Proceedings of DETC'02
ASME 2002 Design Engineering Technical Conferences and Computers and Information in Engineering Conference
Montreal, Canada, September 29-October 2, 2002

DETC2002/DFM-34154

CONCURRENT PRODUCT DESIGN: A CASE STUDY ON THE PICO RADIO TEST BED

Daniel L. Odell
The Berkeley Manufacturing Institute
UC Berkeley, Berkeley, California 94720, USA
E-mail: dano@kingkong.me.berkeley.edu

Paul K. Wright
The Berkeley Manufacturing Institute
UC Berkeley, Berkeley, California 94720, USA

ABSTRACT

This paper presents a case study on the mechanical design and fabrication of the **Pico Radio Test Bed:** a wireless networking node for experimentation with applications, networking, media access layer design, and position locating algorithms. Particular focus is placed on the systematic design process and resolving coupling design constraints between the mechanical and electrical domains. Three generations of the design are presented to demonstrate the evolution of the design as conflicts arose, problems were noticed, and requirements changed.

Keywords: Design for Rapid Prototyping, Concurrent Design, Collaborative Design, Wireless application, Mechanical and Electrical Design Domain Coupling, Injection Molding

INTRODUCTION

Concurrent Design

Concurrent design is also known by several other names, including simultaneous engineering, concurrent engineering (CE), and integrated product development. Though these terms were not coined until the early 1980s, the concepts that CE embodies have been implemented as early as World War II [1].

Noble states that "concurrent engineering is typically defined as the integration of both the product and the manufacturing design processes. The goal of this integration is to reduce the product development time, to reduce the cost, and to provide a product that better meets the customer's expectations." [2]

This definition seems to fall into the common trap of reducing concurrent design to design for manufacturing (DFM). While DFM is a very important consideration for good design [3], it remains a subset of concurrent design.

Perhaps a better definition is offered by Canty [4], "Concurrent engineering is both a philosophy and an environment. As a philosophy, CE is based on each individual's recognition of his/her own responsibility for quality of the product. As an environment, it is based on the parallel design of the product and the processes that affect it throughout its life-cycle." This definition states a key aspect of concurrent design (and focus of this paper): the parallel work of multidisciplinary teams.

The Pico Radio Test Bed

The Pico Radio project is one of the main topics of research at the Berkeley Wireless Research Center (BWRC). The goal of this project is to develop a series of meso-scale, low cost transceivers for ubiquitous wireless data acquisition that minimizes power/energy dissipation [5]. This goal is to be achieved through a three-step implementation, the first of which is the Pico Radio Test Bed (PRTB) [6]. During this step, a macro-scale wireless networking node was produced from off–the-shelf components for experimentation with applications, networking, media access layer design, and position locating algorithms. To complete this phase, a multidisciplinary team comprised of computer science, electrical design, mechanical design, and manufacturing skills was assembled. This paper will focus on the collaboration between the electrical, mechanical, and manufacturing paradigms used to produce the casing for this project.

Design for Manufacturing

The benefits of DFM are well documented [7]. To take advantage of DFM, the downstream manufacturing processes must be identified before the design phase begins. Injection molding was selected as the ultimate manufacturing process as it met several of the key casing requirements. These requirements included: low per part cost, complex geometry, thin walled sections, and low weight. Since only 200 or so casings were required, class B (short run) tooling was targeted. Once this decision was made, the documented DFM rules for injection molding (DFIM) [8,9] could be followed. The primary DFIM rules that were considered in this design included: no undercuts for a simple two-half mold, uniform wall thickness to avoid sink, warp, and residual stresses, bosses and ribs designed to avoid sink, adequate draft angles, and few sharp corners to avoid stress concentrations.

Injection molding requires a significant upfront capital investment for tooling. For this reason it is very important that the design be perfected and verified prior to tooling. This helps avoid any costly changes or re-tooling due to design errors. Rapid prototyping (RP) is ideal for this purpose as it is well suited to producing complex geometries that simulate the function of the finished part. RP is also useful for quickly checking unfinished design concepts, and verifying proper fit and function of parts [10].

In order to simulate the function of the casing (particularly the screw bosses), Fused Deposition Modeling (FDM) was used to create prototype casings. The Stratasys® FDM 1650 was used for this purpose, and the casings were made from P-400 ABS. The FDM process is capable of making very complex geometries, but quality can be improved by following some simple DFM rules [11]. Fortunately, most of the DFM rules for FDM are a subset of the DFM rules for injection molding (e.g. minimum wall thickness). For this reason, a part that follows DFIM rules typically requires only slight modification, if any at all, to be manufactured by FDM.

