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Onsite worker monitoring systems using wireless technology

Safety

One form of active prevention is to set up a series of safety barriers. The “ambient intelligence” concept has now been developed to such an extent that intelligent systems can be built up using wireless sensor networks. These systems are then capable of identifying hazards and assessing risks, as well as helping in the adoption of real-time proactive prevention measures. This study involves the design of a real-time decision-making system capable of identifying a risk situation and deciding on the corresponding preventive measure; it can also detect if a worker has suffered an accident and arrange evacuation if so. An analysis has been made of available technologies, setting up a solution that has been implemented in a prototype system. The prototype has then been put through its paces and its effectiveness assessed in a real-life scenario.

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A principle laid down in article 14 of the Spanish Occupational Risks Prevention Act (*Ley de Prevención de Riesgos Laborales*) 31/1995, of 8 November and its subsequent amendments is that «workers are entitled to an efficient health-and-safety-at-work protection. This right presupposes a concomitant duty of employers to protect their workers from occupational risks». This article also states that «employers will keep up a permanent monitoring of the prevention activity in the interests of continually perfecting and fine-tuning all activities of risk-identification, -assessment, -avoidance or, where complete avoidance is impossible, -control. Protection levels should also be continually improved. Employers shall also be in possession of all necessary wherewithal for adapting the prevention measures indicated in the above paragraph to such modifications as may occur in the working circumstances.»

In a continually changing environment such as a construction site this ongoing adaptation to risk situations is no easy task. Article 15 also identifies «keeping abreast of the evolution of technology» as one of the main preventive principles; this ipso facto implies a need for continual innovation to allow employers to phase in such technologies as might improve the occupational risk prevention performance.

This study incorporates information and communication technologies (ICT) into the improvement of prevention systems, defining new technological tools that provide the best accident-control solutions.

The construction sector’s occupational accident rate is the highest in Spain: 8232 accidents per 100,000 registered workers. The Spanish Institute for Occupational Safety and Health (INSHT[1] in Spanish initials), in collaboration with regional authorities, has drawn up a study of the Causes of Occupational Accident Mortality in Spain 2005-2007 (*Análisis de la mortalidad por accidente de trabajo en España 2005-2007*), identifying the following main causes:

- Absence or deficiency of collective fall protection measures.
- Inadequate or non-existent training/information on risks or preventive measures.
- Non use of obligatory personal protection garments laid on by the employing company.
- Non-existent, confusing, contradictory or insufficient instructions.
- Breach of working instructions and procedures.

Any system capable of improving the identification of the wearing of personal protection equipment and the presence of workers in restricted zones, monitoring their situation and state and giving real-time risk information, would represent a significant technical advance, setting up safety barriers in the sector's most accident-prone areas. This system should be set up together with a proper prevention management system, suitable training and induction measures and worker awareness-raising and motivation measures.

One of the main difficulties on any construction site is access control and the concurrence of workers involved in different tasks, all of which have to be coordinated. A system like the one put forward herein would involve the creation of a second supervision loop based on active worker monitoring.

Products providing partial solutions are now cropping up but without offering any across-the-board protection. Besides this piecemeal approach, these solutions are generally of restricted usefulness on building sites because of the technology used: GSM/GPRS combined with GPS technology.

Wireless Technology

One of the project objectives is selection of the best technology for achieving the sought solution. The concept of wireless sensor networks (WSN) involves the creation of a platform of sensors and communication technology for monitoring not only physical or circumstantial magnitudes (events) within a given scenario (in our case the physical space occupied by a construction site) but also decision making.[2].

