Design and Implementation of a Heterogeneous, Power Efficient Wireless Sensor Network for Smart Toys

Fiona Edwards Murphy
Department of Electrical and Electronic Engineering,
University College Cork,
Ireland.
f.edwardsmurphy@umail.ucc.ie

Michele Magno
Integrated Systems Laboratory,
ETH Zurich,
Switzerland.
magnom@iis.ee.ethz.ch

Emanuel Popovici
Department of Electrical and Electronic Engineering,
University College Cork,
Ireland.
e.popovici@ucc.ie

***Abstract*— Toys play a vitally important role in the lives of children, with critical roles relating to social development, education and entertainment. In this paper, a platform for interactive toys using ultra low power Wireless Sensor Network (WSN) technologies is proposed and developed. These are implemented through the integration of WSN technology into a number of off the shelf micro-robotic toys. The heterogeneous network devices react together, controlled by an external environmental interface realized through the addition of a wireless microphone node acting as a network coordinator. This creates an engaging, interactive concert scenario which responds to music with synchronized dancing and light displays. The proposed WSN interface improves the versatility and application range of intelligent toys at a very low cost and low power overhead. This work represents a first step in the development of intelligent interfaces for enhanced interaction with toys for children. Experimental results show the low power features of the solution and the possibility of providing long lasting real world application scenarios, including potential application of an ultra-low power wake up radio.**

Keywords—Intelligent Environments; Low Power; Smart Toys; Wireless Sensor Networks; Smart Homes;

I. Introduction

Recent technological advances have led to embedded sensing, computing and communication devices becoming integral to daily life; Wireless Sensor Networks (WSN) has been recognized as a key technology for developing ubiquitous platforms. WSN have applications in nearly every aspect of life, including smart homes, security, and personal healthcare, this versatility has greatly increased its popularity in industrial and academic research [1]- [3].

A WSN is comprised of several nodes that integrate communication, sensors/actuators and power management in order to coordinate activities. These devices are generally battery powered; energy is the node's most precious resource. Low power design, power efficiency and power aware devices extend the lifetime of each node and the network [4]. Throughout history it can be seen that the latest technological advances are often reflected in toy design, to provide the most effective development, learning or entertainment activity possible. Novel hi-tech toys are influencing e-entertainment, learning, development and rehabilitation/health [5]. The combination of High-tech robots and WSN provides sensors and distributed intelligence systems, which will significantly increase the interaction options available for children.

This paper aims to improve the accessibility of and interaction experience with toys using the latest emerging wireless sensors, sensor interfaces, novel collaborative signal processing algorithms, and low power networking hardware and protocols [6], [7]. Heterogeneous WSN will allow novel intelligent interfaces which are non-intrusive, usable, natural, effective and empowering for children. The final solution will be highly interactive and personalized and will be an effective toy for everyday use, as well as having applications in the area of therapy for children with developmental or cognitive impairments.

This paper gives a system view combining ultra-low power processing and communication features of WSN's in order to create a versatile, scalable, infrastructure for wireless, interactive, collaborative toys. These toys are deployed together with a custom built low cost wireless sound detection and light system to create an interactive concert scenario.

The system is provides both physical and visual feedback to music in the form of synchronized dancing and light displays. This paper is organized as follows: Section 2 describes recent related work in the area. Section 3 presents the system architecture of WSN and the developed nodes. Section 4 details the proposed approach and the network architecture. Section 5 shows the implemented approach; section 6 outlines some of the measurements, evaluation, and validation undertaken.

II. Related Work

Research in the area of WSN applications has been prolific in recent years; with a variety of techniques investigated to overcome the diverse range of application scenarios [8], which requires flexible and robust design. High-tech toys are an emerging field and the potential for using WSN technology to create new interaction experiences is a hot topic.

