown in Fig. 7. *MineCom* have arranged for the production of new covers that accommodate LAMPS tags for cap-lamp batteries which are supplied by *Oldham* in the UK to *Gilbert Gray & Co.* Some testing of the new covers was carried out by *SIRA* in the UK. The complete tag, cover and cap-lamp battery assembly is shown in Fig. 1.

The phase one LAMPS developments assumed high reader densities and massively redundant connections. In order to track vehicle passengers, the phase two LAMPS tag (average) retransmit interval was decreased from 100 s to 1.5 s. The combination of increased communication traffic rates and diminished opportunities for redundant pathways in longwall mines precluded wireless reader

communications. In the case of sparsely distributed readers, such as the longwall mine applications, packet switches are required to merge the outputs of readers. A switch to filter, queue and route LAMPS packets was developed and combined with the reader and implemented on an *Altera ACEX EP1K30TC144*. External and internal views of the LAMPS readers are shown in Figs. 8 and 9 respectively. The figures show three pairs of fibre optic connectors which allows interconnection with three other readers and supports communication over multimode fibre installed along 5 km gate roads. The readers are powered by IS power supplies available from *Ausdac* (see <http://www.austdac.com.au/>) and *Amp Control* (see <http://www.ampcontrol.com.au/>). The IS assessment of the LAMPS readers is similarly being carried out by SIMTARS.

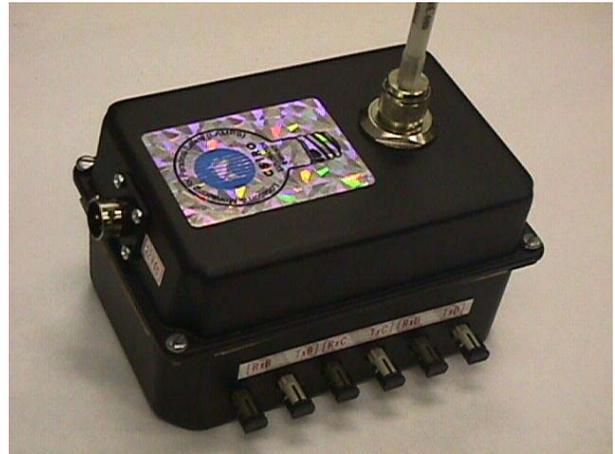


Fig. 8. External view of the LAMPS reader.



Fig. 9. Internal view of the LAMPS reader.

Open Database Connectivity (ODBC) is a programming interface that enables programs to access data in database management systems that use Structured Query Language (SQL) as a data access standard. The developed LAMPS tracker software produces reports using a *Microsoft Access* database which is ODBC compliant and can support batch updates to *Microsoft SQL Server*. The incoming tracking information and reports are accessible to mine staff having a LAN connection to the control room.

The LAMPS system is being commercialised by *MineCom*. The system has been patented in Australia (Application No 6814898) and Canada (Application No 2289752). LAMPS is different to conventional active tag systems in four respects. First, the readers support multiple redundant interconnections and so provides robustness to localised failures in mines. Second, the tags report tilt sensor or man-down information. Third, LAMPS is a bi-directional system. For example the underground personnel can receive and acknowledge hazard or evacuation advice. Fourth, the intrinsically safe readers will operate within safety critical production regions.



Fig. 10. Encapsulated LAMPS tag II mounted on Oldham type T2 and T4 battery cables.

A simplified transmit-only expendable tag has also been developed and submitted to SIMTARS for IS assessment. The so-called LAMPS tag II possesses an internal *Sonnenschein* Lithium battery and is completely encapsulated as shown in Fig. 10. With the receiver disabled, the tag draws approximately 0.037 mA at 3.6 V. The nominal lifetime of the *Sonnenschein* SL350 Lithium battery is

$$0.85 \text{ AH} / (0.037 \text{ mA} * 8760 \text{ H}) \approx 2.5 \text{ years.}$$

The tag detection range is around 100 m in the line-of-sight above-ground case. In underground mines where the roadway dimensions are about 5 m x 5 m, the tag detection range can reduce to around 50 m due to propagation anomalies and intervening obstacles.