Legacy Issues – The Marine Intercom Project

As with most projects, the PRTB project did not "arise in a vacuum." The work was based on the marine intercom project that had been previously completed for DARPA. The goal of this project was to generate a new wireless intercom system for use in marine tanks [12]. It consisted of two earpieces and a handset. The earpieces contained a digital board, a power board, and a radio adaptor board connected to a radio. These boards represent the first generation of boards for the PRTB.

To accommodate the flat-sided oval shape of the existing earpieces without wasting printed circuit board (PCB) area, the PCBs were also shaped as flat-sided ovals (see Figure 1b). This exact flat-sided oval perimeter shape was retained throughout all versions of the PRTB, even though the shape could have been changed to any form after the first generation.

This was because there was no pressing need to change the shape, and many other issues needed immediate attention. However, a change in shape early in the design sequence could have simplified the ultimate casing design. Conversely, a change in shape late in the design sequence would have essentially required starting the casing over again.


a) Helmet Assembly b) Earpiece with PCB

Figure 1: Legacy – the Marine Helmet Project

Legacy issues such as these are common in practice, particularly in the software engineering industry. A classic example of a software engineering legacy problem is the "Y2K" bug. Pescio presents several other examples, along with some approaches that can help mitigate these issues [13].

PRTB – FIRST GENERATION

The first generation of the PRTB casing was intended to be a quick prototype demonstrating the general approach to enclosing the board stack and to mounting hardware. For this reason, it followed only DFM rules for the FDM process. At this point in the design, there were almost infinite options, as the paring of the option space had not yet begun [14].

As previously mentioned, the first generation board stack was comprised of a power board, a digital board, and a radio adaptor board with an attached radio. These were connected together with board-to-board connectors to form the main board stack. In addition, a "dummy" board was included on top of the stack to provide protection to the connectors on the digital board and to allow for connection to external sensor boards (to be designed later). Additional hardware required to make the PRTB a self-contained system included: a StarTAC battery (selected for its integrated snap fit and small size), a power switch, and an antenna. The means for drawing battery power from the battery was neglected for this proof-of-concept prototype.

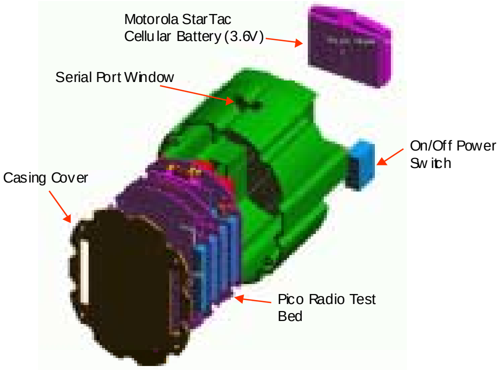


Figure 2: CAD model of PRTB version 1 assembly

The casing shape was selected to be a flat-sided oval (to correspond with the existing PCBs), with scalloped indentations to position and laterally secure the board stack. This approach provided a quarter-inch gap around the PCB stack to allow for wire routing and antenna placement. Four long screw bosses protruded through cutouts in the boards to allow for fastening the lid. Cutouts in the casing side provided for serial port access, and a mounting location for the power switch. A set of ribs extended vertically from the bottom of the casing to support the board stack. Finally, a mechanical battery mount was designed into the bottom of the case to accept the StarTAC battery. Several iterations of this feature were required to generate a tight fit with the battery. The solid model of the PRTB version 1 assembly is shown in Figure 2.

The lid simply followed the contour of the casing, and sat nested inside the top lip. It featured two rectangular cutouts for the connectors on the dummy board, and a hole to access the reset switch on the digital board.

It was recognized early on that the casing (and as a result, possibly the PCBs) would have to change when the design was updated to follow DFIM rules. Figure 3 shows several of the key features of the version 1 casing, annotated with the manufacturability issues that some of them pose. The key issue was that no draft had been applied to any of the features. In addition to slightly changing the shape of the entire casing, a draft angle would significantly increase the size of the long screw bosses at their base. This would cause two problems. First, the large plastic mass that would result at the base of the bosses would cause sink problems. Second, the large bosses would no longer fit through the existing cutouts in the first version of the PCBs.

