A WSN System Powered by Vibrations to Improve Safety of Machinery with Trailer

D. Dondi, G. Napoletano, A. Bertacchini, L. Larcher
Department of Science and Methods for Engineering
Università degli Studi di Modena e Reggio Emilia
Reggio Emilia, Italy
denis.dondi@unimore.it

P. Pavan
Department of Information Technology Engineering
Università degli Studi di Modena e Reggio Emilia
Modena, Italy

Abstract*—In this paper we present an energetically autonomous wireless sensor system designed to enhance safety in industrial machinery comprising a main vehicle with an attached trailer. The proposed system establishes a wireless link between the vehicle ECU and our sensors to provide motion dynamic data of trailer to the vehicle stability control algorithm. The wireless sensor devices we implemented comprise a 3-axial accelerometer and a 3-axial magnetometer to detect the trailer operating conditions. Such motion data are elaborated using an ultra-low power MCU, which communicates to vehicle' ECU using an IEEE 802.15.4 channel at 2.4GHz. To enable perpetual operation of the system, we developed a vibrational energy harvesting system, VIBester, capable to gather kinetic energy from trailer natural vibrations and convert such energy in electrical energy for the system power supply. The vibrational energy harvester adopts a piezoelectric (PZT) transducer to convert the kinetic energy and a custom AC/DC converter to supply the wireless sensor device.

I. Introduction

In the last decades a large amount of electronic control unit (ECU) has been introduced in the industrial vehicle market. For instance, considering the cars market lots of effort have been spent to adopt ECU capable to increase both passive and active passenger' safety. The same solution is highly desirable for off-highway vehicles and industrial machinery [1]; where few safety systems have been introduced in the recent years, and several injuries occur due to driver carelessness.

Considering the industrial or agricultural environment, most of the safety systems focus on passive protection, e.g. roll-bars, seat belt or seat pressure sensors, while active safety system preventing accidents are still not widespread enough. As an example, several worker injuries statistics report that in the United States there is an average of 100 fatalities per year just only in the agricultural environment [2]-[3]. These casualties suggest that there is a huge need for active safety enhancement systems in this field.

Since 80's very few active safety enhancing systems have been concretely integrated into commercial machinery, and most of them are limited to vehicle orientation and inclination monitoring. Some of these systems adopt accelerometers and gyroscopes to gather the information about machinery dynamic working condition, allowing a more accurate reaction with shorter response time. The main limitation of such systems is that they usually focus on the main vehicle, collecting few to no information about any connected; thus, limiting the reliability and effectiveness of the whole machinery dynamic control system.

In this paper we propose a complete wireless sensor system that monitors the presence and the dynamic of a trailer to inform and adjust the vehicle stability control algorithm. The system comprises of two devices: the Wireless Master Device (WMD) that is installed on the main vehicle, and the Wireless End Device (WED), which is installed on the trailer. The WMD acts as access point for the wireless communication with the WED, and interacts with vehicle ECU to indicate that a trailer is connected and its utilization may become dangerous. Moreover, the WMD executes the mathematical model required to detect if a hazardous working condition occurs, and informs the vehicle ECU to warn the driver.

On the other hand, the WED is designed to be installed on a trailer, where there may not be electrical connection to the main vehicle, and power supply may not be available. For this reason, we developed a vibrational energy harvester, VIBester, which converts the kinetic energy of natural vibrations occurring on the trailer into electrical energy for supply the ultra-low power wireless device. In the proposed case study of an agricultural baler, the harvester gathers energy from a 112Hz vibration and provides about 850µW with vibration strength of 1g. Finally, we optimized WED power budget requirements implementing a task manager that leverages system activity to match the available supply power.

The rest of the paper is organized as follows. Section II describes the system architecture, focusing on both hardware and software. Section III reports the experimental results showing dangerous working condition recognition, energy harvesting capability and power consumption optimization. Section IV concludes the paper with results discussion.