3.2 A non-IS active Tag System

There are many non-IS active tag systems available in the marketplace. For example, a *Spider IIIAR Real-time Locating System* is manufactured by *RF Code Inc*, see <http://www.rfcode.com/>. Once the tags are enabled they transmit a digital encoded eleven-character identity every 7 s over a radio frequency of 303.8 MHz. The tags are encapsulated in plastic and are powered by a button cell having a nominal life of 3 – 5 years. *RF Code Inc* also manufacture a mantis tag which is motion activated to transmit at a higher rate. The operating range of the *RF Code Inc* systems varies from 50 m to 300 m depending on the type of directional antenna that is used. The systems are aimed at asset/inventory management and pallet/container tracking applications and have interfaces to 802.11b WLANs and SQL 2000 database. The tags need to be attached to the assets in such a way that there is a minimum of 2.5 cm distance between adjacent tags. The tags can be attached to metallic or non-metallic assets.

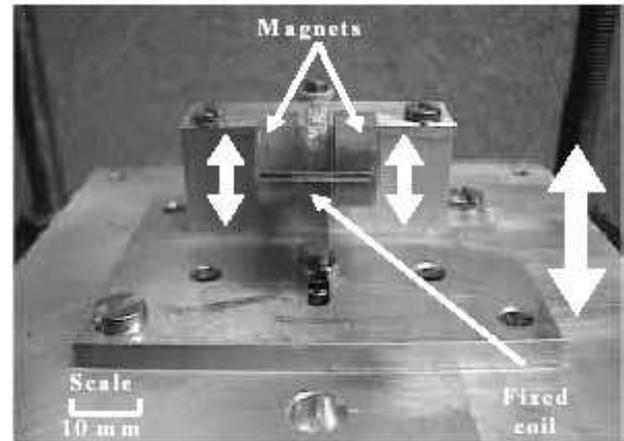


Fig. 11. Prototype coil-magnet [4].

4 Review of Micro-generation Developments

Active tags are reliant on batteries that require periodic maintenance. To address this issue, a brief survey of technologies for micro-generation or self-powering is described herein. This survey seeks to identify some key research groups and indicative output power capacities. Five categories of generators are canvassed, namely electromagnetic, electrostatic, thermoelectric, piezoelectric and solar technologies.

4.1 Electromagnetic Generation

Williams *et al* at the University of Sheffield [4] discuss the feasibility of a generator comprising a mass on a spring connected to an electromagnetic transducer. From accelerometer data recorded as vehicles pass over a bridge, it was predicted in [4] that for a 1 Kg mass the average generated power is 1.5 to 700 μW .

James, Beeby, Glynn-Jones *et al* at the University of Southampton [5], describe a micro-generator in [5], where a magnet displacement of 8 μm at the generator fundamental resonant frequency of 102 Hz produces approximately 0.5 V (RMS) and a constant power of 1.25 mW. The prototype generator comprises a fixed coil and two Neodymium Iron Boron (NdFeB) magnets supported on cantilever beams and is shown in Fig. 11. A transformer having a step-up ratio of 7:1 is used to match the impedance of the generator to the load. A full bridge rectifier using BAT54J schottky diodes is employed for rectification in preference to MAX1672, MAX1722 and MAX1723 DC/DC converters, which are deemed not sufficiently efficient [5].

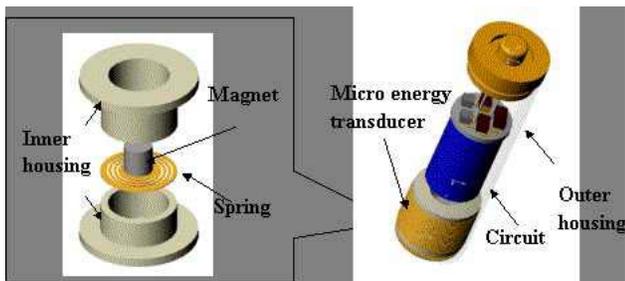


Fig. 12. Illustration of AA-sized microgenerator under development by the Centre for Micro and Nano Systems, Faculty of Engineering, The Chinese University of Hong Kong.

