Study of MEMS and Microelectronics: An Industrial Miniaturisation as COTS Dust

Mayurika JB
Lecturer
Department of Electronics, Government Polytechnic College, Jodhpur, Rajasthan, India

jbmayurika@gmail.com

***Abstract*—The goal of this paper is to provide information on cubic inch autonomous sensordevices otherwise known as Commercial-off-the-Shelf Dust (COTS Dust). COTS Dust iscapable of sensing and responding to environmental changes and communicating to otherdevices. This thesis is the compilation of my experience and knowledge in the design ofCOTS Dust and can be considered a guide for those who wish to design similar systems.Ultimately, it's my wish that material provided within contains enough information forthose unfamiliar with this area of research to be able to design a working COTS Dust oftheir own in a relatively short time frame.COTS Dust was originally designed for Smart Dust, an ongoing project whosegoal is to make cubic millimeter autonomous sensor devices. In the introduction, I brieflydescribe how the design of Smart Dust necessitated the development of these larger prototypes,COTS Dust.Because the length of time to develop a complete Smart Dust system was on theorder of years, there needed to be an alternative means to test basic behavior in a timelymanner. To this end, COTS Dust was created. The quickly-developed prototypes werebuilt using commercial-off-the-shelf components (COTS). COTS Dust had all the basicfunctionality of Smart Dust, but the devices were built in a tenth of the time. Instead ofbeing a cubic millimeter in size, these devices were a cubic inch in size. COTS Dustcould serve as a platform to run a variety of algorithms to test various behaviors that SmartDust would exhibit.**

I*ndexTerms*— COTS Dust, MEMS, COTS dust System, Design.

I. Introduction

One way to realize what future technologies lie before us is to get a history lesson from the past. If you were alive five hundred years ago, would you have thought it was possible to talk to someone within seconds halfway around the world? Would you have even known the world was round? Civilization has been especially active in the last 150 years: the internal combustion engine, the atomic bomb, microelectronics, the human genome project. We take our knowledge for granted, but imagine being alive before the existence of hot water plumbing.

As much as our forefathers would find the present difficult to imagine, we, the present, find the future just as difficult to grasp. The farther out we project our future, the more difficult to predict. Nevertheless, by examining the current trends in technology, we gain a clearer vision of the future. Microelectronics offers one solid example of a consistent and commonly accepted trend to examine. Thirty years after its creation, Moore's law still rings true; the minimum process size continues to decrease. While microprocessor and memory companies try to squeeze progressively more transistors in a given area, the opposite can also hold true: for a given circuit, progressively less area is needed on the silicon wafer. Abstracting away from circuits, systems as a whole will also decrease in size while maintaining similar functionality as their predecessors. Further extending this cavalcade of projections, perhaps 25 years from now, today's Pentium III processor will fill less than one tenth of the area of the period at the end of this sentence.

Additionally, micro electro-mechanical systems (MEMS), a surrogate of the microelectronics industry, promises mechanical miniaturization. Together both MEMS and microelectronics provide the backbone of autonomous microsystems. One hundred years from now, autonomous dust sized particles with capabilities to communicate and sense will number in the trillions, much like what Neil Stephenson created in his book, The Diamond Age. Anything from monitoring weather patterns to tracking human movement might be possible with these incredibly functional, yet microscopic pieces of silicon dust. This miniaturization revolution is in part being realized by Professor Kris Pister's group at UC Berkeley through his project, Smart Dust. Smart Dust's ultimate goal is to create a fully autonomous system within a cubic millimeter volume.

Because the length of time to develop a complete Smart Dust system was on the order of years, there needed to be an alternative means to test basic behavior in a timely manner. To this end, COTS Dust was created. The quickly-developed prototypes were built using commercial-off-the-shelf components (COTS). COTS Dust had all the basic functionality of Smart Dust, but the devices were built in a tenth of the time. Instead of being a cubic millimeter in size, these devices were a cubic inch in size. COTS Dust could serve as a platform to run a variety of algorithms to test various behaviors that Smart Dust would exhibit.