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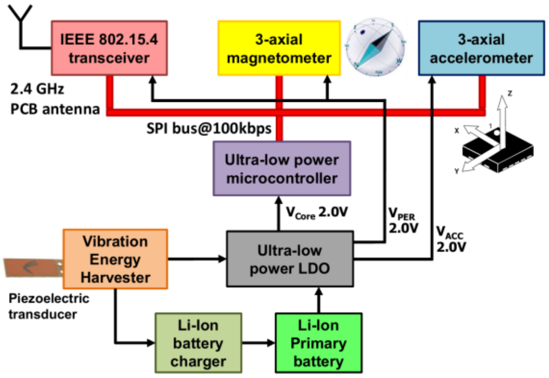

Figure 1. Architecture of the WED device of the wireless sensor system for autonomous vehicle motion tracking.

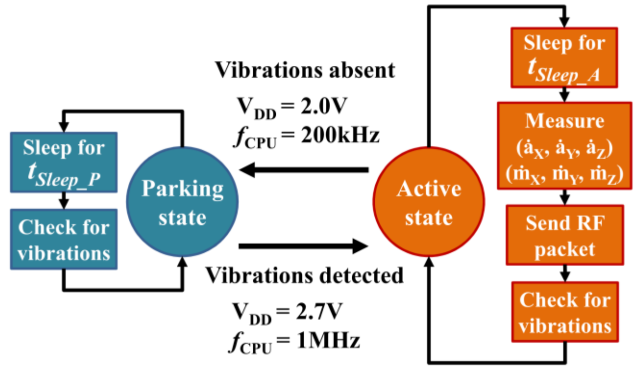

Figure 2. Task management algorithm developed for active/parking power consumption optimization.

II. System Architecture

Proposed system architecture comprises two independent devices: the Wireless Master Device (WMD) and the Wireless End Device (WED). The two wireless devices differ from set of task and the power supply stage. The WMD is powered through the vehicle supply line, while the WED embeds a vibrational energy harvester, VIBester, that integrates the energy provided by a back-up battery. Moreover, since the WMD has no limitation on power consumption, it is the device demanded for the run-time mathematical computation providing the dangerous working condition detection.

A. WSN Device Hardware Implementation

WMD and WED devices adopt the same combination of microcontroller (μC), wireless transceiver and MEMS motion sensors. Fig. 1 shows the block diagram of the WED circuit architecture. The microcontroller adopted for the design is the MSP430 [4], which embeds 4kB of SRAM and 32kB of Flash memory, and consumes ≈250μA when running at 1MHz, and ≈500nA in sleep mode. The μC of the WED device operates at two possible frequencies: 1MHz when executing mathematical formulae calculation, or 200kHz while performing low priority tasks, allowing lower power consumption. On the other side, the μC of the WMD device always runs at 16MHz, which maximizes the calculation throughput. The wireless transceiver is the 2.4GHz CC2500 from Texas Instruments [5], which provides IEEE 802.15.4 standard communication at very ultra-low power consumption.

The motion detection is based on the LSM303DLHC MEMS sensor from STMicroelectronics [6], which integrates a 3-axial accelerometer with a 3-axial magnetometer, and I^2C digital interface. This sensor measures: 3D linear acceleration with full-scale up to ±16g, ±1mg/LSB sensitivity and sampling frequency up to 5kHz in low-power/low-resolution mode; and 3D magnetic field with full-scale up to ±8.1gauss, 2mgauss resolution and sampling frequency up to 220Hz. The LSM303DLHC has very good ultra-low power capability; the current consumption in normal mode is 110μA, while putting the device in power down mode cuts its current consumption down to ≈1μA.

The most important circuit block of the WED device is the power supply section, which integrates an ultra-low power LDO, a Li-Ion battery charger, and the VIBester. The LDO includes a digital line that allows the μC dynamically changing the regulated supply voltage from 2.7V (default) to 2.0V (used to save power when the frequency drops down to 200kHz). The Li-Ion battery charger is a ultra-low power with as low as 550nA operating current, and a power down leakage current of less than 100pA. The vibrational energy harvester is directly connected to both system LDO and Li-Ion battery charger, as shown in Fig. 1. The energy harvesting chip collects the AC voltage from the custom PZT transducer to generate a regulated 3.3V supply for the LDO. The exceeding energy that is not consumed by the WED is delivered to the Li-Ion battery charger for battery replenishment. In this way the energy harvesting module can maximize the utilization of the available kinetic energy.