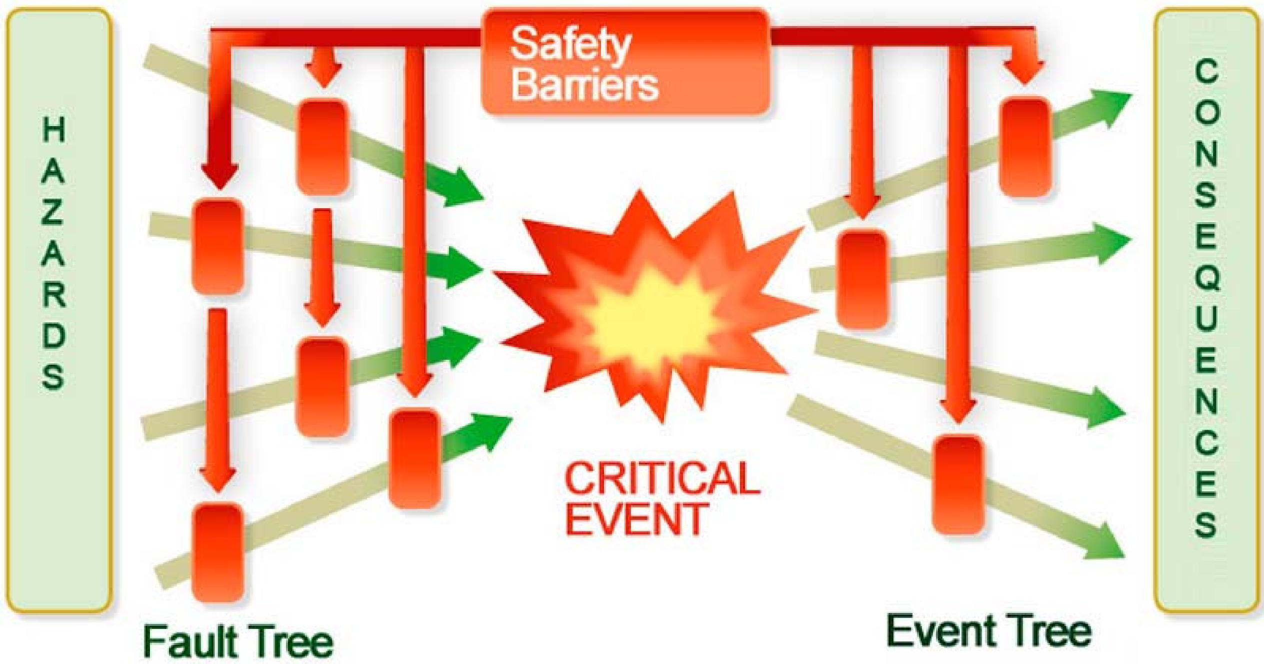
The most suitable communication system in the construction sector (both buildings and civil engineering) is wireless technology. The key reason for the use of this technology is the reduction of installation costs and the possibility of reuse on subsequent building sites, due to the lack of any cabling requirements.

The most widely used wireless modules nowadays tap into the 868 MHz band. Due to the reduced bandwidth thereof, however, there is currently a trend towards wireless systems operating in the unlicensed 2.4 GHz band. The chosen technology belonging to this band has been deemed the most suitable for meeting the needs of this project. This technology includes two short-range solutions like Bluetooth and Zigbee. The latter reaches distances of up to about 500 metres, though there are also some modules that increase this range considerably. Conversely, this is low bandwidth technology (250 Kbps).

Table 1. Comparison of technologies.

Technology	Wi-Fi	WiMAX	Bluetooth	ZigBee
Capacity	54-11 Mbps	70 Mbps	1-10 Mbps	250 kbps
No. of nodes	+100	+1000	8	65000
Autonomy	.5-5 days	Power supply	1-7 days	3-30 months
Range	10-300 m	50 km	1-100 m	100-300 m
Latency	1ms	1ms	14ms	240µs
Security	WEP 802.1x WPA	DES3 AES PKM-EAP		AES-CCM-128
Topology	Point to point	Point to point	Point to point	Point to point
	Point to	Point to	Point to	Star
	multipoint	multipoint	multipoint	Mesh
	Mesh			Tree
Modulation	DSSS and OFDM	OFDM	FHSS	DSSS

For applications needing longer range the technologies GPRS, Wi-Fi and Wi-MAX have been chosen. The idiosyncrasies of each type of construction work (civil engineering – open countryside – or building work – in a built-up area) could call for the setting up of a mixed network using several different technologies, with gateways for passing from one to the other.



Graph 1: A simplified bow-tie representation (Dianous, Fievez, 2006, p. 221; Delvosalle et al., 2006, p. 201).

ZigBee (wireless) technology is the most suitable for building applications, bearing in mind the number of nodes and sensors, autonomy, range and security.

Object and Scope

The ultimate aim of this project is to define an intelligent sensor-based, low-cost, user-friendly system capable of detecting risky situations, taking decisions and therefore favouring a proactive avoidance of occupational accidents.

Before describing the system we first need to give a brief explanation of three underlying principles:

- **Safety barrier concept.** A safety barrier is a damage-control, -limitation or –prevention function [3]. The modern, conceptual accident-prevention models, like MORT[4] (*Management Oversight & Risk Tree*), consider two main types of risk-reduction barriers to protect workers: barriers that prevent the accident from happening and those that mitigate the damage. The barriers are not necessarily physical and might be either logical systems or organisational methods
- **Active prevention.** Active prevention is condition-dependent action. A system based on the active prevention concept takes prevention measures to suit the actual situation being dealt with.
- **Ambient intelligence.** The paradigm of Ambient Intelligence (AmI) is explained in the ISTAG document –(Information Society Technologies Advisory Group), which presents a vision of the future information society, stressing user friendliness, more efficient services support, user empowerment and support for human interactions. People are surrounded by intelligent intuitive interfaces that are embedded in all kinds of objects and an environment that is capable of recognising and responding to the presence of different individuals in a seamless, unobtrusive and often invisible way. The central idea is that technology should be designed for users rather than the other way around[5][6].