II. COTS DUST ARCHITECTURE

COTS Dust was designed with simplicity in mind; the goal being functional generic devices that would provide a fast prototyping tool to test the behavior of Smart Dust. In order to emulate their behavior, COTS Dust assumed the four basic subsystems.

I designed and built several COTS Dust devices. All the COTS motes, as I referred to them, followed a similar architecture but differed in sensor medley and communication type. A diagram of the basic architecture can be found in Fig. 1. An Atmel AVR microcontroller served as the brain, while depending on the flavor of the device, either optical or RF communication was used. Most COTS devices were powered by a 3V lithium battery. Lastly, each device had its own sensor suite chosen from the following list: magnetometers, accelerometers, light sensor, temperature sensor, pressure sensor, and humidity sensor.

The following sections the subsystems are.
a. Power
b. Computation
c. Sensors
d. Communications

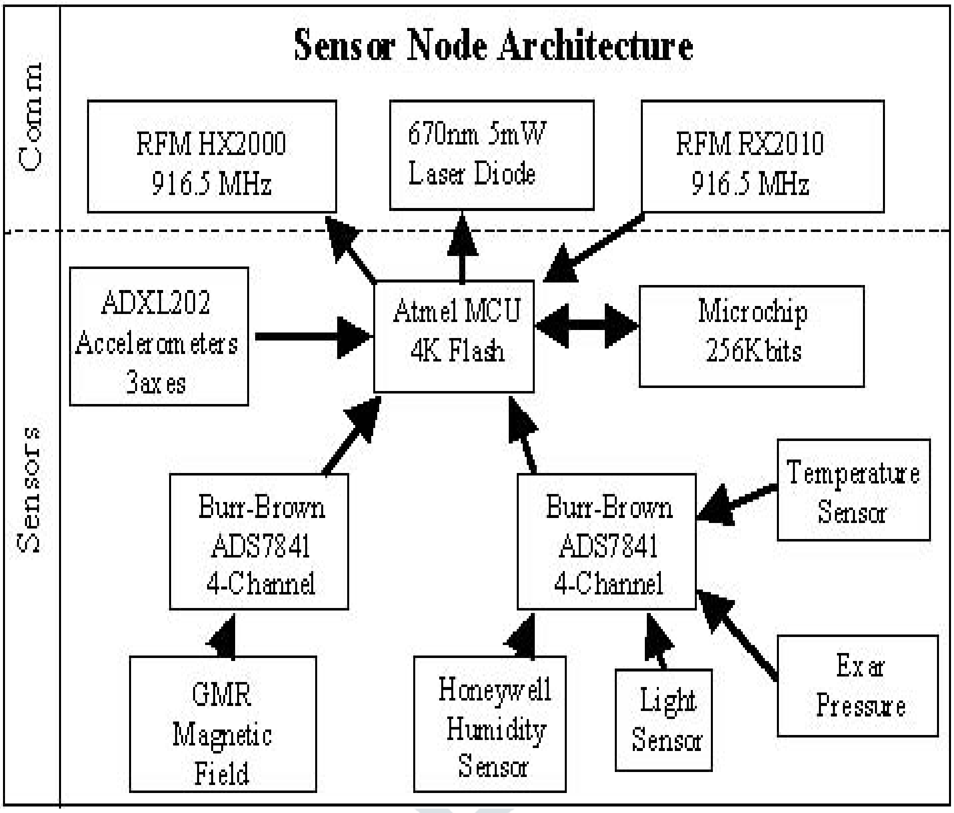

Figure 1: Architecture for COTS Dust.

III. COTS DUST SYSTEMS

Based on the architectures described in Section 2.0, I designed and built several unique systems (see Figure). The descriptions of each COTS Dust system are outlined below. To give the reader an idea of the functionality, each section describes a demonstration of the device's capabilities. Here, I point out the interesting design challenges that arose while making a fully operable system. The sections are ordered chronologically according to when I designed and built each system.