The Centre for Micro and Nano Systems in Hong Kong have a project under development to produce a AA-battery sized micro-generator [6], see <http://www2.acae.cuhk.edu.hk/~cmns/>. Their prototype micro-power generator consists of the following: an N45 grading rare earth permanent magnet; a laser-micro-machined resonating spring which is attached to the magnet; a copper coil; a power-management circuit for transforming and storing the output voltage, and an inner and outer housing.

The orientation of the inner housing, the magnet and the resonating spring is shown in Fig. 12. When input vibration frequencies from 60 to 110 Hz are applied, the generator produces up to 4.4 V peak-to-peak which results in a maximum RMS output power of 680 μW into a 1500 Ω resistive load.

4.2 Electrostatic Generation

Sterken *et al* [7] describe an electrostatic converter based on charge transportation between two parallel plate capacitors and on the use of a charged dielectric (electret). They present a formulation for a linearised energy converter model and output power predictions of between 0.1 μW to 100 μW for loads between 10 M Ω to 1000 M Ω at an electret voltage of 100 V. A so-called Microelectromechanical System (MEMS) device

fabrication is proposed. It is concluded in [7] that 100 μW electrical power is feasible at 1200 Hz for a device displacement of 20 μm .

Amirthsrajah *et al* (funded by the US Army Research Laboratory and the C. S. Draper lab) discuss a MEMS transducer integrated circuit (IC) that converts vibration to a voltage [8]. A controller IC is also described. After subtracting the controller power and switching loss from the predicted MEMS converted energy, the predicted available output power is 4.29 μW .

4.3 Thermoelectric Devices

In a thermoelectric device, the charge carrier movement is due to the heat flow within the selected material. The ratio of heat flow to current for a particular material is known as the Peltier coefficient, which is related to the Seebeck coefficient, a proportionality constant that relates the voltage generated at a junction between two dissimilar conductors to the temperature difference between them. There is a relationship between the Seebeck and Peltier coefficients, known as the Thomson effect which relates to the heating or cooling in a single homogenous conductor when a current passes along it in the presence of a temperature gradient

In 1994, Seiko Instruments Inc. (SII) researchers succeeded in developing a micro-thermoelectric device which relied on the “Seebeck effect” and used Bismuth Telluride (BiTe) [9]. In 1998, they developed and commercialized SEIKO THERMIC, a heat-powered wristwatch that generates power by utilizing the difference between ambient and body temperatures. The back lid of the watch receives heat from the user's arm as the high-temperature end, while the case emits heat from the back lid as the low-temperature end. Thermoelectric watches require to have a thermoelectric conversion device that can generate more than 1.5 μW from a temperature difference of 1 to 3 $^{\circ}$ C. Generally, a single element of thermoelectric devices generates a voltage of 200 μV for a temperature difference of 1 $^{\circ}$ C. The Seebeck element has a thermo-electromotive force of 0.2 mV/deg C. SII fabricated a module by sandwiching 104 elements between 2 mm x 2 mm silicon substrates and connecting 10 modules in series. This gave a voltage of 0.2 V which was up-converted to a voltage suitable for charging a secondary newly developed Ti-Li battery with a capacity of 4.5 mAh. This was sufficient to drive the watch for 10 months without supply of any heat.

A low power thermoelectric generator (LPTG) device has been produced in Germany by D.T.S. Thin Film Thermoelectric Generator Systems GmbH [10]. The LPTG device measures 9 mm x 7.5 mm x 2.8 mm, weighs 390 mg and is shown in Fig. 13. The nominal output is greater than 10 μW (see the technical data published in [10]).

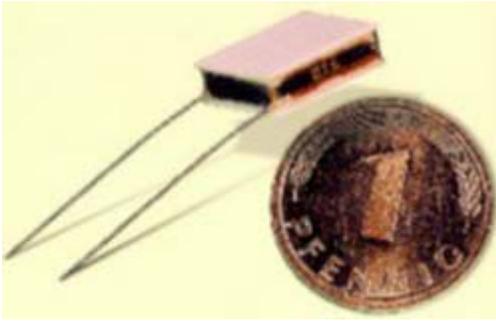


Fig. 13. LPTG device available from D.T.S. Thin Film Thermoelectric Generator Systems.

