BIONIC EGG: Sealed Mobile Sensor Packaging Design with Adaptive Power Consumption

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Abstract— **The goals of this research are to design a 3D printed environmental data logger while considering sensor packaging space constraints and to implement a smart power consumption system for increased endurance. The product is sealed for harsh environmental conditions per IP65 standard as well as for impacts. In this paper, we share our electronics packaging design approach for a mobile sensor suite so called "Bionic Egg" which is capable of logging ambient conditions as well as external forces on a turkey egg during transportation. While available space is limited due to the shell size, there is an insufficient amount of room to mount a large enough battery to execute all day long operation requirement. We designed an adaptive power consumption methodology which adopts a reactive sensory usage logic by adjusting processor clock between 2-72Mhz. The power consumption of Low Profile Quad Flat Package (LQFP) 32 bit ARM Cortex microcontroller could be reduced as low as to 230 µA in deep sleep mode with a maximum of 62.1 mA drain for continuous logging state. The Mobile sensor suite includes inertial measurement unit (IMU), temperature and humidity sensors, Global Positioning System (GPS) unit with an internal antenna as well as a SD (Secure Digital) card board for data logging. The overall design approach, hardware structure, power consumption data as well as software structure are presented.**

Keywords- mobile sensor suite, electronics packaging, power consumption optimization, smart singal conditioning

I. INTRODUCTION

Low cost, open architecture electronic components as well as additive manufacturing technologies offer rapid prototyping opportunities to test and validate multi-sensor fusion systems. In addition to that, reduced power semi-conductor technology makes it feasible to design such systems as a mobile unit. In this paper we investigate sensor packaging technologies and share our 3D printed design approach for a ruggedized mobile sensor suite with IP65 standard.

Mobile sensors are commonly used in agricultural industries for last decade. Low power consumption processers made it possible to conduct remote and outdoor measurements with an appropriate casing [1]. Increased sensor accuracy as well as reduced cost helped researchers measure micro-environmental changes of the farms which is critical for agricultural efficiency [2].

Wearable technology is another research topic that is widely studied after electronic components got cheaper while improving sensor accuracy and reducing energy requirements. Manufacturing facilities benefit from this technology not only for health monitoring and emergency medical care situation [3]. Another use for a manufacturing facility is continuous remote monitoring of the facility [4]. Similar technologies combined with mobile devices are also used for health monitoring of the elderly [5].

Technologies discussed above are operated in a sort of controlled environment when compared to space exploration missions. It is one of the most challenging harsh environments when it comes to sophisticated sensor fusion tasks. In this study [6], researchers had built an environmental multi sensor system for Mars exploration rover. The environmental monitor station, contained two sensors that measure different parameters. A pressure and temperature sensor unit is kept in a Faraday cage which is built with a composed material that consists of fiberglass cloth and an epoxy binder. The enclosure is also flame resistant. Each of the sensors can be triggered together so that the data can be made reliable through redundancy. There are several different types of pressure sensors being utilized in this design: one high-stability and three high-resolution sensors. The sensor operates by measuring wafer strain with a capacitor in a vacuum chamber. The pressure difference between environment and chamber generate a slight displacement of capacitor plates and capacitance value is correlated with external pressure.

The same sensor suite [6], utilizes wind sensors working with thermal anemometry principle. This is a method used to measure the flow of fluids by measuring the amount of heat lost to the surrounding fluid. First, an initial reading of temperature of the wind would be read before passing through the system. The system used for these rovers utilized hot wires that wind would pass through. When the wind passes through it will take some of the heat, proportional to the speed, from the wires and carry on. This wind would then be measured using a temperature sensor. The change in temperature would then allow for the calculation of the wind speed. This methodology was implemented on the Viking 1 and 2 and REMS. Pathfinder used three windsocks mounted at different heights in addition of the hot wire system. These windsocks would get the wind speed by getting the dynamic pressure put onto a thin Kapton tube. This type of measurement was also implemented on the Phoenix Mars lander. Both of these methods were well liked because of their simplicity. Direction of the wind was also measured.

Above studies are designed for multiple purposes including; agricultural monitoring, wearable health equipment and manufacturing facility monitoring, as well as space exploration missions. In this project, our goal is to build a stand-alone mobile sensor system that could monitor environmental conditions of turkey eggs during transportation for extended periods of time with a limited battery. The problem statement and our approach is discussed in the following sub-section.

