Overboard
Expansion Board for actuation on Wireless Sensor Networks

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***Abstract*—This work, developed inside the Group of Embedded Networked Systems and Heterogeneous Networks at Instituto Superior Técnico, has the purpose of integrating actuation functionalities in Wireless Sensor Networks (WSN), focusing also in the control of the actuators and their impact on power consumption. The solution proposed permits the use of actuation functionalities through the integration of a daughter board, named Overboard, into the nodes (also known as motes) that require these functionalities, allowing these boards to be controlled by those same nodes. The interface between the node and the Overboard is made through a hirose connector specifically chosen to guarantee the compatibility between the Overboard and the MoteIST mote. This choice also permits the board to be compatible with the MicaZ and Iris motes.**

Keywords: Wireless Sensor Networks, Wireless Sensor and Actuator Networks, Actuators control, Automation Protocols, Overboard, MoteIST, Iris, MicaZ

I. Introduction

WSN are widely employed nowadays in a variety of areas, such as, environment, agriculture, buildings and area monitoring, among others [1]. This type of networks is constituted by spatially distributed sensor nodes that cooperate with each other in order to transmit their data through the network to a main location. Each node is usually constituted by a processing unit, sensors, a communication device and a power source. Among their main features stand the reduced physical dimensions, limited processing capabilities and low energy consumption[3]. Although their huge popularity, these type of networks can only be employed in sensing applications. Their implementation in applications that require actuation operations is prevented due to the inexistence of hardware in the nodes for this purpose. In order to overcome this obstacle it's necessary the integration of hardware, specifically for actuation functionalities in the desired nodes. The integration of actuators increases the range of applications suitable for the implementation of this type of network, more specifically in autonomous operations, making available their employment in areas such as health care, mode-based services, entertainment, logistics, transportation, environmental protection, among others, that require sensing and acting operations.

The integration of actuators changes also the requirements of the network. Usually its main concerns are power consumption, latency and network lifetime, but with the actuator's integration, real-time actions and communication reliability have to be taken into consideration. From the communication protocol point of view, the inclusion of actuators usually demands bidirectional communication and the ability to address several nodes simultaneously in order to allow more complex operations [2].

The approach described in this article to allow the control of actuators in this type of networks uses a daughter board, entitled Overboard, for the actuation functionalities, permitting its integration in already existing networks. The analysis of existent Wireless Sensor and Actuator Networks (WSAN) allowed the implementation of the most popular actuation functionalities of those networks in the Overboard, with the purpose of making it as general purpose as possible. These functionalities include the control of electric motors, solenoids and devices connected to the AC power line. The control of actuators through automation protocols was also implemented due to its usefulness. These allow the control of numerous devices connected to the same bus with a single or multiple control unit(s) without the need for the control unit to power or directly control those devices, resulting in higher autonomy and the control of greater amounts of actuators for the control unit. The most popular protocols were integrated into the board, these are, the X10, Konnex (KNX) and Controller Area Network (CAN) Bus. The X10 popularity is due to its easy installation in existent infrastructures because it uses the AC power line has a communications bus. The KNX on the other hand is widely used because it is the only worldwide open standard for building and home control. As for the CAN bus, its main feature is its robustness, making its implementation very popular in applications where reliability is important[4].

The development of the Overboard was made inside the Group of Embedded Networked Systems and Heterogeneous Networks at Instituto Superior Técnico. It was created with the purpose of being a daughter board for the MoteIST also developed in-house. Their compatibility is assured through a 51 pins hirose connector existent in both boards. This connector provides communication between boards, power supply and physical support for the Overboard. It allows also the Overboard to be compatible with the MicaZ and Iris motes.

Being the Overboard powered by a battery, its power consumption is directly proportional with its autonomy. In order to increase it, the board allows the activation and deactivation of its modules.

The remainder of this article is structured as follows: Section II presents the system requirements and architecture; Section III describes the board's design and implementation; Section IV presents the results obtained from the prototype built; Section V concludes this paper with an overall view of the performed work.

II. System's architecture

A. Requirements and Specifications

The requirements defined for the Overboard are the result of the study of several WSAN actuation functionalities and of the discussions that took place inside the Group of Embedded Networked Systems and Heterogeneous Networks. These are the following:

- Compatibility with the MoteIST, MicaZ and Iris motes.
- Ability to control electric motors, solenoids and devices connected to the AC power line.
- Ability to interact with the X10, CAN bus and KNX protocols.
- Existence of a Test mode in the Overboard.
- Existence of a MCU, for the automation of the actuation functionalities.