Further, the serial connector and power switch openings would create undercuts in the mold. Since these molds were to be short run prototype molds only, any undercuts would add unacceptable cost and complexity.

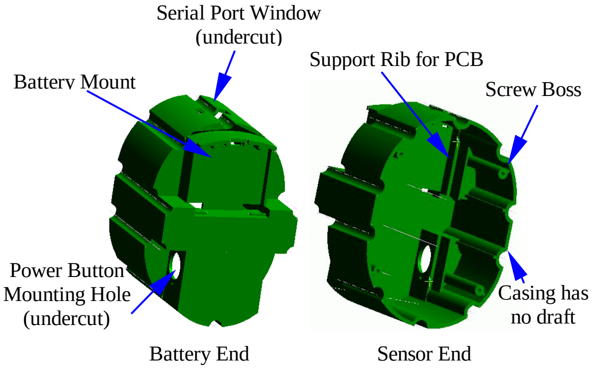


Figure 3: CAD model of PRTB V1 casing & features

PRTB – SECOND GENERATION

It was at this point that true concurrent design began. This is because the PCBs needed to be redesigned for electronics functionality reasons, allowing input and feedback from the mechanical disciplines to also be considered. Additionally, the DFM rules for the design became much more stringent at this point as the manufacturing method switched from FDM to injection molding. This change affected both the mechanical and electrical domains of the design.

The first step was to identify the areas of the design in which there were couplings between the mechanical and electrical domains [15]. These coupling design constraints required particular attention from the different engineers involved, as well as concerted communication between them. This was necessary to insure that the components designed by the different engineers interfaced properly in the final product. The key areas that were identified were: PCB stack mounting, battery and battery connectors, antenna, port access, and wire routing. Figure 4 graphically shows some of these high-level constraints and couplings.

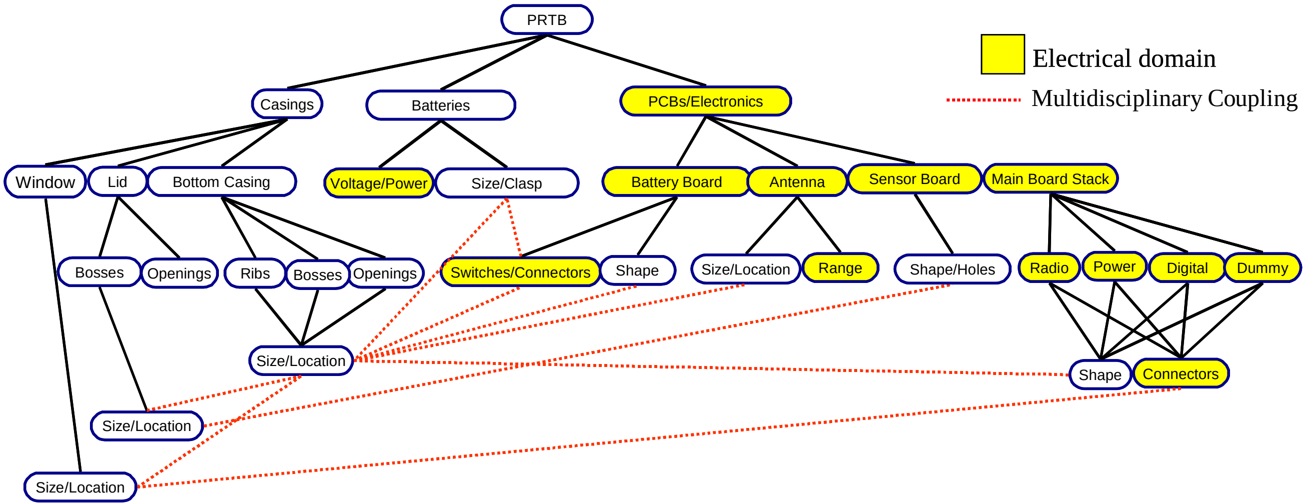
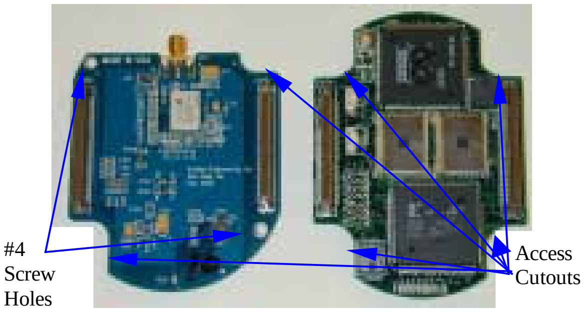