A. Our Approach

Our senior year capstone project was to create a device that could measure the conditions that turkey eggs are subjected to as they are shipped. The purpose of the Bionic Egg is to monitor environmental conditions that turkey eggs are put in as they are shipped. This device, however, needs to be put in the exact same conditions as the regular eggs to ensure accurate readings. To this end, the device will be made into the shape of an egg and contain all the electronics required to properly monitor the environment.

The problem statement itself defines a large restriction on the design that it must be small. The dimensions of a large turkey egg will be used for this project. The dimensions of such an egg comes out to be roughly 2” x 2.7” with a 5” circumference. In Fig. 1, there is a comparison in size of a turkey egg (left) and a chicken egg (right) to demonstrate the size requirements.

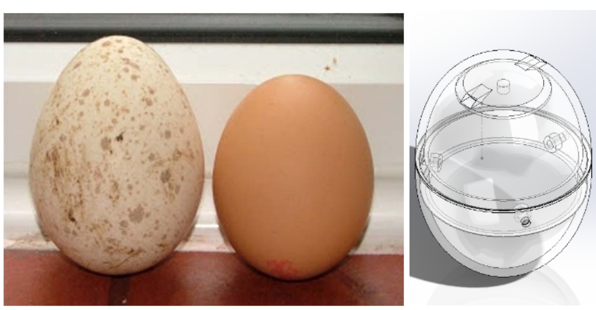

Figure 1. Left: Turkey and chicken egg size comparison. Right: 3D Printed shell of a similar size represents dimensional contraints of the Bionic Egg

The Bionic Egg will be filled with different electronic components so that it can fulfill its purpose. It should be able to read temperature, humidity, impact force, and location to adequately monitor the eggs. These will be measured using several electronic modules. The temperature and humidity will be measured by a temperature and humidity sensor. The impact force will be monitored by an Inertial Measurement Unit (IMU). This will act as an impact force sensor so if the eggs undergo any sudden forces then they will be documented. The last of the data to be recorded is the location. This will be done by utilizing a GPS (Global Positioning System) module. This module will keep track of where in the world the Bionic Egg is. Systems that require for the measurement of various conditions will need many different sensors. Also, the type of sensor and the implementation of those sensors must be appropriate for the given task.

In addition to having these on-board sensors there also must be a microcontroller. This central unit will control all electrical aspects of the Bionic Egg. This is where a program will be loaded so that the system will behave as needed and return the appropriate values. These values being returned will need to be saved so that an operator can access after each mission is completed. An additional module will be added for the sole purpose of storing the collected data onto a MicroSD card. This unit will store all the collected data for the user to access later.

With these aspects combined, the result is a small egg-shaped data logger. A data-logger is a device that will collect data and save it as a log over a period of time at a set interval. The Bionic Egg is no different in that it will need to gather data and make a log of it. This means that the system will not be continually obtaining data but will be collecting data at a fixed interval.

Based on calculations, an interval of 15 minutes is sufficient enough to log the data continuously for selected battery. However, a periodic sampling might cause missed readings of external high impacts. To overcome this issue, an interrupt based system is designed as following: Measurement period is set by an internal hardware clock. Then processor is put into deep sleep by reducing oscillator frequency to 2 MHz from 72 MHz to 2 MHz. During this idle state, only the IMU generated signal is allowed to send a wake-up interrupt. Once a signal is received, the system clock is set back to 72 MHz – fully functional state— and all sensors are stated so data can be logged for a short period of time. The system goes back to sleep mode after the impact signal ends and regular sampling period timer is reset. In this way, the system current drain switches between 230 μA and 62.1 mA that the mobile sensor suite can operate more than 24 hours.

Briefly, current impact force is not of interest during the standard logs. It is desired to know the time and intensity of impact forces affect the egg shell. Instead of recording the force on a standard data log, the system will take a log whenever the impact force is high enough to raise a concern. Detailed electronic component power consumptions are discussed in the following sections.