In terms of the compatibility with the MoteIST, MicaZ and Iris motes, it is assured through the 51 pins hirose connector. This connector is present in all boards and with equal pinout. It is responsible for the communication between boards, for the physical support of the Overboard and for its power supply. This connector is capable of providing 3 V, which is the voltage used by the motes. Regarding the communication between boards, several protocols are available through this connector, namely Universal Asynchronous Receiver Transmitter (UART), Inter-Integrated Circuit (I^2C) and Serial Peripheral Interface (SPI), being the I^2C chosen for this purpose due to its ability to communicate in Multi-Master environments and also because it only requires two signal wires for communication.

The control of electric motors and solenoids by the Overboard is made through two bipolar drivers. This solution was chosen due to its versatility, which allows the control of bipolar stepper motors, DC motors, brushed and brushless, push-pull solenoids and many other similar actuators. Regarding the control of servomotors, these are controlled through a digital interface which is compatible with most of the servomotors existent in the market nowadays. The control is made through a Pulse Width Modulation (PWM) signal, being the width of the signal directly proportional to the rotation angle of the motor's shaft, as shown in Figure 1.

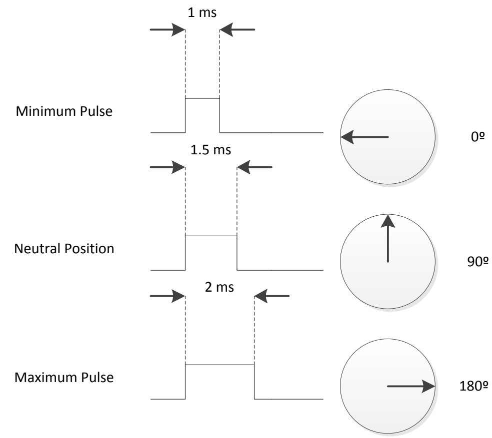


Fig. 1. Servo motor rotation angle control.

As for the control of devices connected to the AC power line, it is made through a triac with optical isolation. The implementation has the advantages of not having moving parts, and having electrical isolation, which protects the Overboard from any accidental short-circuit with the AC power line.

Regarding the automation protocols, the interaction with the X10 and KNX protocols is made by the intermediate of serial transceivers, not integrated in the board. This solution simplifies the integration of these protocols in the Overboard since, it only requires the interaction with the transceivers, which is made through the RS-232 standard. Since both these protocols have the ability to communicate through Radio Frequency (RF), a connector was integrated in the board for the purpose of attaching RF boards trough it, providing RF communication to the Overboard. The connector used is the same as the one used by the MoteIST for RF communication, permitting the use of the already existent RF boards for the MoteIST. As for the CAN bus protocol, the integration of a CAN transceiver allows the direct interaction of the board with the CAN bus.

The implementation of a test mode in the Overboard has the purpose of allowing the board to be fully tested. In order to make the test mode easily accessible, it was specified that the tests would be made trough a console in a host PC, using RS-232 communication.

Regarding the integration of a MCU in the Overboard, its existence is essential in order to provide automated tasks. The MCU is responsible for the board's energy management, actuation functionalities, test mode functionality and the communication with the mote connected to the board. In order to fulfil these requirements, it must support I^2C, SPI, CAN, UART, must be able to generate PWM signals, have the ability to enter low power consumption states and be supplied with a voltage of 3 V.

B. Block Diagram

The block diagram presented in Figure 2 shows the main blocks of the Overboard and the Power board. This last one was designed specifically for the control of devices connected to the AC power line. The Power board separation is due to safety reasons, since the Power board will be subjected to currents and voltages that could permanently damage the Overboard if a short-circuit occurred.