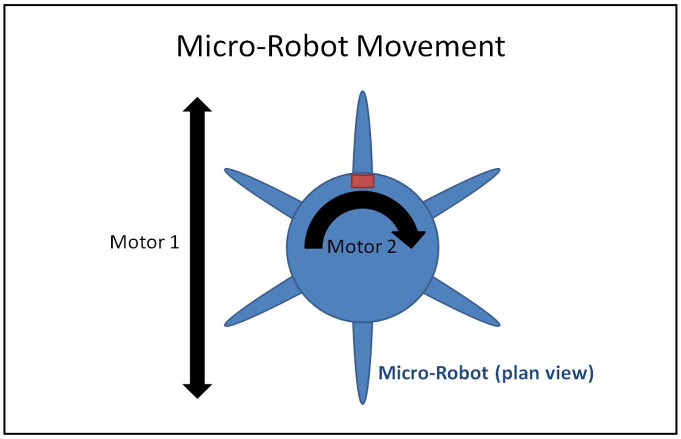

Fig. 1. Hexbug Spider Operation

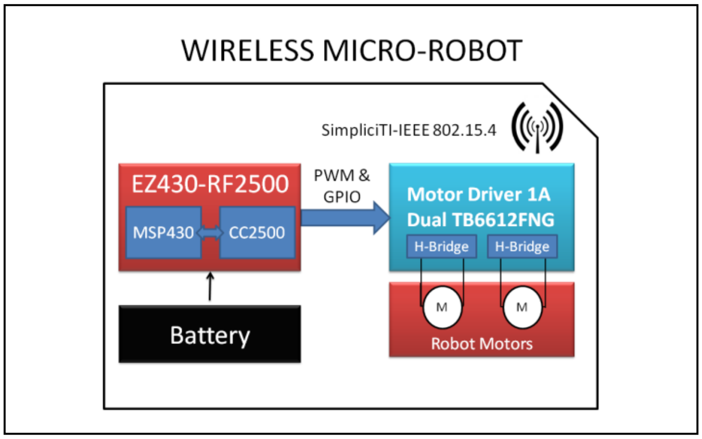

Fig. 2. Architecture of Robot Node

One area that has received much attention is the possibility of using WSN technology to create new experiences in gaming. In [9] the popular "co-operative" video game concept has been expanded into the world of physical remote control toys. The authors proposed to use WSN technology to develop this infrastructure. The concept of combining smart home technology with games is explored in [10]. Here a range of environmental WSN nodes (light, temperature, etc.) are deployed in a house. This information is uploaded via the WSN to a server. A mobile (smart phone) game where the user takes care of a virtual pet is developed using the WSN data. This paper aims to expand on these previous works by developing a low power system that is cost effective and which can be seamlessly integrated into a child's environment without requiring the child or the play supervisor to understand the technology involved. The combination of low power hardware, software, network and low power wake up radios are exploited in the proposed approach.

III. SYSTEM ARCHITECTURE

In this paper a heterogeneous WSN is presented with three types of node: a wireless micro robot with a dual motor driver interface, a wireless LED array node which provides lighting effects and an audio sensing node which acts as coordinator of the network. The three types of node collaborate and interact with music to entertain the users. Typically, a wireless sensor node has four main components; a processor unit, a power unit, sensing units, and a transceiver. The core platform used to develop the network nodes is Texas Instruments' (TI) EZ430-RF2500 development kit. The TI EZ430-RF2500 includes a 2.4GHz CC2500 RF transceiver, a MSP430F2274 microcontroller (16bit RISC, ultra-low power microcontroller operating at up to 16MHz) and power management unit with battery [14].

A. *Wireless Micro-Robot Node*

To create the intelligent toys WSN technology has been integrated into "Hexbug Spider" micro-robotic toys. Hexbugs are a range of small robotic toys manufactured by Innovation First [11]. The attractive feature of the Hexbug spider is its clever mechanical legs, which, controlled using only two DC motors, can move the robot to any desired point on a plane with high accuracy and minimal effort (Fig.1).

The Spider platform is adapted by replacing its own motor control with a custom built wireless system which follows the characteristics of a typical WSN node (Fig. 2). The motors of the Hexbug spider are driven by a dual H-bridge TB6612FNG. This chip controls the two DC motors at a constant current of up to 1.2A. The TB6612FNG is controlled by the EZ430 with speed varied using a pulse width modulation signal (PWM) up to 100 kHz. A small, light, rechargeable lithium polymer battery powers the unit to power the robot effectively without causing balance or weight issues. A miniaturized charging circuit, which decreases the cost of the system, is also included.

B. *Wireless LED Array Node*

The architecture of the LED array nodes is presented in Fig. 3. The network uses these nodes to provide transitioning light displays for the concert scenario. To create these nodes the Texas Instruments TPS62260LED-338 development module was used in conjunction with the TI EZ430-Rf2500.

The TPS62260LED module has three LED's (red, green and blue) each powered with a constant current by an individual TPS62260 2.25MHz 600mA step down voltage converter. The converters are controlled by a MSP430F2131, which varies the current level using PWM. Network compatibility is provided in this node by the EZ430-RF2500.