The reason behind the creation of the Bionic Egg is so that the merchants shipping the turkey eggs can get data on what their eggs are being subjected to during the shipping process. If eggs are not kept at the correct temperature, for example, that could have devastating results on the shipment. While the Bionic Egg does not prevent problems from happening it does have a record of any problems that may have occurred. This data will allow the company shipping the egg to adjust any setups they have in order to account for any issues that may occur. The reason that all of this is important is so that the company does not lose product due to shipping conditions as that will cost money which will cut into profit.

In the next section, design considerations including power consumption calculations are discussed. It is followed by mechanical design steps, hardware selection methodology as well as software structure sections. Finally, the conclusion summarizes the work done and lists future work for the research.

II. Design Considerations

A. Egg Shell

The egg shell must be made to contain all the components in a manner that prevents them from being damaged. This includes a resistance to water and dust. More specifically the shell will have a rating of IP65. This is a rating on how resistant the system is to the environment. The IP stands for "International Protection Marking" and per IEC standard, number 65 is for its rating of resistance to dust and water. The 6 means total protection from dust, meaning that no dust will enter the system. The 5 is a water resistance rating. The rating of 5 will protect against a water jet from any angle with no harmful effect. The completion of this shell will increase the longevity of the device as it will not be damaged by dust or water in most cases. In this specific application, the Bionic Egg will be transported with turkey eggs. If an egg were to break and get onto the system, it would be bad if liquid could get in and destroy the system. So, making sure that the egg shell is structurally sound and resistant to environmental effects is important to the reliability of the design.

B. Battery life

The system must last a reasonable time on a single charge of the batteries. The system cannot run out of power mid delivery because data will not be gathered. An approximate battery life should be greater than 12 hours. Travel time could be from 1 to 2 days. Therefore, the device needs to remain powered on for the whole operation. If the first set of batteries die before reaching the final destination, then there must be another option to power up the device for the remainder of the trip. A back up power source is going to be available for long distance travels.

Power consumption calculations were used to determine the right size of battery needed for the device. First the average current per hour was calculated because all the sensors would be powered for almost two minutes in 15 minute intervals. Table-1 presents individual component power consumption in continuous and idle states.

TABLE I. Power Consumption of Components

#	Individual Component Power Consumption [mA.]		
	Component	***Continuous(74MHz)***	***Idle (2 MHz)***
1	Microcontroller	30	0.23
2	IMU	4.6	4.6
3	GPS	25	-
4	Temperature+humidity	2.5	-
	TOTAL	62.1	4.83

For initial calculations, it is assumed that a high impact event might occur 1% of the overall process. And once system is woken up, it goes on logging the data for 1% more time not to miss any high acceleration event till it ends. In addition to that, every 15 minutes a typical 10 seconds sampling will be executed. Total duty cycle for continuous sampling—max. power consumption— is given by

$$CSA_{DC} = (HIE * C + RE)/C \quad (1)$$

where CSA_{DC} is continuous sampling current duty cycle, HIE is high impact event percentage including additional sampling, RE is the regular event sampling time and finally C is the overall cycle duration. Based on the above assumption, CSA_{DC} is calculated with (2/100*3600+40)/3600= 3.1%. Therefore, idle sampling current duty cycle, ISA_{DC} is 96.9%.

Now, mean current consumption could be calculated by using tabulated data presented in Table-1. Average current consumption A_{AVG} is given by

$$A_{AVG} = \frac{(CSA_{DC} * 62.1 + ISA_{DC} * 4.83)}{C} \quad (2)$$

where multipliers represent continuous and idle current consumptions from Table-1. A_{AVG} is calculated to be (0.031*3600*62.1+0.969*3600*4.83)/3600 = 6.60537 mA. And finally with a battery degrade of 30%, 48 hours operation requirement is calculated by

$$BC = \frac{T * A_{AVG}}{0.7}\ mAh \quad (3)$$

where T is total time in hours. BC is calculated to be (48*6.60537)/0.7= 452.93 mAh. If system were using continuous duty cycle, requirement would be 4258.28, roughly ten times more than adaptive power consumption.