B. System Task Manager

It is known that adoption of ultra-low power architecture cannot intrinsically provide an outstanding ultra-low power behavior if not properly arranged with a task manager [7]-[8]. In the embedded systems field, a task manager acts as μC and hardware supervisor, leveraging block's power consumption as function of both performance requirements and available energy budget.

In the proposed wireless sensor system the WED has very strict constraints on the power consumption, because its energy budget arises from the VIBester. To this end, we developed a task manager that modulates the WED working condition with respect to the environmental context. The context recognition feature is exploited using the 3D accelerometer data reading. The accelerometer measures if there is a vibration applied to the trailer structure, which allows detecting if the trailer is on duty or parked in the shed. This trailer context acts as trigger for the two defined working states: active state and parking state, as shown in Fig. 2. The active state refers to when the trailer is on duty, and the WED has to measure both acceleration and magnetic data to detect if a dangerous condition may occur. On the other hand, the parking state refers to when the trailer is parked in a shed, and the WED needs to check only the presence of vibrations.

The proposed task manager implements a DVFS (dynamic voltage and frequency scaling) algorithm that adjusts the μC performance as function of the working state. In particular, when the WED is in parking state, the task manager reduces power consumption by dropping down both the supply voltage to 2.0V and the µC frequency to 200kHz. When the WED runs in active state, it needs to perform complex mathematical computation to detect dangerous working condition; thus, the task manager sets the supply voltage to 2.7V and the µC frequency to 1MHz.

The mathematical model implemented on the WED' MSP430 uses the 3D accelerometer reads to compute the roll, ϕ_T, and pitch, θ_T, angles of the trailer. These two angles are used to track if the trailer is drifting into a dangerous working condition. In such case, the WED increases the task execution frequency by reducing the active state sleeping time, t_{SLEEP_A}. At the same time, the WED transmits the 3D accelerometer, ($\dot{a}_{XT}$, $\dot{a}_{YT}$, $\dot{a}_{ZT}$), and the 3D magnetometer, ($\dot{m}_{XT}$, $\dot{m}_{YT}$, $\dot{m}_{ZT}$), reads to the WMD.

Similarly, the WMD uses its own 3D accelerometer and 3D magnetometer data to compute the roll, ϕ_V, pitch, θ_V, and yaw, ψ_V, angles of the vehicle. Moreover, combining WED's accelerometer and magnetometer data, the WMD compute the trailer yaw, ψ_T, angle w.r.t. geomagnetic north, and the relative yaw, ψ_R, angle between main vehicle and trailer. The six angles allow the vehicle stability control algorithm recognizing if there is a dangerous working condition, as well as if the dangerous working condition is approaching.

Moreover, to further reduce the overall power consumption the task manger can adjust the period between task execution, which correspond to modulating the average power consumption. This is exploited by changing the sleeping time duration of both parking and active states, t_{SLEEP_P} and t_{SLEEP_A} respectively. Obviously, the modulation of the sleeping time can be done coherently with the presence of a safe working condition.

III. Experimental Results

The proposed wireless sensor system has been built and tested to verify its capability to both detect dangerous working conditions and being able to gather energy from system natural vibrations. In the next subsections we will describe the mathematical algorithm used to detect dangerous working conditions, which runs on both WED and WMD devices. Then, we will show the measurements of the amount of power the harvester can provide to supply the WED. Finally, we will discuss the power consumption optimization introduced by the adoption of the task manager

A. Dangerous Working Condition Detection

The mathematical algorithm developed for our sensor system is derived from [9], [10] and [11], and is divided into two main blocks: one running on the WED and one running on the WMD. The algorithm running on the WED detects if the trailer is operating in a critical condition, in particular it detects the instantaneous roll and pitch angles and the strength of the accelerations the trailer undergoes. These information are used by the task manager to increase the amount of sensor observations if the working condition become critical.