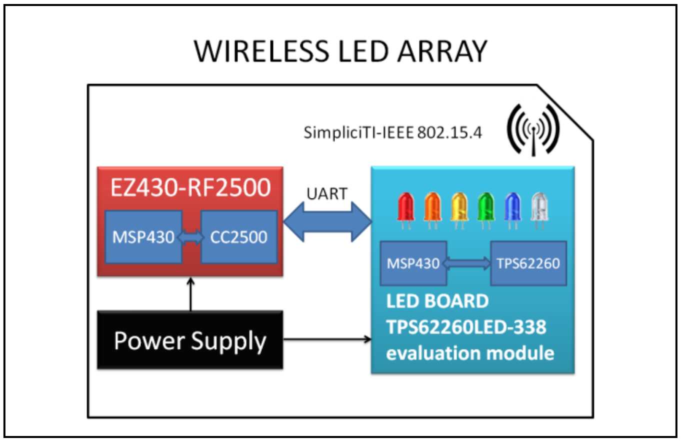

Fig. 3. Architecture of LED Node

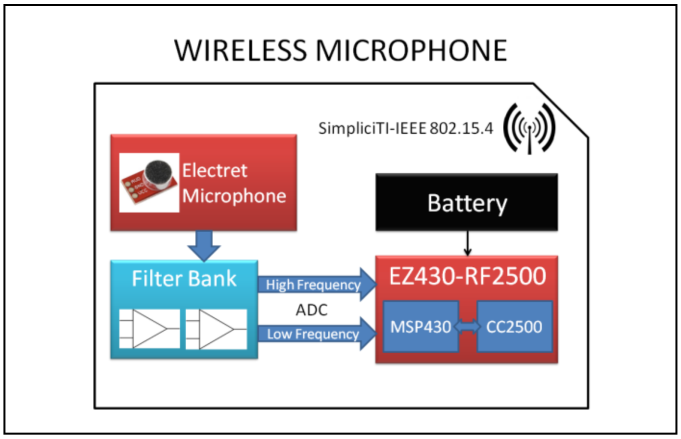

Fig. 4. Architecture of Microphone Node

The EZ430 kit is interfaced with the LED module using the TPS62260LED's expansion pins, which connects two pins of each MSP microcontroller together, allowing the MSP430F2274 to pass messages received over the network to the MSP430F2131 using a basic ("bit-banged") version of UART.

C. Wireless Microphone Node

In order to create an effective toy concert scenario an audio detection WSN node was developed, (Fig. 4). This unit acts as the coordinator of the network; it detects music, processes it, and disseminates a broadcast based on the results. The various network nodes then respond to this broadcast individually. The microphone component is a small low power omnidirectional foil electret microphone with an amplifying circuit. The output signal from the microphone is fed into a bank of filters. This filtering is achieved using low and high-pass multiple feedback filters with cut off frequencies at 1 kHz, the approximate mid-range of audible music. The separated audio bands are fed into the 10 bit ADC of the EZ430-RF2500 for sampling and processing in software, the music received by the node is shown in Fig. 5.

IV. NETWORK ARCHITECTURE

Fig. 6 shows the deployment using the three wireless node topologies presented in the previous sections. The nodes communicate in the 2.4GHz ISM band and a star network topology was chosen. The microphone node acts as a coordinator and all other nodes act as clients. Each toy and LED array detects the broadcasted message and provides an individual and autonomous response. No acknowledgements or replies are required, network traffic is always downstream. Texas Instrument provides an open source ultra-low power protocol for 2.4GHz RF communication called SimpliciTI. It is designed for use in simple star or peer to peer networks, such as smoke alarms and security systems. The protocol has a low data rate and supports the low power modes of the MSP430.

V. EXPERIMENTAL SETUP

In order to provide an attractive and engaging demonstration a concert scenario was envisioned (Fig. 6). The three wireless lights systems were mounted at the top of a toy stage on metal railings. The three modified toys were placed on the stage where they dance and create rhythmic noise when their legs tap the floor. The wireless coordinator node equipped with microphone sensor was placed nearby with a source of music. The sound is then processed on the node and commands are sent to both the lights and the robot nodes. The effectiveness of the demonstration is shown when they respond to traditional Irish music and seasonal music. Two videos of the demonstration were uploaded to YouTube [12].