C. Sensor Measurements

The Bionic Egg will have three onboard sensors. These are the temperature and humidity sensor (temp-RH), the inertial measurement unit (IMU), and the global positioning system (GPS) receiver. All sensors must be fully functional for the project to be considered complete. For the temp-RH sensor, the system must receive accurate data that represents the current values of the temperature and humidity. The temperature values will be in the form of Celsius and Fahrenheit, while the humidity sensor will obtain relative humidity represented by a percent value. The next sensor is the IMU. This sensor will behave as an impact sensor, so it will detect any sudden forces that the system undergoes. This is important because when the IMU finds a sudden force it will create a data log to document the mishandling of the product. The last sensor is the GPS receiver. In order for this module to be fully implemented it will have to return the GPS coordinates of the device. This will be in the form of longitude and latitude. For this device, there is more leeway for the accuracy of finding the shipment within a few meters, as it is only meant to give an idea of where the shipment is.

D. Coding

The code that will be loaded into the microcontroller will have to do many things successfully. For one thing, it will have to properly request the data from each of the sensors. After that data is received it must be formatted and saved (see Data Saving for more detail). It will have to make a log of data every 15 minutes. Additionally, the code needs to put the necessary systems into their sleep modes to save on power when not in use. The code must also be able to recognize that if an impact is detected then it needs to enable all of the modules and create a log outside of that 15-minute cycle. All of these aspects are important to the code and will have to fully function in order for the system to be considered complete.

E. *Data Saving*

The system must be able to save all the data obtained from the sensors in a manner that is understandable. The data will be stored as an easy to read text file. The data outputs will be labeled with what they are so that it is straightforward for the user to understand. This is important because this data is the feedback of the system. Having this organized in a manner that is simple to understand from a human's perspective is very important. If it were too difficult the user may decide it was not worth using the product despite its benefits.

F. *Data Retrieval*

The data saved must be able to be reached in a simple manor. This could be done in several ways, whether it could be an external SD card, or a USB connector. In both cases, data retrieval should be intuitive and require little effort or knowledge from the user.

III. Mechanical Design

The mechanical design of this system must ensure that the electrical components are protected and usable. This means that the mechanical aspect of this system is mainly to ensure that all of the electrical components will function without an issues. This makes the mechanical design very important, because without a proper design the performance would be unreliable and susceptible to damage. The design itself takes place in the size and shape of a turkey egg. The dimensioning and the weight are the two main constraints. It means that the layout of the egg will have to efficiently use the space while still being protected.

The egg will come in multiple parts. These can be divided into the internal structure and the egg shell. As for the shell it will need to be shaped like a turkey egg and meet the space requirement. The shell will be made in multiple parts. The shell will be split about its circumference to get access to the inside. There will also be flaps made from a more flexible material to cover up the holes made for any battery or USB port. These flaps are necessary to keep the system contained, to protect it from the conditions of the environment. There is an exception to this. The temperature humidity sensor will need access to the outside in order to measure the temperature and humidity of the environment. Specifically for this sensor a small channel has been made in the egg shell to allow for air to reach the sensor. This channel is not direct to the sensor but forms a 'T' shape so that two holes will lead to the sensor. This is to prevent foreign objects from coming in contact with the sensor. The sensor will be placed at the base of the 'T' and then sealed off to prevent any partials from entering the system, while keeping the electrical connections available.

The next mechanical design element is the internal structure. This is a structure that will be used to hold all of the electrical components in place to prevent damage. This is a separate structure from the shell and can be removed. It will house all of the electronics in a single compact structure. This and the shell will be made using multi-material 3D printers. The system will be held together using three short screws. The system will be made resistant to the environment with the inclusion of a rubber gasket in the seam, where the two halves meet. Overall shell design is presented in Fig. 2.

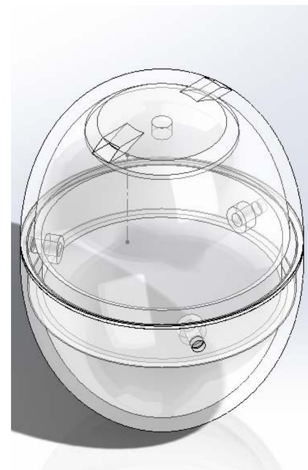

Figure 2. 3D rendering of egg shell with the hole for the temperature and humidity sensor.