Figure 4: High Level Design Constraints Between Electrical and Mechanical Domains

Printed Circuit Board Stack Mounting

Some of the issues revolving around PCB stack mounting were realized with the completion of the first generation prototype. There were two key issues with mounting the PCBs: 1) the PCB shape prevented screwdriver access to the screw holes in the bottom (radio) board, 2) the board cutouts were insufficient to allow the required draft on the lid bosses. An implicit assumption for the first issue is that the PCB stack was to be fastened with screws. This allowed more relaxed tolerances than would be required for a friction fit to be relaxed. Since only a few hundred casings were required, the trade-off for simpler, lower- tolerance tooling seemed worth the price of slightly more difficult assembly.



a) radio/sensor board shape b) power/digital/dummy board shape

Figure 5: PCB shapes for PRTB Generation 2

Two approaches were taken in order to address these two issues. First, access cutouts were added to the PCBs to allow larger bosses to pass through them, and to allow screwdriver access to the bottom board (see Figure 5). Second, the bosses connecting the lid to the bottom casing were split so half of the length of the boss was connected to the lid, and half to the casing. This significantly reduced the size of the boss at the base, addressing both the sink issue for injection molding, and reducing the size of the necessary cutouts. Guiding ribs were included in the case interior to help position the PCB stack in the casing (and onto the screw bosses).

The radio adaptor board coupled with an off the shelf radio board was abandoned in favor of a single Bluetooth-based radio board of our own design. This integration allowed for a reduction of one quarter of an inch in the stack height, as well as a simplification in assembly for the ME domain, and lower power consumption for the EE domain.

Battery and Battery Connectors

The Ni-MH StarTAC battery used in the first generation PRTB was found to be insufficient to meet the demands of the second generation PRTB. First, the battery voltage of 3.6 V was too low to reliably provide the necessary 3.3 V required by the circuitry. Second, the charge capacity of 550 mAh would require frequent recharges of the hundreds of units. To address these issues, without discarding the design work done for the first generation, it was decided to use two "super capacity" StarTAC batteries connected in serial to yield a 7.2 V power source. These batteries each can store 1400 mAh of charge, and are compatible with the same snap mechanism (although they have a slightly thicker form factor).

Although the mechanical fastening of the batteries had been addressed in the first generation design, this was only half of the story. Making electrical contact with the batteries to draw power from them still had not been looked at in detail.

The first step was to consider at how electrical contact was made with batteries in existing designs (the existing StarTAC first and foremost). The StarTAC uses PCB mounted spring-loaded connectors to reproducibly contact and draw power from the batteries, as do other similar designs. This solution required a new board to be added to the design, a "battery board," as no case mounted connectors could be located. While not a part of the main PCB stack, this PCB sat at the very bottom of the casing and held the connectors to the battery, as well as a power connector to wire power to the main stack. Later, the main power switch was also moved to this board to allow power control at the source. The battery board was the very last board to be designed and fabricated.

Sourcing the spring-loaded connectors to contact the battery proved to be a significant challenge. This point is covered now briefly, but the search for these connectors required several weeks. Ultimately, the Molex 90827 series was selected (see Figure 6). These connectors were small enough to fit under the lip of the battery, and two of the four contacts are far enough apart to make good contact with the contacts of the battery. Mechanical ribs were provided in the casing to provide support to these connectors, relieving the stress that resulted from their required orientation on the PCB.

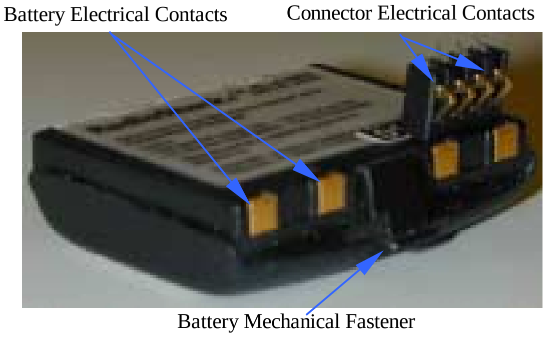


Figure 6: Battery and Battery Connector

The positioning of these connectors on the board was critical. This portion of the design was the nexus of the design as all three major components (casing, battery, and PCBs) came together here. The connectors had to protrude through openings in the casing, rest properly on the supporting ribs, and make good electrical contact with the battery. As a result, extra care and communication between the electrical and mechanical domains was given to this portion of the project.