The main technological requirements are:

- Unobtrusive hardware: miniaturisation and nanotechnology, smart devices, embedded computers, power supply, sensors, activators …
- Continuous information infrastructure based on landline and mobile web access.
- Networks of dynamic and distributed devices, interoperable devices and bespoke configurable networks, network embedded intelligence.
- Lifelike human interfaces: smart agents, multimodal interfaces, context sensing models.
- Reliability and security: robust and reliable systems, self-checking, self-repairing and self-organising software.

The sensor-based intelligent system defined by this project is therefore an active prevention system involving the implementation of ambient-intelligence type safety barriers. The key to success is the development of user friendly, responsive, interconnected, context-sensitive, transparent and intelligent technologies and systems.

Functionalities and Architecture

Functionalities: ambient-intelligence based design

The system is based on embedded processing power in the various objects of the system, mainly in the wireless elements. In other words the various wireless elements – the static elements (environmental and location sensors), mobile elements (tracking and monitoring of the workers' vital signs) and semi-static elements (tracking and monitoring of machinery operation conditions) – would act as intelligent cooperating objects embedded in an ambient-intelligence system.

The main functionalities to be offered by an ambient-intelligence-based system are:

- **Detection of the site personnel's situation and location.** The capacity of detecting person-related data such as their mobility, location, state (for example, detection that a worker is not moving because he or she has suffered an accident or has fallen, etc.) is one of the new possibilities offered by the system to be developed. This is an activity based wholly on the sensor network's capacity of capturing ambient information. It also allows detection of unauthorised personnel on site or in certain areas.
- **Detection of factors affecting the system.** The sensor network identifies exposure to toxic and hazardous environments, to situations of poor visibility or adverse hydrothermal conditions.
- **Capacity of acting in hazardous circumstances.** The system response may consist of giving out alarms to the safety-coordination resources or to the worker him/herself or the tripping of protection elements (lighting, ventilation, speed limitation or steering guidance of equipment and machinery, etc).
- **Active signage.** The system gives out active and sensible information on the site situation, the surrounding environment, the situation of other workers and their state.
- **Detection of emergency situations.** The installation of different types of onsite sensors enables emergency plans to be activated on the basis of the information obtained.
- **Remote site-monitoring capacity.** Depending on the type of attributes to be controlled on each type of site, it may or may not be necessary to set up remote, real-time monitoring, especially in cases where the working processes to be controlled might trigger emergency situations or when the coordination resources – due to the size or complexity of the site – need remote situation information (tunnels, high-rise buildings, etc).

Basic System Architecture

The basic intelligent infrastructure for setting up the communications network and processing the information comprises the following items:

- **Nodes**
  - **Static facilities.** These will be considered as the main constructive elements of the infrastructure. They will be fitted with wireless sensors capable of picking up information about the surrounding environment, embedded software capable of processing the captured information using intelligent algorithms and communication devices capable of sending on the information to other system items.
  - **Mobile or semi-static elements of each type of site.** These will be similar to the static elements and, depending on their geographical situation, might be fitted with the same sensors as the former. They shall be fitted with embedded software capable of processing the sensor-captured information and also equipment for sending on this information to other system elements, bearing in mind that their location might not always be known beforehand.
  - **Gateway or coordinating node.** This will be considered as the main element for processing the data sent in by the rest of the intelligent system elements. It will be an open source development, able to monitor this information and interact with system elements. The gateway's main function will be site monitoring. It will, however, receive much more information, such as environmental agents, system-affecting factors, etc, plus all safety-related aspects. Finally, the gateway will endow the system with the capacity of two-way communication with the outside.

- **Physical layer.** The communication network links in this system will never need a capacity of more than 100 Kbps. This is because the sensors' data-taking cadence is high in comparison with the sample taking of other applications, where data evolution is very swift. Nonetheless the data in applications of this type are unlikely to undergo any change in a short period of time. The physical layer will have to offer sufficient wireless sensor connectivity to match the nodes forming part of the intelligent structure developed herein. A sufficient wireless communications network, connected up to all system nodes, shall exist for transmission of all processed data.