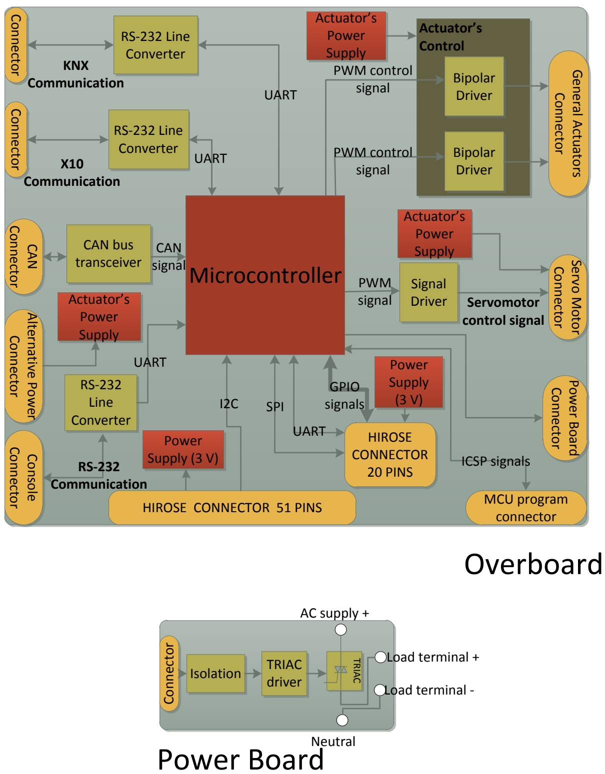


Fig. 2. Overboard and Power Board Block Diagram.

The heart of the Overboard is the microcontroller which controls all the functionalities of the board. It is programmed through In-Circuit Serial Programming (ICSP) which can be accessed to the MCU program connector. The interaction with the motes is made through the 51 pins hirose connector, using the I^2C protocol.

The integration of the RF boards is made through the 20 pins hirose connector. As described in the previous Section, the connector has the same pinout has the already existent RF boards in-house, in order to maintain compatibility. It features twelve General Purpose Input Output (GPIO) lines, one UART communications protocol, one Serial Peripheral Interface (SPI) communications protocol and one power supply line.

The board also features line converters, used to convert the UART communication voltage levels into the RS-232 voltage levels. These are used for the communications with the X10 and KNX automation protocols transceivers and also for the communication with a host PC during the board's test mode functionality. Regarding the CAN bus protocol, a transceiver is integrated in the board, in order to allow the Overboard's communication with the CAN bus.

As for the direct control of actuators, the board features two bipolar drivers and a digital interface for the servomotor, both control by PWM signals. In order to use these features, an external power source is required. The reason for this power source is to allow the control of more power demanding actuators, without depleting the node's power supply.

In terms of the Power Board, it allows the switching of devices connected to the AC power line, which is done by a triac. An optoisolator is also integrated in the board in order to ensure electrical isolation from the board to the Overboard.

III. Hardware Design

A. Microcontroller

The selection of the MCU was made, in an initial phase by filtering all the MCUs that didn't fulfil the specified requirements and, in a final phase through the analysis of the characteristics of each MCUs. The requirements for the MCU are the following:

- Existence of I^2C, SPI and CAN controllers.
- Ability to be powered through 3 V.
- Existence of at least two UART controllers.
- Ability to generate PWM signals.
- Existence of low power modes.

These requirements narrowed the suitable MCUs into the following MCU families, being their characteristics shown in Table I.

- STM8S208xx family from STMicroelectronics.
- PIC24HJ family from Microchip.
- CY8C38 family from Cypress Semiconductor.

TABLE I
MCU FAMILIES ANALYSIS.

Device family		STM8S208	PIC24HJ	CY8C38
Architecture		8-bit	16-bit	8-bit
SPI Modules		1	2	Yes[1]
I^2C Modules		1	2	Yes[1]
CAN Modules		1	2	Yes[1]
UART Modules		2	2	Yes[1]
Max. Operating Frequency (MHz)		24	80	67
Operating Voltage (V)		2.95-5.5	3-3.6	1.71-5.5
Max. N of MIPS		20	40	33
Memory (KBytes)	**Flash**	128	256	64
	RAM	6	16	8
Current Consumption (mA)	**Performance Mode[2]**	60	90	15.8
	Sleep Mode[3]	0.009	0.013	0.0002
Min. Price [4]		4.28	4.35	22.34

[1] Functionalities are generated through the use of Universal Digital Blocks.
[2] Operating at maximum frequency, no peripheral modules are operating, all I/O pins configured as inputs.
[3] Lowest current consumption state available.
[4] Retrived from the *Farnell*™, *Mouser*® and *Digi-Key Co. USA* websites.