Antenna

The antenna was one of the more difficult aspects to address due to the unknown effects of positioning on reception. For instance, it was unknown how other electrical components or the plastic casing or the might affect reception. Similarly, the ideal orientation of the antenna within the casing was unknown. For this reason, the key to designing for the antenna was incorporating versatility. To account for these issues, three separate possibilities were created for antenna placement.

Port access

Several components in the casing needed to be easily accessible from the outside. This access was necessary to provide debugging and data collection facilities for the node, but the DFIM rules prohibited a simple side cutout.

In addition, the project managers added a few more requirements to the side cutout feature. First, the digital board had a bank of light emitting diodes (LEDs) to provide visual feedback on the function of the board stack. Visual access to these LEDs was desired. Second, the antenna needed to protrude from the side of the casing to accommodate an external antenna option.

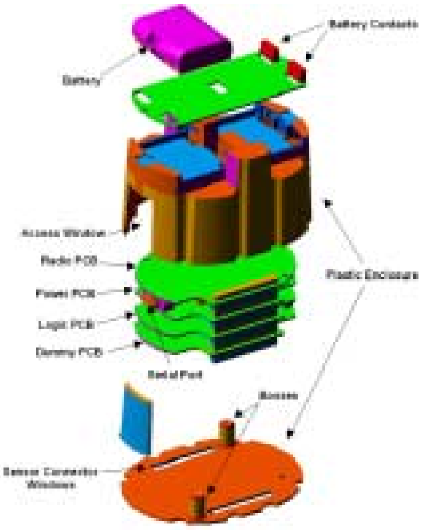


Figure 7: CAD Model of PRTB Version 2 Assembly

To address these needs, it was decided to add a window to the one side of the casing (see Figure 7). This window slid out of the top of the casing, and was removable with the lid on. By sliding out the top of the casing, the window feature could be created by a two half mold; thus eliminating the need for the expensive slider that the first generation casing required.

The window was to be made from transparent material to provide visual access to the LED bank with the window in place. A press fit with the casing eliminated the need for any undercuts (as would be required for a snap fit) while keeping the window in place. At the same time, it was to be easily removable to provide access to the board stack components.

Wire Routing

Wire routing is often an overlooked aspect in concurrent design. This is because it is a design issue that is not fully claimed by either the mechanical or electrical domains. Electrical designers tend to be primarily concerned with the way that wire harnesses connect with the PCBs (i.e. the PCB mounted connectors), and not the harnesses themselves. Mechanical designers tend to consider wire harnesses an electrical design issue, and often overlook them unless the electrical designer specifically mentions them. Even if the mechanical designer is aware of the harnesses, they can be difficult to model in MCAD systems, and therefore are often left out of the system model. However, if wiring is not considered early in the design process, major last-minute design changes may be required to accommodate the space it requires as well to provide a routing path. This can lead to major delays and cost overruns. Some of these issues are addressed in the literature [16]. To avoid these problems in the PRTB design, wire routing was specifically considered at this point in the design phase.

Similar to the first generation casing, a gap of one-quarter inch was left between the main board stack and the casing. With the addition of draft to the casing, this gap progressively increased toward the top of the casing. This yielded even more room for the wires, and for an internal antenna option.

Only two wire harnesses were required for the PRTB, as the rest of the connections were made by board-to-board connectors mounted on the PCBs. A two-wire power harness ran from the battery board to the power board, providing power to the system. This was a relatively long wire (approximately 8 inches) to accommodate the removal of the main stack from the case while the battery board remained. This length was easily accommodated by the available space, but the assembly method occasionally caused the wire to block access to the radio board screws, an unforeseen occurrence caused by the extra length.

The internal antenna option also required a small coaxial wire to run from the radio board to the antenna. As it was coaxial, it was a fairly stiff wire making it difficult to thread around tight corners. A bigger problem with this wire however, was locating SMA connectors small enough to fit. Ultimately, the internal antenna required two right angle connectors to turn the tight corner in the available space.