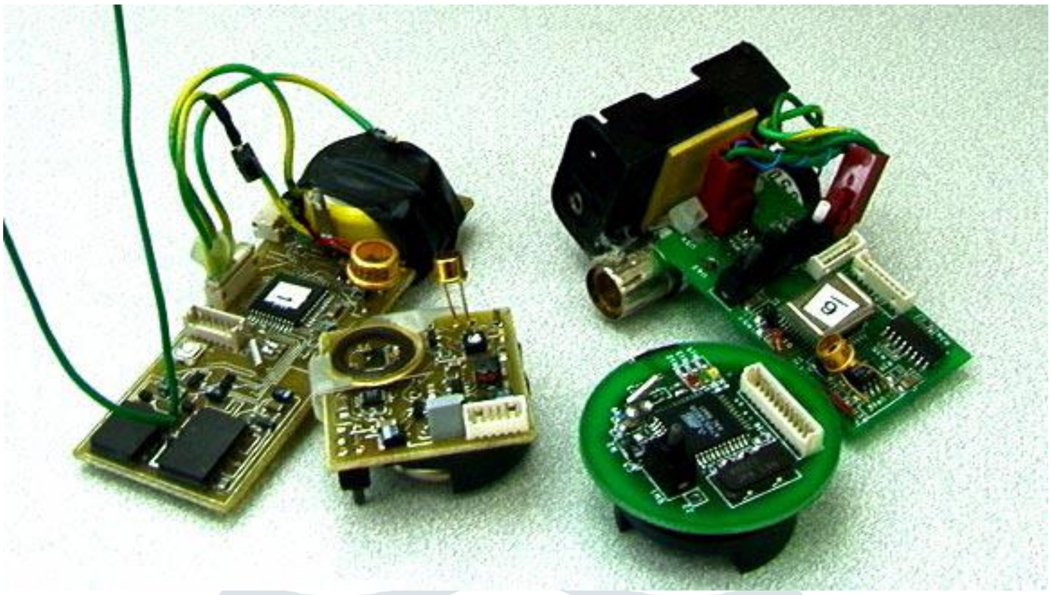

Figure 2: COTS Motes. From left to right: RF Mote, CCR Mote, we C Mote, Laser Mote.

Radio Frequency Mote (RF Mote)

The RF mote follows the architecture found in Fig. 1. The autonomoussensor mote consists of the Atmel AT90LS8535, an RF Monolithics 916MHz transceiverset, and 7 sensors (temperature, light, barometric pressure, 2-axis acceleration, and 2-axismagnetometers). A single 3-V lithium coin cell battery powers the mote, sustaining eitherfive days of continuous operation or 1.5 years at 1% duty cycling. See Fig. 18 on page 40for a commented picture of the RF mote. Unlike the CCR motes, the RF motes can communicatewirelessly with one another where reliable RF communication has been demonstratedat distances ranging from 5 to 30 meters.