Balancing all the characteristics of the MCUs shown in Table I, the choice went to the PIC24HJ since it provides more digital interfaces, operates at higher frequencies, and offers the best price for the features provided, in comparison with the others.

B. Bipolar Drivers

The implementation of the bipolar drivers is made using the DRV8833 from Texas Instruments Integrated Circuit (IC). The choice to use an IC over discrete components, is due to the fact that the IC requires less board space to be implemented. The IC chosen is the result of an analysis on the available bipolar drivers nowadays.

The DRV8833 features:

- Capability of driving both bipolar drivers independently or simultaneously.
- Ability to obtain 2 A of peak current in each bipolar driver.
- Current regulation and limitation in each bipolar driver.
- Internal shutdown in the presence of over and under voltage, over current and over temperature.
- Features electrostatic discharge and shoot-through protection.
- In normal operation mode, current consumption is 3 mA.
- In sleep mode, the current consumption lowers to 2.5 uA.
- Existence of fast and slow current decay modes.

The control of the DRV8833 is made through the use of PWM signals, each driver requires two signals. The control logic is shown in Table II.

TABLE II
BIPOLAR DRIVER CONTROL LOGIC.

Input 1	Input 2	Function
PWM	0	Foward PWM, fast decay
1	PWM	Foward PWM, slow decay
0	PWM	Reverse PWM, fast decay
PWM	1	Reverse PWM, slow decay

The fast and slow decay modes are related to the current. In the fast decay mode the current in the driver vanishes quickly, while in the slow decay mode, it vanishes slowly.

C. CAN Bus Transceiver

The interaction with the CAN bus requires the use of a CAN transceiver. The choice of this transceiver was based in the voltage supply range, existence of a sleep mode, and power consumption. Focusing on these characteristics, the MAX3051 from Maxim IC was found the most appropriate.

The MAX3051 features:

- Data rates up to 1 Mbit/s.
- Capable of being connect to 112 nodes in simultaneously.
- Provides protection against short-circuit conditions, high voltage transients and high temperatures.
- Current consumption in normal operation mode is 35 mA, when it is dominant, and 2 mA, when it is recessive.
- Current consumption in shutdown mode is 1 uA.

D. Power Board

The method chosen for the control of devices connected to the AC power line is through the use of a triac with optoisolation. This method was chosen due to the inexistence of moving parts, which allows higher operating speeds and doesn't suffer from contact arcing or electromotive force effects, which occurs in the relay case. The optical isolation provides electrical isolation, protecting the Overboard from any accidental short-circuit with the AC power line. The topology chosen, shown in Figure 3, permits only the switching of devices. Its implementation requires the presence of zero voltage crossing detector, for the re-triggering of the triac at each zero voltage point.

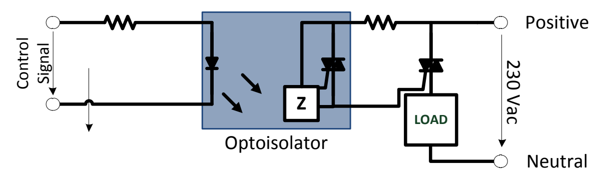


Fig. 3. Power Board schematics.

In order to choose the most appropriate components, a study, shown in Table III, was made on the most common power devices, with the purpose of evaluating their power ratings. Based on this study the T410-800 triac from STMicroelectronics and the IS622 from Isocom were found the most suitable.

TABLE III
COMMON APPLIANCES.

Appliance	Power Rating(W)	Current(A)
Compact Fluorescent Lamp CFL	8-35	0.03-0.15
Bulb	25-100	0.11-0.43
Fluorescent Lamp	20-40	0.01-0.2
Fan	25-80	0.1-0.4
TV	80-400	0.4-2
Fridge	200-300	1-1.4
Vacuum Cleaner	150-400	0.7-2
Washing Machine	800-1000	4-4.5
Microwave	600-1500	2.6-6.5
Desktop Computer	80-150	1-1.3
Laser Printer	1000-1500	4.3-6.5
Ink Jet Printer	25-50	0.11-0.22
Electric Iron	450-1000	2-3
Hair Dryer	1200-1500	5.2-6.5
Music System	20-40	0.09-0.17

IV. Software Application Design

In order for the microcontroller to control the Overboard functionalities, a software application was created. Through it, it is possible to activate or de-activate the different modules of the board, control the actuation functionalities, test the board and communicate with the mote connected to it. The application flowchart is shown in Figure 4.