CAD Issues

All mechanical CAD (MCAD) work for this project was completed by a single designer on SDRC I-DEAS Master's Series 8. The electrical CAD (ECAD) work for PCB layout was performed by three engineers on three separate ECAD systems. OrCAD was used to design the radio board, PADS for the sensor board, and Zuken-Redac for the rest of the boards. Obviously, coordinating all of these designers and ensuring that their designs were compatible was a very difficult problem. This task was handled by a lead PCB designer armed with design specification documentation. While standards and methods exist for designing within a domain, very little work has been done to facilitate designing across domains, Wang being one exception [17]. In fact, of the three ECAD systems, only OrCAD was capable of exporting a format compatible with MCAD systems, DXF, without additional software.

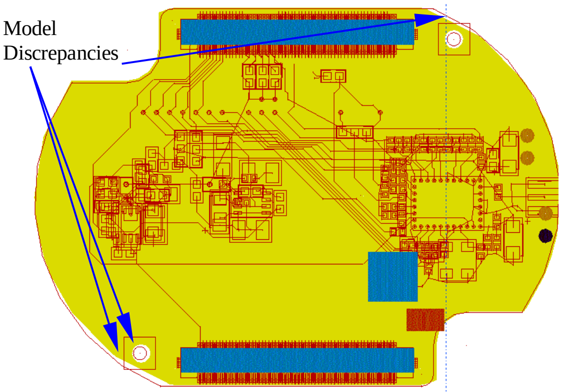


Figure 8: Comparison of ECAD and MCAD Models

Communication between CAD systems was often reduced to capturing a screen shot of a CAD model with critical dimensions showing. An Adobe PDF file was then created from the screen capture, and sent between the designers. Obviously, this is an inexact (and inefficient) method of communication, and does not insure that the two separate models on the different CAD systems match. Even when a compatible format is available, there is no guarantee that the two models will match perfectly. Figure 8 shows the mechanical radio board model in a light solid fill, the electrical model in dark lines, and the discrepancies between the two.

In addition, there are several other issues in bridging the ECAD-MCAD gap. First, ECAD is fundamentally a two-dimensional layout tool, whereas MCAD is a three-dimensional solid modeling tool. Therefore, even using a DXF file directly exported from an ECAD system still requires additional modeling of individual electrical components for the mechanical designer in tolerance critical areas. This work must be completely re-done every time an ECAD design change occurs to insure that the models match.

Another cross-domain communication issue is the fact that several ECAD systems (e.g. Zuken-Redac) are based around an absolute coordinate system. Almost every MCAD system works in a parameterized relative coordinate system. This means that comparing dimensions can require an extra step in the communication process, as absolute dimensions must be converted to relative dimensions, or vice versa. This extra step can introduce errors, and can be very time consuming.

Not only do these differences in modeling tools represent a communication challenge between domains, but also a fundamental difference in the way designers think about their projects. This can result in an even larger obstacle to communication than the previously mentioned issues.

One new approach to this problem is the development of the Standard for the Exchange of Product model data (STEP) Application Protocol 210 (AP210), or ISO 10303-210. This standard seeks to bridge the electrical and mechanical engineering domains by providing a common format to both. More information on STEP AP-210 is available at http://ap210.aticorp.org/, and from Kemmerer [18].

Manufacturing Issues

Once the design for the second generation casing was completed, it was analyzed to insure that it was moldable using a simple two-half mold. Two methods were used to check the design. First, the geometry was carefully inspected by the mold maker and the designer. Second, Cimatron's Quick Concept software was used to analyze the part's draft angles.

Upon close inspection, the mechanical designer noticed a significant undercut created by the window capture feature of the bottom casing. Figure 9 shows a close-up of this feature from the parting direction. Any features not visible from this view (the draw, or parting direction) result in undercuts. The obstructed areas in Figure 9 are circled.

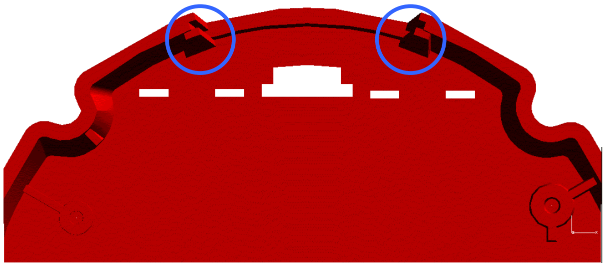


Figure 9: Undercuts in Window Capture Feature

The mold maker offered standard mold maker feedback – "more draft!" This somewhat ironical statement emphasizes the difficulty that manufacturers can have in convincing designers of the difficulties encountered in part ejection, and of the large effect that proper design can have on it.