- **Middleware Layer.** This will comprise connectivity software offering a set of services. These services will facilitate running of the intelligent system's distributed applications on the created platform. It functions as a distributed software abstraction layer and lies between the applications layer and the physical layer. The main task of this layer is to render all the following transparent to the applications layer: the low level details of the hardware, of the operating system and, especially, the data distribution details through a distributed infrastructure. It hence provides a high level programming interface that can be used for external applications or for interaction with other infrastructure. From the complexity and heterogeneity of the communications network developed herein, the Middleware layer abstracts a hybrid wireless network of embedded systems. This will facilitate the possibility of real-time connection/disconnection of nodes to the network.
- **Applications Layer.** The applications layer develops the system's required functionalities. These functionalities, already described above, refer to different active-prevention aspects to be implemented.

Prototype Components

- ***Transreceivers*.** The chosen models, with inbuilt RF modules, are based on the Freescale technology.
- **Sensors.** Some (not all) of the possible sensors have been selected. Likewise, in system implementation, not all sensors are integrated into all the nodes (for example, the nodes linked to the infrastructure where the work is carried out do not include the accelerometer). Nonetheless the sensors considered herein have enabled performance tests to be conducted.
- **Temperature Sensor.** A low-consumption sensor with a two-line digital communication interface has been chosen. This device can operate in a temperature range of -40 ºC to 125 ºC, with a resolution of 0.05 ºC.
- **Accelerometer.** A digital output 3-axis linear accelerometer has been chosen, incorporating a sensor and digital interface capable of giving information on the sensor and providing an external signal of the acceleration reading through a serial interface. The device can be set to generate an inertial wake-up/free-fall interrupt signal when a programmable acceleration threshold is crossed in any of the three axes.
- **Luminosity sensor.** A low consumption sensor with digital interface has been chosen. The device transforms the luminescence (ambient light readings in lux) into a digital output signal accessible by means of the I2C bus.

Development of node prototypes

Two types of hardware-referenced nodes have been developed: static coordinating nodes and mobile nodes. The main difference between both is that the mobile node has a three-axis accelerometer. The basic structure of the first type of node consists of:

- *Transreceiver.*
- Temperature sensor.
- Accelerometer (mobile node).

For the second node version a transreceiver with external antenna was chosen, giving a higher working range and allowing the final node size to be slightly larger. A luminosity sensor was built into this node.

Figure 1. First prototype. Static and mobile nodes. **Figure 2.** Second node prototype.

Prototype tests and results

Design of testing scenario

In this chapter we aim to demonstrate the feasibility of the selected active worker-monitoring technology (IEEE 802.15.4 and Zigbee). The chosen scenario was simplified to allow the test to be carried out in the framework of this project and also in view of time- and budget-limitations.

In the proposed scenario we will assess the system's capacity to identify a worker's position, using an accelerometer to check the subject's activity and any changes in his or her state. The system consists of mobile nodes (workers) and static nodes (construction site). The static nodes have a dual function: give coverage to the infrastructure and serve as a reference for ascertaining the position of the mobile nodes. Furthermore, there is a central or coordinating node, which culls information and sends it on to the management computer (figure 3).