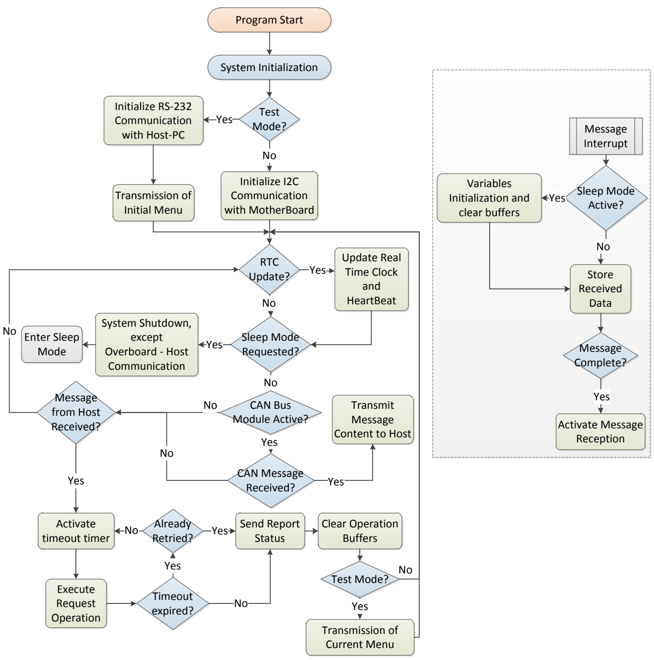


Fig. 4. Overboard application, block diagram.

The application starts immediately after applying power to the board. At each initialization, the selected mode is checked. The available modes are the normal mode and the test mode, being the selection of each mode made by hardware. In the normal mode, if the Overboard is in the idle state, the application is continuously checking for received messages, otherwise it is performing the requested functionality and discarding any incoming messages. After the completion of each task, a report stating the success or failure is sent back. The test mode is used for the testing of the board. A user is required for the control of the Overboard, being the control made through a console in a host PC. It interacts with the user by transmitting menus with the available functionalities to the console. In this mode, the user has access to a manual with instructions about the control of the Overboard functionalities existent in the application, created with the purpose of facilitating the control of the board.

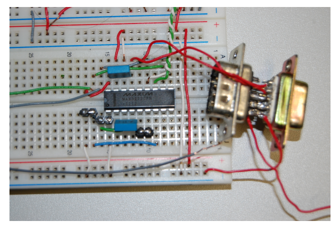
With the purpose of simplifying the interaction with the Overboard, a proprietary protocol was created. Through it, it is possible to communicate with the board independently of the communication protocol used. The communication with the Overboard can only be made by this protocol. It is based in the transmission of arrays, being each command sent all at once.

V. Implementation and Evaluation

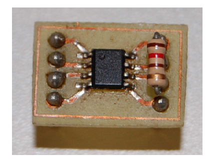
A. Hardware Implementation

The hardware implementation of the Overboard was made in two stages. In the first stage, it was implemented in a breadboard, for debugging purposes and in the second, a Printed Circuit Board (PCB) was designed and built.

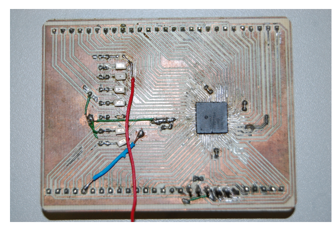
1) Breadboard Implementation: In this stage, Dual In-line Package (DIP) components were used, when available, and when these weren't, sockets were created in order to make the connection between the component and the breadboard, as shown in Figure 5.



(a) MAX3222 from Maxim IC, breadboard circuit



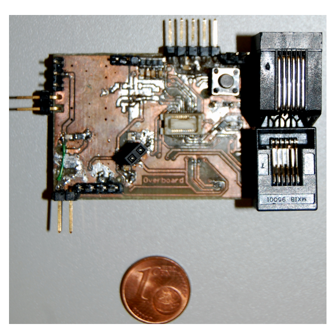
(b) MAX3051 from Maxim IC, PCB circuit



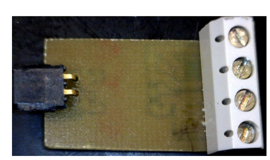
(c) PIC24H from Microchip, PCB circuit

Fig. 5. Overboard prototype, breadboard implementation.