VI. EXPERIMENTAL RESULTS

Tests were undertaken to evaluate the performance of the platforms to verify the low power consumption of the solution. This preliminary analysis was performed by measuring the current consumed by each node in each state. Along with this information the voltage requirement was used to calculate the power consumption of each node. Table I confirms that the solution is low power, particularly the wireless dongle (less than 20mA when transmitting), as well as showing the higher power of the motor driver (up to 90mA) and LED's (69mA). Evaluation of the life-time of the network was undertaken (Table II). The potential lifetime of each node, in its most power hungry state, if powered by a 560mAh battery (initial demonstration), was calculated. These lifetimes are a worst case scenario for each node.

To extend this lifetime an improved listening mode setup has been proposed for the end devices. A wireless wake up radio [4] [6] will be deployed in conjunction with an ultra-low power switch [13] replacing the mechanical switch (Fig. 5 d). This proposes to reduce the current during sleep mode from 500nA to approximately 200nA. Thus, the node lifetime will be extended significantly while maintaining or even improving its reactivity. The output signals from the microphone and filters were also observed using an oscilloscope during testing (Fig. 5 a,b,c). The low and high frequency music components are clearly separated in the two graphs and are used to generate the commands for broadcast to the robots and lights.

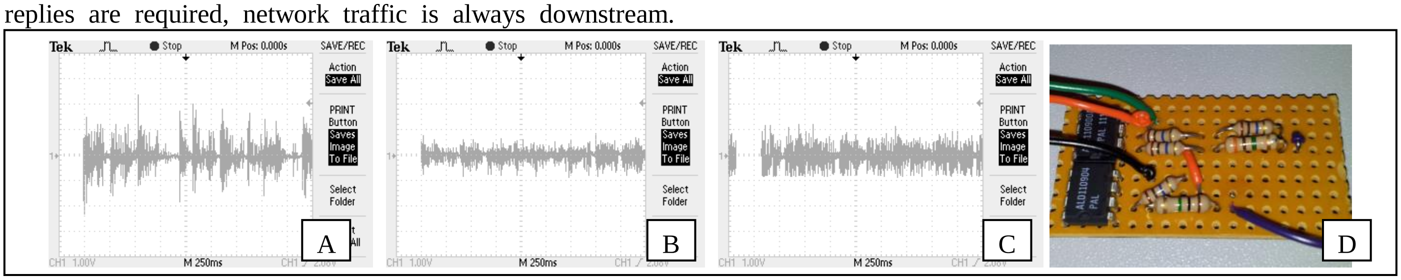

Fig. 5. Audio signal detected throughout microphone node: a) microphone output, b) low-pass filter output, c) high-pass filter output, d) early development of ultra-low power switch.

TABLE I. POWER CONSUMPTION OF SYSTEM NODES

Unit	Power Results			
	Task	***Current***	***Voltage***	***Power***
Microphone	Detecting Music	2.2 mA	5V	11mW
	Transmitting	19.8 mA	5V	99mW
Micro-Robot	At Rest	27.6mA	3.7V	102.12mW
	Walking Forward	89.9 mA	3.7V	332.63mW
	Walking Backward	84.1 mA	3.7V	311.17mW
	Turn Left	84.0 mA	3.7V	310.8mW
	Turn Right	85.1 mA	3.7V	314.87mW
LED Unit	At Rest	26.43mA	5V	132.15mW
	Flashing LED 1	49.9mA	5V	249.5mW
	Flashing LED 1+2	65.16mA	5V	325.8mW
	Flashing LED 1+2+3	69.09mA	5V	345.45mW

TABLE II. 560MAH BATTERY LIFE ESTIMATION

	Battery Life estimation		
Unit	***Microphone***	***Micro-Robot***	***LED Unit***
Lifetime	56.56hrs	6.5hrs	8.1hrs

VII. CONCLUSIONS

In this paper the infrastructure for collaborative toys using wireless sensor network technologies has been proposed, developed and tested. Low power, accurate motor control is a key feature as it allows for toys to provide immediate feedback to stimulus. The motor driver developed was demonstrated by deploying it on a robotic spider creating a remote control toy controlled by the WSN. The LED unit provides a low power disco style light display which can be wirelessly controlled. The LED's provide a bright, stimulating response and effective feedback for an educational toy. The audio detection unit provides the system with a means of responding to music and sounds in its environment. This allows the toys to respond to external stimuli, which is a key feature of toys as part of the "internet of things", as well as paving the way for features such as voice control.

This work represents the first steps towards a full implementation of a collaborative toy using WSN technology. It has verified the feasibility of such a concept and has cleared the way for future development in this area. Finally experimental results on the developed systems demonstrate the low power aspect of solution. Future work will focus on further power saving techniques as well as energy harvesting technology.