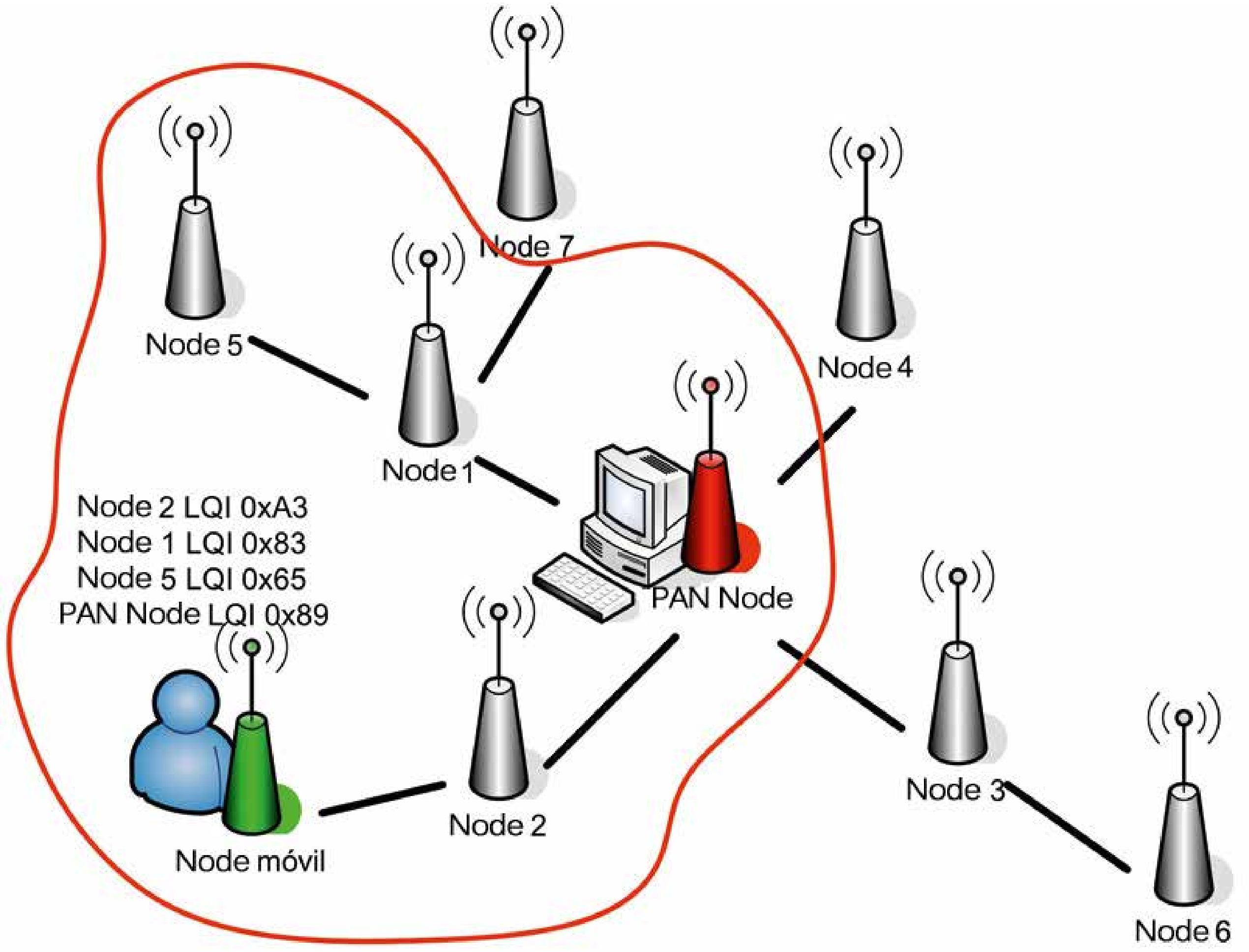


Figure 3. Network Architecture.

The coordinating node, shown in red in the diagram, is connected up to a central server. There is also a node infrastructure deployed throughout the site (for example, nodes fitted in the luminous signage) to increase the coverage zone. These will serve to locate the worker (given that the position of the infrastructure is known, we can compute by triangulation the worker's position using the Link Quality Indicator or LQI, whose reading shows the distance between devices and hence the relative location according to signal intensity).

To conduct the tests in the scenario, various nodes had to be manufactured:

- **Reference Node.** This node has a fixed and known position. It is configured with X and Y coordinates corresponding to its location. It single task is to await a Broadcast message (i.e., to all of them) with the LQI reading and then send it on to the coordinating node. The reference nodes communicate with the sensor nodes and with the coordinating node of our network.
- **Mobile Node.** This node will send out a Broadcast message whenever it needs to ascertain its network position. It is also fitted with an accelerometer to monitor the worker's situation and movements.
- **Coordinating node.** This node receives the messages from the sensor nodes and stores them in an LQI readings table for each sensor node. Once the address of the reference node is known, it will access a table where the corresponding fixed address of this device is stored. Working from these input parameters it will then estimate the location of the

device by means of the localisation algorithm. Once this position has been obtained it will be sent on to the coordinating node.

Network functioning

The implemented system was assessed by means of the following tests:

- Network functioning tests, e.g., acknowledgements, relays, Multicast messages, network self-organisation, etc.
- Worker tracking tests (mobile node).
- Worker event monitoring tests (mobile node): worker activity level, falls, etc.

The key to success lies in the development of user friendly, responsive, interconnected, context-sensitive, transparent and intelligent technologies and systems

A programme has been designed to manage the sending and receiving of messages between the radio modules issued to each system member. This message management will be geared towards providing the coordinating equipment or node with the necessary real-time information to give it an overview of the location and state of the mobile node (worker).