Fig. 3 shows the representation of both NED (North, East, Down) coordinates [12], and angle definitions on the vehicle plus trailer combination. The first step in the calculation of the instantaneous working condition consists of converting the sensor reading in the NED (North, East, Down) geographical coordinate system. Then, WED' mathematical algorithm computes roll, ϕ_T, and pitch, θ_T, angles using the following set of equations:

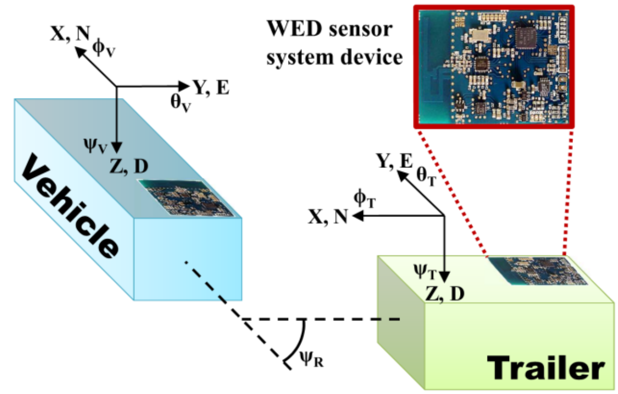

Figure 3. Definition of both NED coordinates and representetive angles on the main vehicle and on the trailer.

$$\begin{cases} \phi_T = \arctan.2(\dot{a}_{YT}, \dot{a}_{ZT}) \\ \theta_T = \arctan\left(\dfrac{-\dot{a}_{XT}}{\dot{a}_{YT}\sin(\phi_T) + \dot{a}_{ZT}\cos(\phi_T)}\right) \end{cases} \quad (1)$$

where $\dot{a}_{XT}$, $\dot{a}_{YT}$, $\dot{a}_{ZT}$ are the acceleration components measured with the accelerometer installed on the trailer. The trailer yaw angle, ψ_T, calculation is more time consuming for the µC. Moreover, since the system needs to calculate also the relative yaw, ψ_R, angle all yaw angles calculations are demanded to the WMD device. Indeed, on the WMD device the mathematical algorithm consists of both the same set of equations as in eqn. (1), but referring to the vehicle, plus the computation of vehicle' yaw, ψ_V, angle as expressed in (2).

$$\begin{aligned} \psi_V = \arctan.2(&\dot{m}_{ZV}\sin(\phi_V) - \dot{m}_{YV}\cos(\phi_V), \\ &\dot{m}_{XV}\cos(\theta_V) + \dot{m}_{YV}\sin(\phi_V)\sin(\theta_V) \\ &+ \dot{m}_{ZV}\sin(\phi_V)\cos(\theta_V)) \end{aligned} \quad (2)$$

where $\dot{m}_{XV}$, $\dot{m}_{YV}$, $\dot{m}_{ZV}$ are the magnetic field components measured with the magnetometer installed on the vehicle. Similarly, using eqn. (2) and selecting the magnetic field components measured on the trailer, the WMD calculates the trailer yaw, ψ_T, angle. Last step is the calculation of the relative yaw, ψ_R, angle that indicates if the whole vehicle with trailer is operating in a dangerous working condition.

$$\psi_R = \begin{cases} \psi_V - \psi_T & if\, |\psi_R| \le 180 \\ \psi_V - \psi_T - 2\pi & if\, \psi_R < -180 \\ \psi_V - \psi_T + 2\pi & if\, \psi_R > 180 \end{cases} \quad (3)$$

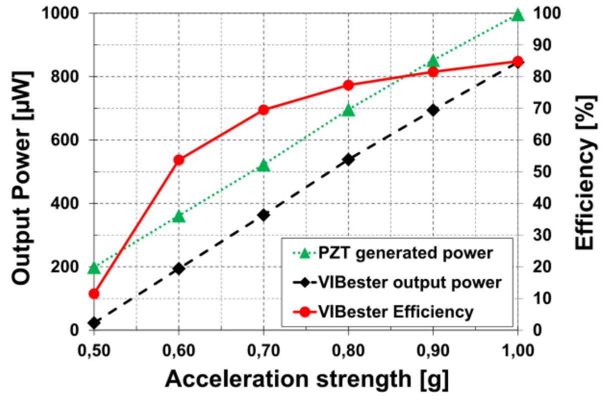

Figure 4. Vibrational energy harvester measurements of both available output power and conversion efficiency for different vibration strenghts.