IV. Hardware and Software Architecture

A. *Physical Constanraints*

The size and weight constraints are the result of the need for the device to be in the same containers as the turkey eggs. The Bionic Egg needs to be shipped the same way in order to get accurate data for what the eggs are getting subjected to. The approximate dimensions of a larger turkey egg are 2.7” x 2” with a 5” circumference and a weight of 114 grams. This is an approximate volume of 5.65 square inches. This does not leave much space for all of the components. To address this all of the selected components are small. The largest one is the microcontroller at 1.4” x 0.7”. Weight is not an issue until the battery is added, as batteries often add a lot of weight. However, due to the lack of space only very small batteries will be able to fit which keeps the weight down.

B. *IP-65 Requirement*

This requirement is a rating on how resistant the system is to the environment. The IP stands for Ingress Protection and the 65 is for its rating of resistance to dust and water. The 6 means total protection from dust, meaning that no dust will enter the system. The 5 is a water resistance rating. The rating of 5 will protect against a water jet from any angle with no harmful effect. This makes it so that the system will be much more durable. In order to meet this requirement several aspect of the design were necessary. For one element the egg needed to be as sealed off as much as possible from the environment. This means that the holes in the surface of the egg will have to be kept low as to prevent the increase in points of failure. This brought several aspects of the egg into question. The temperature and humidity sensor will need access to the outside otherwise it will be taking measurements of the inside of the egg and not the environment. To create an access a conduit was put into the egg with a small opening so that the temperature and humidity sensor could be put there, granting access to the outside. This would then need to be sealed off to prevent water and debris from entering the system, pictured in section III Mechanical Design. Another point of interest is that the egg needed to be opened in order to put the elements in the egg. This means that the device needs to be resealed in such a way that IP-65 is still met. Another aspect is the data retrieval. If this is to be a USB connection, then another hole is going to need to be made in order to make that connection. That means that the hole is going to need to have a cover and be sealed properly.

C. Hardware Selection

The company that is sponsoring this project made a few comments about what they wanted this egg to do. They wanted the temperature, humidity, GPS location and impact to be measured. Which drove sensors to become a constraint for this project. In addition, the sponsor mentioned that the employees for the company may not be so tech savvy, which meant the data retrieval should be simple for an everyday user to work with.

The first sensor will be the temperature and humidity sensor. This sensor is important because eggs need to be kept in certain conditions or they will go bad. If eggs go bad then the company will lose product, and if they lose product they will lose money. These sensors will provide information on how well the environment of these eggs is being maintained so that any found issues can be resolved. To do this the Bionic Egg employs the CC2D35S-SIP. This is a chip on a small board with thru hole connectors. It can be seen in Fig. 3.

Figure 3. Temperature and humidity Sensor

The sensor was chosen due to its accuracy, which is befitting of the application. The accuracy of the humidity reading is +/-2% relative humidity (RH) and the temperature reading is +/-0.3ºC. These accuracies will not impede the user from determining whether or not the eggs are in a bad environment as the conditions will need to change several degrees to have any harmful effect. This sensor also communicates using the I2C serial communication protocol which the microcontroller accepts.

The next sensor will be the Inertial Measurement Unit (IMU). This sensor will detect any acceleration as a result of force that is exerted on the Bionic Egg. This is to find out when the eggs are being mishandled, which can destroy product as eggs are fragile. The sensor selected for this was LSM9DS1, depicted below in Fig.4. This sensor has three acceleration, angular rate, and magnetic field channels. This sensor also communicates using the I2C serial communication protocol which the microcontroller accepts. Additionally, this sensor has several interrupt pins. These interrupts are also configurable. This is important because the IMU needs to halt the systems operation when an impact is detected. It will be implemented in such a way so that if the acceleration exceeds a certain threshold it will trigger the interrupt.

Figure 4. IMU Breakout – LSM9DS1

The final sensor is the Global Positioning System (GPS) receiver module. This device will allow for the tracking of the location of the Bionic Egg. With this module, the location of the recorded temperatures and impacts will be recorded. To do this an off the shelf GPS was added to the system (seen in Fig. 5). This module was chosen because it is easy to interface with and it has an internal antenna.