4.4 Piezoelectric Devices

Two piezoelectric devices have been mounted within shoes for assessment of electricity generation potential [11]. Electrical energy is generated when the devices are compressed and bent from their nominal shape. The two piezoelectric devices tested in [11] were:

- A multilayer laminate of polyvinylidene fluoride (PVDF) foil developed by the Sensor Products Division of Measurement Specialties. When the laminate is bent, the eight PVDF sheets on the inside and outside are subjected to different rates of compression and expansion, which produces voltages across the sheets' electrodes.
- A unimorph strip made from piezoceramic composite material developed by NASA Langley. Power is extracted from pressure by bonding a unimorph strip of spring steel to TH 6R and TH 7R PZT (lead zirconate titanate).

The estimated mechanical to electrical efficiencies were 0.5% for the PVDF, 1.5% for the TH 6R and 5% for TH 7R. The measured peak power, discharging into 250 k Ω resistors, were 20 mW for the PVDF and 80 mW for the PZT. The measured average powers (due to the slow excitation) were about 1 mW for the PVDF and about 2 mW for the PZT. The application of a shoe insole-mounted TH 6R PZT powered RF transmitter is also described in [11]. In particular, the output of the PZT is bridge rectified and powers a 5V regulator that supplies 3.3 mA for approximately half second durations. It is remarked in [11] that more efficient voltage conversion circuits (such as charge pumps) are desired. For comparison, an electromagnetic generator from a flashlight was fitted to the outside of a shoe. A hinged heelplate with a 3 cm stroke, was used to crank the rotary generator. The generator possessed a flywheel and was observed to provide a peak output power of about 1 W and an average power of about 0.25 W into a 10 Ω load. It is concluded in [11] that although the magnetic generator produces two orders of magnitude more power than either of the two piezoelectric systems, it was much harder to integrate within footwear.

The proof-of-concept and performance of an electromechanical Helmholtz resonator with a piezoelectric composite backplane is reported in [12]. An acoustic resonator cavity measuring 12.7 cm diameter and 19 cm deep, was coupled together with a PZT unimorph bender element from American Piezo Corp. The output of the PZT was connected to a 5 V switched linear regulator circuit and provided 7.4 mW of power into an electrical load.

The University of Florida team that investigated acoustic energy conversion [12] have reported analysis and experiments of strain energy conversion using a flyback converter circuit in [13]. The output of a vibrating PZT piezoceramic beam is connected to an ac to dc flyback converter which is estimated to provide greater than 80% conversion efficiency at an input power of 1 mW and 75% efficiency at an input power of 200 μ W.

MODEL	AREA	Specifications	Cost (USD)
Siemens BPW-34 SCPD	3.2 x 3.2 mm	0.475 volts, 1.86mA	\$1.39
Panasonic BP-242221	24 x 22 mm	3.5 V (OC), 6 mA (SC), 17 mW	\$7.00
Panasonic BP-243318	24 x 33 mm	2.7 V (OC), 16 mA (SC), 28 mW	\$7.95
Panasonic BP-37774	37 x 33 mm	5.5 V (OC), 15 mA (SC), 43 mW	\$8.50
Panasonic BP-376634	37 x 66 mm	5.5 V (OC), 30 mA (SC), 110 mW	\$9.95

Table 1. Typical PV solar cell specifications.

4.5 Solar Cells

Miniature active tags having solar cells could possibly be mounted on cap-lamps and mine vehicle lights. Samples of photo-voltaic (PV) cells that are typically used within consumer electronics were purchased from *Hobbytron* (see www.hobbytron.net) and their specifications are shown in table 1.

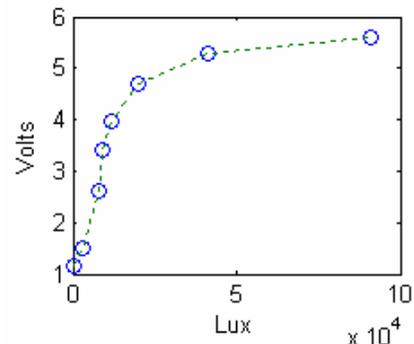


Fig. 14. Measured voltage output versus light intensity for Panasonic BP-376634 with 1 k Ω load.