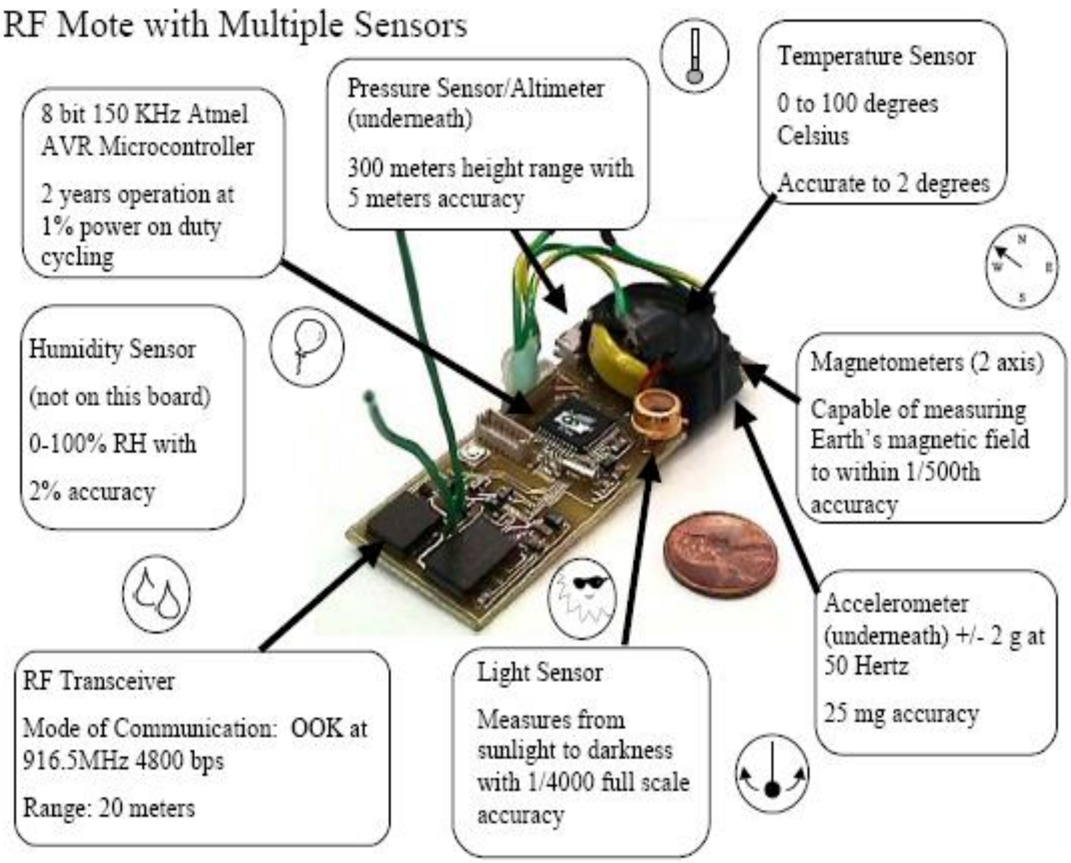

Figure 3: RF Mote. Captions indicate the various subsystems of the RF Mote.

IV. Design Advice - Failures and Successes

The COTS Dust motes were successfully built and demonstrated. During the design cycle, though, I encountered a number of problems. In this section, I discuss some of the problems I encountered and how I solved them.

I went through two versions of the RF mote before I settled on the one described in this thesis. The first RF mote was designed with a Scenix SX28AC series microprocessor. The SX28AC series can operate with clock cycles up to 50 MHz. However, when I populated my first circuit board, I had trouble getting the RF Monolithics transceiver chipset to work in the presence of the Scenix microprocessor. There are two reasons for why the transceiver chipset did not work correctly. Namely, the receiver was saturated with noise generated by the MCU. The MCU was clocked at a slow speed of 1 MHz, but I believe the fast rise and fall times of the MCU contributed to noise in the receiving band. Secondly, the circuit board did not contain a ground or power plain. Ground and power planes in circuit boards help isolate signals from one another and maintain a stable power supply voltage. The engineers from RF Monolithics recommended a ground plain directly under the receiver on the top circuit board layer with multiple vias connecting it to a global ground plane underneath. In the second version of the RF mote I chose the Atmel AVR microprocessor whose maximum clock speed was no more than 4 MHz. Its low frequency and power operation suggested that the noise generated in the RF band would be lower than that of the Scenix chips. In addition, I added a comprehensive ground plane and physically separated the RFM chipset from the rest of the components on the board.

Another problem in the first version was the choice of power supplies. Because the Scenix MCU operated at 5 volts and the RFM chips operated at 3 volts, I needed a way to generate both power supplies. My original thought was to use 3 n type alkaline batteries in series to provide 3 and 4.5 volts. Even though the MCU operated at 4.5 volts, the batteries themselves lost voltage over their lifetime. In essence, the batteries voltage dropped from 4.7 volts to 3.9 volts over its lifetime. The voltage quickly fell below the operating range of the MCU. The idea of using two voltage converters for both the MCU and the transceiver chip set was also unappealing due to the added complexity and increased component count. To solve the problem, I focused my designs towards a single operating voltage, namely that of a 3 volt lithium ion battery. All components were designed to operate within the battery range of 2.75 to 3.25 volts.