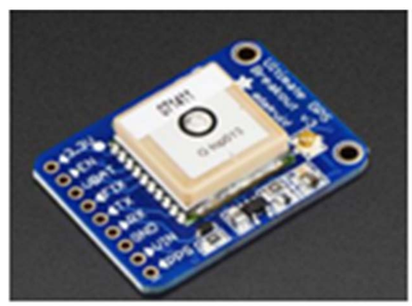

Figure 5. GPS Breakout

The next requirement is that the system must take a data log every 15 minutes or when the IMU detects excessive force. This entails reading data from the temperature and humidity sensor as well as the GPS receiver. The reason that the 15-minute interval was decided on was that eggs do not spoil instantly and can last weeks if refrigerated. This means that the time scale is increased so they do not have to be monitored constantly. It takes roughly two hours for eggs to go bad at room temperature (“Egg Safety Center”). With 15-minute intervals, there are 8 logs of data before the eggs go bad which should provide adequate information that can be used latter. Logs can also be created when the IMU detects excessive force. These logs behave in the same manner when they are triggered and then report to inform of the applied force. This is important because eggs are fragile and excessive force may result in loss of product.

The battery life of the device is another aspect that must be explored. It is important that the internal battery lasts for at least two days. This is because shipments can take. The internal battery can be used for short shipments and when more power is required, external, larger, batteries can be added on in a modular fashion. One way to improve the battery life is to reduce the amount of time that the system is fully functioning. This is where the 15 minute intervals for data logging come in. With this rate most of the functionality of the system can be shut off for the vast majority of the time which saves power.

Another aspect of the design constraints is that this data must be stored. To do this a MicroSD card will be used. The microcontroller selected has a MicroSD card adapter which can be loaded with a MicroSD card. All of the logs will be saved to this card, which is non-volatile memory, meaning the data won't be lost if it loses power. To go along with data storage the data must also be able to be retrieved. There are two solutions to this that will be implemented. The first is an external MicroSD card port, so that the user just must take out the SD card and connect it to a computer to reach the data. Another possibility is an external USB port. This port will interface directly with the microcontroller to access the information.

To get all of these components there needs to be a device that will control when and how everything is done. This is where a microcontroller comes in. This device will hold the program that makes the data logs by receiving the data from all of the other modules. The selected microcontroller for the Bionic Egg is the Teency3.2, see Fig.6. This controller was selected for three main reasons. The first is that it is very small, it measures at 1.4" by 0.7" and has a low profile. This makes it ideal for the Bionic Egg in that there is not much space to work with, so the small size is a large benefit. This microcontroller also runs off of a popular programming environment. It also comes with a huge library of resources that can be utilized to help with the programming of the Teency3.2. The final important reason it was selected is that it has all the ports needed to operate all of the desired sensors and other modules. This includes many interrupt pins which will be needed for the IMU.

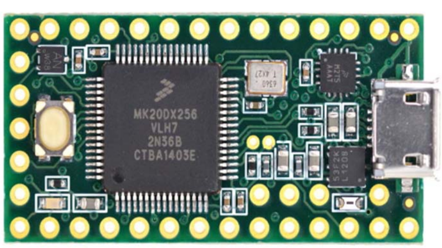

Figure 6. Teency3.2. Microcontroller of the Bionic Egg.

V. Conclusions and Future Plans

This was a successful development for the design of a data logger for the specific task of measuring the conditions of turkey eggs. This was done by making sure the data logger would be put in the same conditions as the eggs. To do this the device was shaped and sized to be the same as a turkey egg to allow for it to be packaged the same way. The device was designed to measure the location, temperature, humidity, and impact force. It has all of the elements needed to take all of these measurements. The device was also designed for harsh environments per IP-65 standard. This was accomplished by creating minimal holes in the surface of the shell. Also any holes that are made are sealed and/or covered from the outside.

The fundamental challenge was the small physical space requirement, which required all the sensor packaging had to be designed properly. Once all the components were assembled, there wasn't much room left for the power supply, battery. To address this challenge, a smart, adaptive power consumption logic is implemented. System is put into deep sleep –72 Mhz to 2Mhz—and is woken up once a high impact event –such as drop, vibration— occurs on the egg shell. In this way, power requirement is reduced to 10% compared to continuous data logging.

As for the future there are many steps to be taken. The shell and support structure will be manufactured. Additionally, all of the electrical components will be combined to create the electrical system. This system will also be tested for internal heating behavior. Current junction to ambient thermal resistance of the system with natural convection—still air— is 59 °C/W based on JEDEC Standard tests. Heating profile of the system will be tested under various conditions including varying ambient temperatures. After the system is constructed field testing will commence.

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