- **Coordinating Node.** This node starts with an energy detection scan to choose the best channel for starting the Personal Area Network (PAN). Once the network has been started, the coordinator switches to reception mode to await association requests from other nodes and network node data. The coordinator controls the network nodes by tripping a meter. When the meter has finished counting, it checks the nodes from which it has received information messages. A missed-message meter will then be started for all nodes from which no information has been received. Any node for which three successive missed messages are detected will be assumed to have lost connection and will then be removed from the list of network nodes.
- **Sensor Node.** Sensor nodes are considered to be all those other than the coordinating node and mobile node, as distributed around the scenario covering the range of the latter.
  Sensor nodes are continually in a message waiting loop. These messages may be of two types: Broadcast messages and messages relayed from other nodes. We will look first at how the former are managed. The sensor node receives a Broadcast message from the mobile node; from the data packet in that message it obtains the LQI reading between both.
  The rest of the messages received by the sensor mode will be Unicast. If the message received comes from another sensor node, it will contain the LQI readings of the node it comes from and of the corresponding nodes associated therewith. The only thing it will do with such a message, therefore, is add the LQI reading of the sensor node and send it on to the node it is associated with until it reaches the coordinating node. The sensor node also sends information on ambient temperature and the light level of its corresponding area.
- **Mobile node.** The application designed for the mobile node limits itself to sending the information obtained from the sensors and sending a Broadcast message so that the other nodes can obtain the LQI reading of the respective links. The abovementioned algorithms are implemented for information processing purposes.
  A 3-axis accelerometer has been used to find out the state of the mobile node. The worker information provided will be threefold: the temperature, whether or not the worker is breathing (by processing the accelerometer information) and if he or she has suffered a freefall. This will give rise in turn to three different worker states: ACTIVE, ALARM (sudden movement) and EMERGENCY (no movement at all).

Network functioning tests

The implementation tests involved final system tests and then successive tests during the development period. A description is now given of the tests carried out during system implementation:

- **Association with a network device.**To check a final device's capacity of linking with a PAN, the test consisted of the coordinator initiating a PAN upon start-up. When the final device starts up and one of the board buttons is pressed, it will automatically scan the frequency channels in search of a network and associate with it. The final device seeking network association chooses one of the PAN coordinators that have been found during the scan.
- **Data sending and reception.** To check the capacity of sending messages from one device to another, the addresses assigned to each device are stored and then used for sending a message from one device to another. The receiver will remain in data reception mode while it is not busy.
- **Range.** The prototype node boards offer a range of about 800 metres in direct vision; in indoor spaces this is cut down to 200 metres.

- **Node control and acknowledgement.** To control network nodes each device has a table of associated nodes (child nodes). To monitor permanence it will receive a message from each child node every set period of time. For its part each child node will have to check that it has received acknowledgement of messages sent to the coordinating node. Missed messages are relayed and a check is kept on the number of relay attempts; if these exceed a set limit the device will reset and try to associate with the network again, either with the former coordinating node or a new one within its range. The system thus resets in the event of losing any network node.

Localisation of mobile nodes

The localisation algorithm used is based on the LQI (Link Quality Indicator), whose reading varies inversely with the distance between the devices. Various types of localisation algorithms have been developed.

One of them, used in the first network prototypes, was based on the sending of a Broadcast message. The other algorithm used is based on carrying out a scan to find the nodes neighbouring the mobile node, thus cutting down message traffic, limiting itself to sending on the reading of the nearest nodes. Both algorithms are based ultimately on the quality reading of the inter-node link. Good localisation therefore depends on knowing the position of the various static nodes.

The coordinating node receives all the messages from the static nodes and sends them on through the information packets using the PC interface. According to these readings an estimation will be made of the location of the mobile node (worker).

The LQI readings are obtained by the scanning operation carried out by each node each set interval of time. The result of the scanning is a series of neighbouring static nodes identified by the node's dual MAC address and the LQI reading. The mobile node sends a message with the LQI readings of each neighbouring node to the network coordinator. The mobile node therefore sends to the coordinator only the LQI readings of the nearest nodes, thus cutting down message traffic. If a node's LQI reading is not sent, this is because the node is sufficiently distant to be outside the mobile node's scanning range.

It may so happen, however, that, remaining in the same place, a mobile node does not scan all nearby nodes. This is because the mobile node remains in scanning mode a set interval of time and not all the nodes may respond to the initial scan. For this reason the best way of managing mobile node tracking in the control gateway connected to the coordinating node is by averaging out all the LQI readings of each static node every few seconds, when several node-related LQI readings have been taken.

The test results are not sufficiently precise (by about one or two metres) when using only the LQI, so an algorithm will have to be developed in the future using also the wave propagation time, which is insensitive to obstacles. The obtained precision allows the worker zone to be demarcated (inside the static nodes corresponding to their location) but not his or her position within this zone. This is due to the fact that the LQI reading might deteriorate depending on the presence of obstacles.

Worker Monitoring

The mobile node will have to be fitted with an accelerometer to provide readings of vital signs and/or falls.