The circuit boards were designed in Cadence’s Orcad Capture and Layout Plus 9.0 tools. I used Techcons System Inc. TS9701 to dispense solder paste. Touch up soldering was done with a MetcalSmartheat soldering iron. Most testing was performed with an HP54645D Digital oscilloscope. Assembly was done by hand, though for large quantities, companies like Quote PCBoards Services, Inc. can also populate the boards.

V. The Future of COTS Dust

When I refer to COTS Dust I am referring to devices on the order of a cubic inch which contain the four basic subsystems 1) power 2) computation 3) sensors, and 4) communication. Currently, a number of research institutions in the U.S. are working on centimeter- scale distributed sensor networks. While the BWRC group in Berkeley is developing an entire radio on a single CMOS substrate, the WINS group at UCLA is focusing on low power wireless MEMS. Other groups are investigating the routing and connectivity issues that arise from mobile wireless networks. In terms of power, Amirtharajah et al. have demonstrated a MEMS system that extracts electric energy from vibrations. Spanos et al. have developed wafers with autonomous sensor arrays on them that allow for calibration, control, and monitoring of semiconductor manufacturing processes.

The future of COTS Dust communication lies in both RF and optical communication. MEMS is playing an active role in the development of optical micromirrors with integrated lasers. In the near future, complete subsystems in cubic centimeter sizes could be commercialized. A number of impediments, however, stand in the way of the future commercialization of optical communication. To stay competitive with existing RF systems, optical communication systems need to have high data rates. High data rate (~Mbps) imaging receivers are being developed for Smart Dust. In a matter of years, the commercial market could see a low power, high data rate imaging receiver.

Since low power free space optical communication is relatively new, algorithms are still under development to establish optical links between devices. As discussed in “Active Laser Communication”, establishing optical comm links involves both spatial and temporal acquisition steps while RF communication only requires temporal acquisition.

RF is a well established field and in the next 10 years will be the communication system of choice for COTS Dust. As mixed signal systems become further integrated onto chips, fully packaged RF transceivers like those from RF Monolithics will become more available. In addition, Bluetooth, a generic communication standard, offers a way for devices to communicate in clusters, much like distributed sensor networks.

Power consumption will also play a key role in the design of COTS Dust. While microcontrollers are following Moore’s Law, consuming less power with like functionality, battery energy densities have not improved significantly over the years. Likewise, power consumption of the RF communication systems depends largely on the range of communication. Depending on the application, there will be a direct relationship between battery size and transceiver capabilities.

Since computation will require less power in the future, I expect COTS Dust to migrate to a 32 bit core, for example the Arm core. Even further in the future, custom circuit design could replace commercial microcontrollers as the preferred choice of electronics. Additional functionality would allow future COTS Dust to perform more complex functions: for example, wireless reprogrammability and more intelligent data routing and sensor processing.

VI. Conclusions

Smart Dust is an ongoing research project whose main goal is to develop cubic millimeter autonomous sensor devices. Because it would take years to develop a single Smart Dust particle, It is necessary to developed COTS Dust, devices that could be designed and built in one tenth the time yet mimicked the behavior of Smart Dust. COTS Dust provided the testing platform to develop algorithms that could be used in Smart Dust. COTS Dust technology leveraged off the commercial industry. Readymade commercial parts were integrated together to form cubic inch autonomous systems. Like Smart Dust, COTS Dust had four major subsystems: power, computation, sensors, and communication.

In most of the COTS Dust systems, lithium batteries provided the power source. The Atmel AVR microprocessor satisfied the majority of the computation needs of the system. In the literature search, I found that newer microcontrollers offered equivalent power performances with additional functionality. The Atmel 16/32 Strong Thumb for example offers 32 bit processing power with only a fractional increase in power. A number of sensors were also integrated into COTS Dust systems: magnetometers, accelerometers, a light sensor, temperature sensor, pressure sensor, and humidity sensor. By analyzing the data from the accelerometers and magnetometers, the attitude information of the COTS Dust device can be obtained. The Acceleration Sensing Glove (ASG), for example, used the gravity reading off the accelerometers to determine finger orientation of the wearer. The final subsystem of COTS Dust is communication. RF and active and passive laser communication subsystems were successfully built and demonstrated.

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