A Panasonic BP-376634, measuring 37 mm x 66 mm, with a nominal open circuit voltage of 5.5 V and a maximum output power of 110 mW in noon sunlight was load tested by the author in afternoon sunlight with a 1 K Ω resistor. The measured voltage across the 1 K Ω resistor from shade to sunlight is plotted in Fig. 14. The figure shows that in afternoon sunlight (ie at least 40000 Lux), the solar cell can deliver at least 5 V or 25 mW, that is around 23% of the nominal maximum output power. For about 45 degrees off-axis orientations or semi-shade (ie at least 9000 lux), the observed voltage was at least 3.4 V or 12 mW, that is around 10% of the nominal maximum output power. Variations in light intensity and orientation could be accommodated by a suitable solar cell and rechargeable battery combination.

4.6 Summary

The performance off the micro-generation and self-powering technologies is summarised in Table 2.

System	Input conditions	Output power
Bridge-mounted vibration-electric generator [4]	Car over new bridge 12 Hz and bus over new bridge 6 Hz. Car over old bridge 14.5 Hz and truck over old bridge 4.5 Hz.	4 s bursts of 50 – 500 μ W (estimated)
MEMS transducer [7, 8]	20 μ m displacement 1200 Hz vibration frequency	4.3 - 110 μ W
Magnet-coil generator [5]	0.4 mm displacement, 102 Hz resonant frequency	0.5 V RMS and constant power of 1.25 mW
Low power thermoelectric generator [10]	10 $^{\circ}$ C temperature difference	10 μ W/0.21cm ² =48 μ W/cm ²
PVDF piezo-electric material within a shoe [11]	1 mJ per step	Approx 100 V peak and 1.1 mW power with 250 K Ω load
PZT piezo-electric material within a shoe [11]	2 mJ per step	Approx 50 V peak and 1.8 mW power with 250 K Ω load
Electro-mechanical Helmholtz resonator with piezo-electric backplate[12]	2.18 KHz resonance frequency, 157 dB SPL, diaphragm motion 180 mW	7.4 mW with 2.2 K Ω load
Vibrating PZT piezo-ceramic composite beam [13]	Input force 12 mN and input velocity 65 mm/s. Average mechanical power of 0.8 mW.	0.16 mW into 12 K Ω load
AA size vibration induced micro energy transducer [6]	60 Hz – 200 Hz vibration frequency, 200 μ m vibration amplitude	680 μ W RMS max with 1500 Ω load.
BP-376634 PV solar cell	50000 lux (outdoors)	5V with 1 K Ω load, and 25 mW/ 24.4 cm ² = 1 mW/cm ²

Table 2. Performance micro-generation and self-powered technologies.

5 Video Tags

Suppose that requirements exist to identify up to 255 mine vehicles or mobile equipment as they pass within the field of view of a video camera. This can be accommodated by black labels possessing a two dimensional array of up to 12 white dots (8 to span an address space of 0 to 255 plus a further 4 for error detection). For example, the label can be painted on the bonnet of mining vehicles. The label recognition task can be undertaken by convolving the images with templates for each label for various scales and rotations and then employing a decision or classification function.

Some new theory developed by the author for smoothers that enables data to be optimally extracted from noisy measurements is presented in [14]. The results of [14] are used in [15] to track noisy dots over a sequence of images.

The noisy images were convolved with the above bivariate Gaussian function that generated the measurements. The mean square error (MSE) of the coordinate estimates, produced by this so-called matched filter are indicated by the top line within Fig. 15. The estimates produced by the matched filter served as inputs to the Kalman filter and the fixed interval smoother described in [14]. The MSE performance of the Kalman filter and the fixed interval smoother are indicated by the middle and bottom lines within Figure 15. It can be seen from the figure that when the measurement noise is sufficiently small (*i.e.*, above -27.5 dB SNR), the matched filter, Kalman filter and smoother exhibit the same performance. However, at -35 dB SNR, compared to the matched filter, the Kalman filter and smoother provide improvements of about 7 dB and 8 dB respectively. In underground mining applications, the available image quality tends to be degraded due to the combination of poor lighting conditions, dirt on the camera lens and dirt on the label. It can be inferred from the figure that the root mean square tracking error is less than 4 pixels provided that the ratio of the dot intensity variance to the noise intensity variance is greater than -27.5 dB.