2) PCB prototypes: After the debugging of the Overboard implementation in breadboard, the Overboard and the Power board were designed and fabricated in PCB. The design was made using the Altium Designer program, and for the fabrication it was used a photographic method. After the fabrication of the PCBs, the components were assembled in them. The Overboard PCB is shown in Figure 6(a) and the Power Board in Figure 6(b).



(a) Overboard



(b) Power Board

Fig. 6. PCB prototypes.

B. Evaluation

1) Power Consumption: Since the Overboard is to be powered by batteries, the measurement of its power consumption is essential in order to determine the autonomy of the board. In order to measure the power consumption of the Overboard's functionalities, the test mode was used, enabling the control of the board by a host PC. The board was powered through an external power generator with a fixed voltage of 3 V, which is the voltage available at the motes that are to be connected to the Overboard. The current measurements were made between the power generator and the Overboard. For the direct actuation functionalities, another power generator was connected to the board in order to supply the actuators. Since the power consumed by the actuators is independent of the power consumed by the rest of the board and its consumption is only dependent on the actuator used, no measurements were made on this secondary generator.

The following tests were designed in order to determine the power consumption of each functionality.

1 Microcontroller in sleep mode with the system clock disabled. All the ICs of the Overboard disabled[1].

2 Microcontroller running the software application [2]. All the ICs of the Overboard disabled[1].

3 Microcontroller running the software application [2]. CAN Module is enable but there is no communication in course[1].

4 Microcontroller running the software application [2]. CAN Module is enable and transmitting[1].

5 Microcontroller running the software application [2]. KNX Module is enable but there is no communication in course[1].

6 Microcontroller running the software application [2]. KNX Module is enable and transmitting[1].

7 Microcontroller running the software application [2]. X10 Module is enable but there is no communication in course[1].

8 Microcontroller running the software application [2]. X10 Module is enable and transmitting[1].

9 Microcontroller running the software application [2]. Dual Bipolar Drivers Module is enable but no control is being made[1].

10 Microcontroller running the software application [2]. Dual Bipolar Drivers Module is enable and both drivers are operating[13].

11 Microcontroller running the software application [2]. Servomotor interface is controlling a servomotor[413].

1–*The module that communicates with the host PC is enable.*

2–*The system clock uses the internal oscillator with a frequency of* 80 *MHz.*

3–*The PWM signal used is irrelevant.*

4–*The servomotor used is the Futaba*3003.

The results of these tests is shown in Table IV.

TABLE IV
OVERBOARD POWER CONSUMPTION TESTS.

Test	Power Consumption(mW)
1	0.186
2	184.14
3	193.05
4	225.15
5	201.6
6	223.68
7	200.28
8	222.6
9	185.91
10	186.168
11	193.8

Through the analysis of the results, the first conclusion that can be seen, is the correct functioning of the power management functionality of the Overboard, which is essential in order to extend the autonomy of the batteries connected to the board. The results also show that the direct control of actuators, through the bipolar drivers or through the Servomotor interface, only increase the power consumption in 1.1% and 5.25% respectively. The reason for this, is because this consumption is only related to the control of the actuators, being these supplied by another power supply.

VI. Conclusions

In this work, we intended to integrate actuation functionalities into WSN. In order to do so, a daughter board called Overboard, with actuation capabilities, which would be integrated in a node of the WSN was proposed. The board was designed to be compatible with the MoteIST mote, and its functionalities were based on the analysis of several WSAN. Since the board's power supply is intended to be a battery, a power management solution was created, with the purpose of diminishing its power consumption, through the activation and de-activation of the board's different modules.

Another importance aspect of this work is the creation of a test mode for the Overboard, with the purpose of testing the board for errors.

The results of this work are the PCB prototypes and their functionalities, which also serve to validate the successful implementation of the actuation functionalities into a WSN node, the designed power management solution and the test mode functionality.

Having achieved the goals laid down for this work, there is still room for the improvement of the software application, the board's design and the further integration of actuation functionalities in the board. The Power board can also be further improved into being able to dim the power delivered to devices connected to it and not only switch, which is, its present functionality. The creation of RF boards, in order to interact with the automation protocols through RF is also another functionality that should be developed in the future.

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