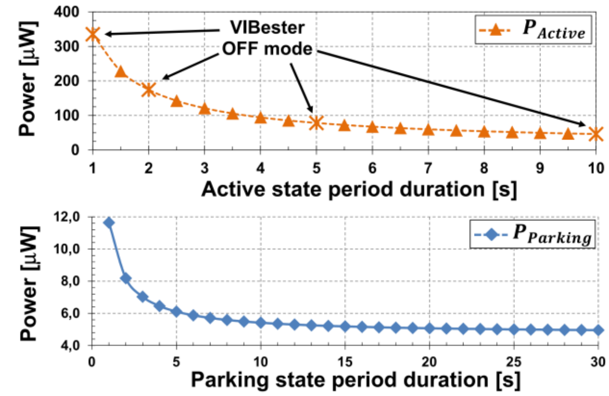

Figure 5. Per period wireless end device power consumption managed by proposed task manager when running in both active and parking states.

B. *Vibrational Energy Harvester Characterization*

After verifying the capability of the wireless sensor system to detect the occurrence of dangerous working conditions, we focused on verifying the amount of kinetic energy the system can harvest. In particular, the developed VIBester and the custom PZT cantilever tuned to resonate at 112Hz vibrations were characterized for the set vibration strengths available on the target trailer. Fig. 4 shows the experimental results of both the available output power generated by the PZT transducer and the available output power regulated by the VIBester to supply a 3.3V system, and the measured efficiency. As shown in the measurement results, with vibrations strength ranging from 0.5g to 1g the VIBester can generate from 23µW to 845µW, which can widely sustain WED activity. Moreover, the VIBester efficiency ranges from 70% to 86% when the vibration strength is from 0.7g to 1.0g. While for vibration strength below 0.7g the amount of power generated by the PZT transducer is mostly consumed to enable the VIBester circuitry, and thus both the available output power and efficiency drop.

C. *System Power Consumption Optimization*

Finally, we measured the WED power consumption for the two operational modes, active and parking, and for different running conditions imposed by the task manager. In particular, focusing on the active mode, where the WED µC runs the left-hand side of task graph in Fig. 2, the power consumption is mostly dependent on the sleeping time occurring between two consecutive executions of the task graph. The duration of the sleeping time is function of both vehicle working condition and amount of energy gathered from the VIBester. Indeed, to optimize the power consumption of the WED operating in the active state, we defined two sets of sleeping time intervals where the task manager can select the more appropriate one. In particular, the VIBester has a digital line that informs the µC if the energy harvesting feature is enabled. Based on such information, the proposed task manager changes the discretization in the sleeping time interval steps. When the WED, operating in active mode and the VIBester is gathering energy the steps are 1 second wide. On the other hand, when the VIBester harvesting feature is low or zero, the task manager can select only 1, 2, 5 or 10 second wide time steps, which gives more granularities to the instantaneous system power consumption.

IV. CONCLUSIONS

In this paper we presented a fully autonomous WSN system capable to detect dangerous working conditions for vehicle operating with a connected trailer, and improve the pre-crash safety system. The proposed system, based on two independent wireless devices, exploits the dangerous working condition detection using the two inertial sensors, integrating a 3D accelerometer and a 3D magnetometer, installed on both WMD and WED. Moreover, to eliminate the need for battery replacement on the WED device, we developed a vibrational energy harvester, called VIBester, capable to gather up to 845µW with 86% of maximum efficiency. Finally, the combination of the VIBester with a smart task manager allows the WED to efficiently operate in each working scenario.

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