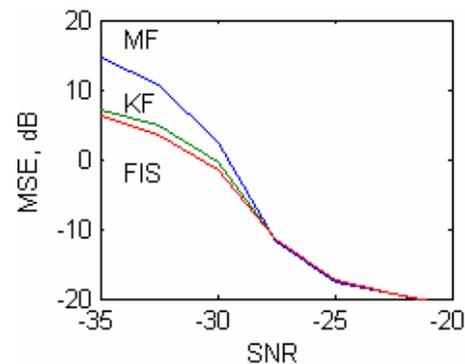


Fig. 15. Mean square error performance versus signal to noise ratio: matched filter (top line), Kalman filter (middle line) and fixed interval smoother (bottom line).

6 Conclusions

Short-range passive tag systems such as *MineCom's eProx* are work well for applications where personnel manually swipe their tags at a reader stationed at a mine entry/exit. However within longwall mines, it is vitally important to have up-to-date information about which districts personnel are travelling in. In particular, it is important to ensure that the number of personnel within a district matches the available safety equipment and facilities in case the mine environment becomes hazardous.

Recently developed UHF passive tag systems such as *TrolleyScan* provide operating ranges of up to 3 - 4 m. The *TrolleyScan* system requires 1 mW to be delivered to the tag. This requires the use of high gain antennas and correctly oriented tags. They require a minimum 1 mW (ie 0 dBm) input signal power level whereas the receiver sensitivity of active tag receivers is typically in the region -80 dBm to -100 dBm. This would suggest that in general active tag systems can offer greater operating ranges than passive tag systems.

LAMPS has been specifically developed for underground longwall mines. The system is different to conventional active tags in four respects. First, the readers support multiple redundant interconnections and so provides robustness to localised failures in mines. Second, the tags report tilt sensor or man-down information. Third, LAMPS is a bi-directional system. For example the underground personnel can receive and acknowledge hazard or evacuation advice. Fourth, the intrinsically safe readers will operate within safety critical production regions. Certificates of conformity for the tags can be viewed at <http://www.mining-automation.com>. Simplified expendable transmit-only tags have also been produced and submitted to *SIMTARS*. The so-called LAMPS tag II draws about 0.037 mA from an internal 3.6 V Lithium battery which has a nominal operational lifetime of approximately 2.5 years. The readers are similarly undergoing IS assessment and support multiple optical fibre connections along 5 km gate roads.

Active tags are reliant on batteries that require periodic maintenance. To address this issue, electromagnetic, electrostatic, thermoelectric, piezoelectric and solar technologies have been reviewed. PV cells are the most mature and can typically deliver 1 mW/cm². This compares with 48 μ W/cm² for a thin-film thermoelectric device. A number of experiments with piezoelectric materials are reported in the literature. At this stage data is scant about the reliability of piezoelectric approaches. The most promising technology is the AA-sized microgenerator developed by the *Centre for Micro and Nano Systems* at the Chinese University of Hong Kong. The microgenerator produces up to 4.4 V peak-to-peak which results in a maximum RMS output power of 680 μ W into a 1500 Ω resistive load.

Underground vehicle tracking could be carried out by using a two-dimensional bar codes and video cameras. For example, the label possessing an array of dots can be painted on the bonnet of mining vehicles. The vehicle identification task can be accomplished via standard pattern recognition approaches. In underground mines the available image quality tends to be degraded due to the combination of poor lighting conditions, dirt on the camera lens and dirt on the label. The results of a simulation study are presented which indicates that the approach can be successful provided that the ratio of the dot intensity variance to the noise intensity variance is greater than -27.5 dB.

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