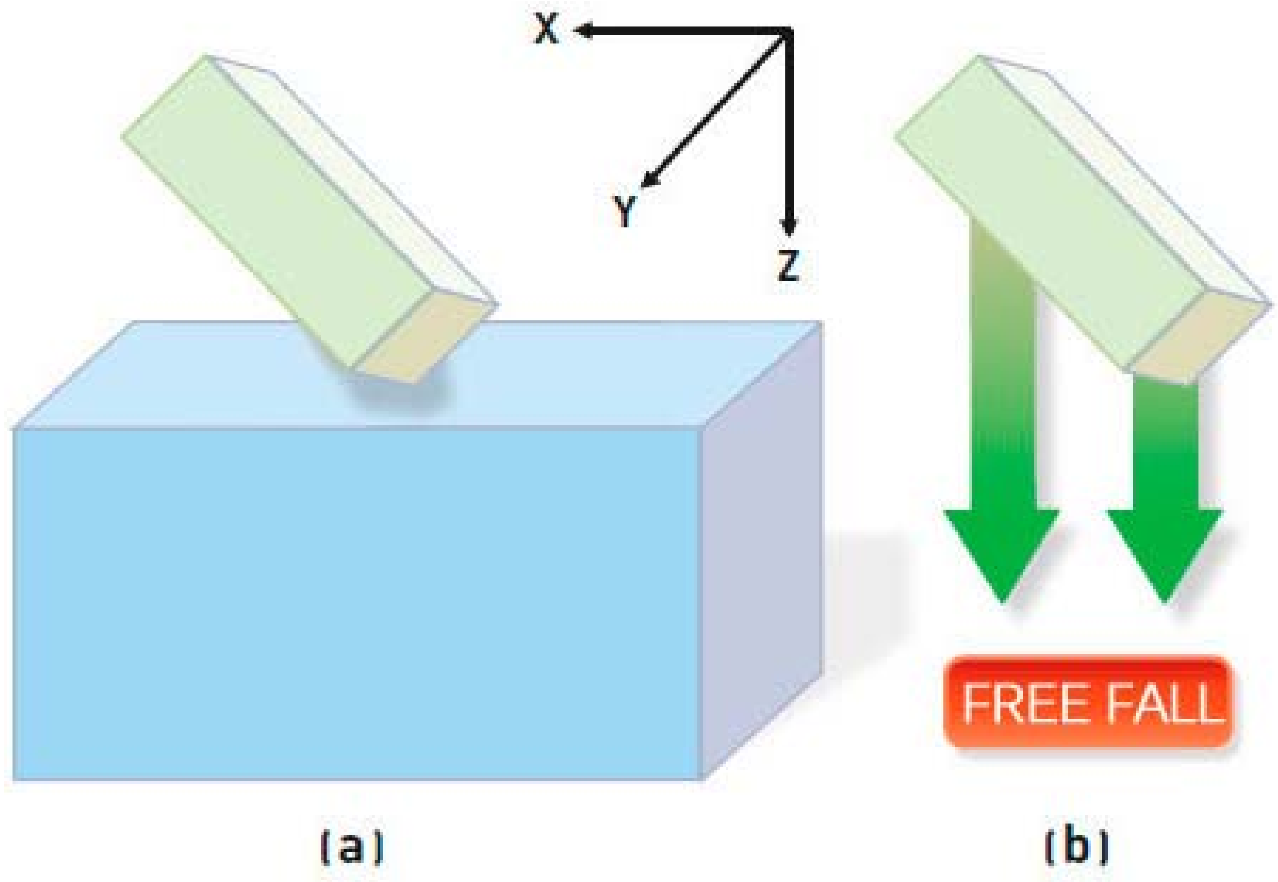


Figure 4. Freefall Model.

Detection of free fall. Take the case of a node with an arbitrary orientation (figure 4). Its axes form the angles α with respect to the x axis; β with respect to the y axis; and γ with respect to the z axis. On this basis the accelerometer outputs are:

$$X_{OUT} = X_{OFFSET} + \left(\frac{\Delta V}{\Delta g} \cdot 1g \cdot sen\alpha\right)$$

$$Y_{OUT} = Y_{OFFSET} + \left(\frac{\Delta V}{\Delta g} \cdot 1g \cdot sen\beta\right)$$

$$Z_{OUT} = Z_{OFFSET} + \left(\frac{\Delta V}{\Delta g} \cdot 1g \cdot sen\gamma\right)$$

where:

VOUT = Accelerometer output in volts

VOFFSET = Offset reading at 0 g of the accelerometer

ΔV/Δg = Accelerometer sensitivity

1 g = Earth's gravity

When the object falls, the acceleration reading in all three axes is zero, regardless of the object orientation, because no acceleration will be detected in any axis. This is so, as already explained, because the accelerometers fall with the same acceleration as that exerted by the force of gravity.