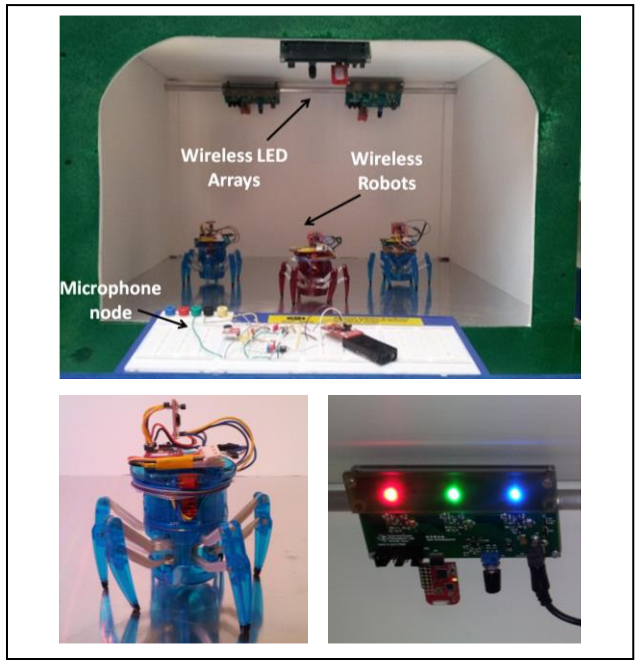

Fig. 6. Experimental setup and final platforms

REFERENCES

[1] Z. Shiwei, Z. Haitao, "A review of wireless sensor networks and its applications," Automation and Logistics (ICAL), 2012 IEEE International Conference on, pp. 386-389, 2012.

[2] D. Estrin, et al. "Instrumenting the world with wireless sensor networks." Acoustics, Speech, and Signal Processing, 2001. Proceedings.(ICASSP'01). 2001 IEEE International Conference on. Vol. 4. IEEE, pp. 2033–2036, 2001.

[3] Magno, M.; Tombari, F.; Brunelli, D.; Di Stefano, L.; Benini, L., "Multimodal Abandoned/Removed Object Detection for Low Power Video Surveillance Systems," Advanced Video and Signal Based Surveillance, 2009. AVSS '09. Sixth IEEE International Conference on , vol., no., pp.188,193, 2-4 Sept. 2009

[4] E. Popovici, M. Magno, S. Marinkovic, "Power management techniques for Wireless Sensor Networks: A review,"Advances in Sensors and Interfaces(IWASI), 5thIEEE International Workshop, pp.194-198, 2013.

[5] M. Srivastava, R. Muntz, and M. Potkonjak. "Smart kindergarten: sensor-based wireless networks for smart developmental problem-solving environments." 7th annual international conference on Mobile computing and networking. ACM, pp. 132-138, 2001.

[6] S. J. Marinkovic and E. M. Popovici, "Nano-Power Wireless Wake-Up Receiver With Serial Peripheral Interface", IEEE journal on selected areas in communications, pp. 1641-1647, 2011.

[7] Le, T. N., Magno, M., Pegatoquet, A., Berder, O., Sentieys, O., & Popovici, E., 'Ultra low power asynchronous MAC protocol using wake-up radio for energy neutral WSN'. 1st International Workshop on Energy Neutral Sensing Systems, ACM, p. 10, November, 2013

[8] S. Iyengar, and R. Brooks, eds. "Distributed Sensor Networks: Sensor Networking and Applications". Vol. 26. CRC Press, 2012.

[9] P. Guerrero, M. Cilia, & A. Buchmann. "Relying on wireless sensor networks to enhance the RC-gaming experience". 3rd International Workshop on Pervasive Gaming Applications (PerGames 2006) Ireland, pp. 37-44, 2006.

[10] L. Liu, and M. Huadong "Wireless sensor network based mobile pet game." Proceedings of 5th ACM SIGCOMM workshop on Network and system support for games. ACM, pp. 30, 2006.

[11] Innovation First, http://www.innovationfirst.com/ (2013)

[12] http://www.youtube.com/user/smartsync1 (2013)

[13] B. Chao and L. Harrison, "Re-designing normally-on load switches with zero-power MOSFETs reduces power consumption", Design article, Advanced Linear Devices, 2008.

[14] Jelicic, V.; Magno, M.; Brunelli, D.; Bilas, V.; Benini, L., "An energy efficient multimodal Wireless Video Sensor Network with eZ430–RF2500 modules," Pervasive Computing and Applications (ICPCA), 5th International Conference on , vol., no., pp.161,166, 1-3 Dec. 2010.