The free-fall detection algorithm samples the accelerometer readings and supervises these acceleration rates. Depending on the orientation, each accelerometer will have an acceleration range between 1 g (when the accelerometer axis lies parallel to the gravitational force) and 0 g (when the axis lies perpendicular to the gravitational force). The S-factor is a way of considering the total acceleration acting on the device at a given moment of time.

$$S - factor = \sqrt{X^2 + Y^2 + Z^2} \leq umbral$$

During freefall the three axes will all detect 0 g. As the S-factor is defined by the total acceleration in all three axes and these accelerations all equal 0, the S-factor will also equal 0. Election of the threshold value will depend on the system response times, the precision of the A/D converter and the characteristics of the accelerometers, such as sensitivity, offset, variation with temperature and the number of samples taken and type of algorithm. This threshold has been determined experimentally as lying between 1 and 100 ms (figure 5).

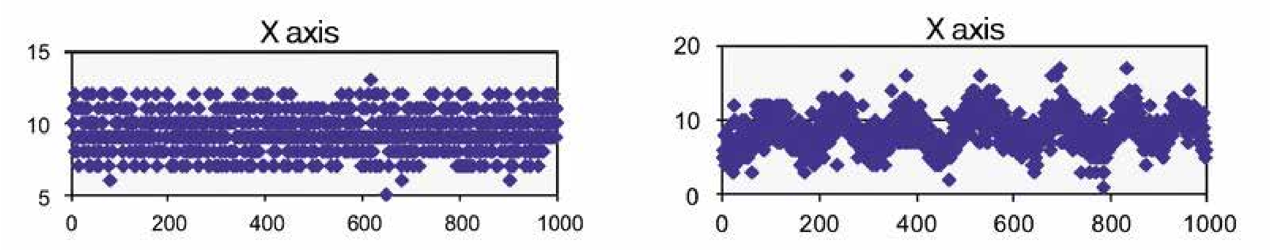


Figure 5. Accelerometer response differences (the righthand graph shows the readings when worn by the worker).

Detection of worker's vital signs

Certain accelerometer readings tell us whether the worker presents any signs of activity, triggering an alarm if not.

The oscillation frequency is low so the sample acquisition time was set at 40 ms and at least 200 samples will be necessary to obtain a signal period. Accordingly, the time needed for diagnosing the user state is 8 seconds. The threshold choice is crucial because there might be time when the worker is at absolute rest, tripping a false alarm for lack of vital signs. The results obtained are sufficiently robust despite the accelerometer's low sensitivity and the A/D converter's quantization noise.

Conclusions and future developments

The results of the experiments show that it is possible to design an active accident-prevention system from a wireless sensor network organised under a scheme of ambient intelligence.

Some functions such a fall detection or the monitoring of vital signs are clearly possible, while others, like tracking, need some fine tuning. In a construction-site-sized scenario direct communication between all nodes is possible, using the natural coverage extension provided by IEEE 802.15.4 technology. Even so, a network has been designed that resets itself in the event of communication losses, duly notifying the user of this.

With the current state of technology this system is feasible and affordable, especially in view of the fact that it can be reused from one site to another. The solution proposed herein does not currently exist on the market, so this study represents a starting point for its pre-competitive development. These future developments could enlarge the basic architecture as tested here and graft on systems based on IP camera vision, risk zone access control with RFID or the identification not only of personnel but also of their equipment and machinery.

> *It is possible to design an active accident-prevention system from a wireless sensor network under the aegis of artificial intelligence*

As for the mobile node (worker) tracking system, it has not proven possible to implement the required algorithm. The aim was to monitor the approximate node coordinates in the scenario, finding out the dimensions of the latter with a triangulation algorithm with LQI readings of the sensor nodes, but these readings largely depend on node orientation. The system therefore estimates only the worker's current zone but not his or her actual position therein with submetre precision. A possible improvement here might be to increase the number of the infrastructure's static nodes (boosting system redundancy) or tag on other calculation algorithm parameters (such as wave propagation delay). Be that as it may, the first results are very promising.

As for worker monitoring, the results are acceptable in spite of low accelerometer sensitivity and A/D converter resolution. Satisfactory results have been obtained in terms of worker state patterns. Customising the hardware from here and using the peripherals best adapted to the application concerned would ensure a reliable system with significantly improved results.

ACKNOWLEDGEMENTS

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TO FIND OUT MORE

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