Quick Concept is a software package offered by Cimatron that performs automatic parting plane detection and undercut analysis. The bottom casing geometry was analyzed using this software, and the results are shown in Figure 10.

Areas identified by the arrows in Figure 10 are the areas that Quick Concept identified as undercuts. The "good news" is that these two areas did contain areas where the draft had been reversed, resulting in small undercuts. These areas had gone unnoticed by both the designer and the manufacturer. The “bad news” is that Quick Concept did not identify all of the undercuts. First, it identified undercuts on one half of a symmetrical part, but not the other half. Second, it missed the very large undercut shown in Figure 9. This experience indicates that Quick Concept can be a useful tool, but should not be relied upon.

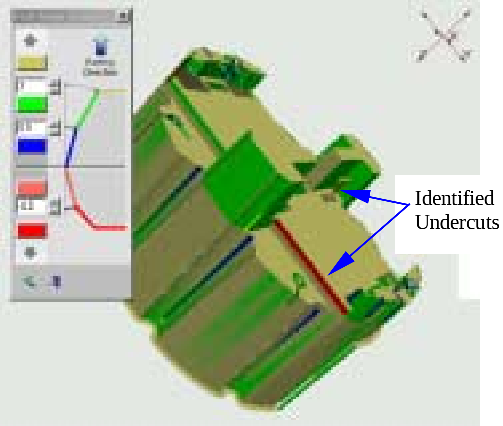


Figure 10: Casing Draft Analysis in Quick Concept

Lead-time was a key issue for getting the second prototype built. Not only was the design of the electronic PCBs more time consuming than that of the casing, but so was prototype manufacturing time. The casing required a total of thirty-six hours to make via FDM. Conversely, each PCB required approximately four weeks lead-time. This time was broken into: acquiring the board gerbers, fabricating the PCBs, part acquisition, and assembly (e.g. pick and place). For this reason, more careful design was required for the PCB design as feedback was much slower, and potential errors much more time consuming. Due to the faster turnaround time of the mechanical manufacture, errors found in the geometry of the PCBs were often compensated for by changing the mechanical design. Examples of these changes follow.

PRTB – THIRD GENERATION

At this point, all of the PCBs had been fabricated and several problems were noticed. First, the sensor board had been designed to the initial Marine Helmet shape rather than the expected updated radio board shape! This board had been designed early in the design cycle, and the design had not been updated to reflect the PCB shape design changes. As the PCB design was completed, and numerous boards had been made, it was decided to change the lid design to accommodate either sensor board shape (see Figure 13). This was accomplished by adding a second set of screw bosses to the lid for either screw configuration. Fortunately, the old sensor board shape did not block access to the lid screw holes.

Second, several problems with the battery board design arose. Ironically, the battery connections that were the main concern worked perfectly, while other, seemingly simple, design aspects caused problems. This is typical, however, as areas of concern receive careful scrutiny – it is the unanticipated issues that tend to cause problems. The first oversight was that no method for powering the PRTB externally had been provided. Fortunately, this oversight was caught prior to fabrication. A connector was added to the battery board to provide this function. The battery board was the natural place for this connector as it allowed the power switch to control all power sources, and it was the simplest board to modify. This addition required another casing change in that the window cutout had to be extended to provide access to this connector. Further, the mounting scheme for the battery board was affected somewhat, as the required position of this connector sat directly over the provided screw slot. This resulted in an asymmetrical board, but the fasteners were kept close to the battery connectors to provide proper support.

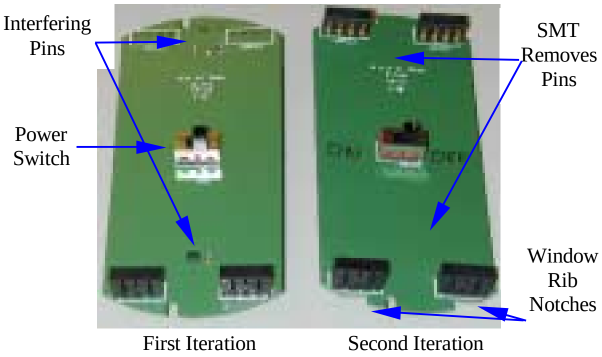


Figure 11: Battery Board Problems

Once the external power connector had been added, another serious problem was noticed. Through-hole mounting had been used to attach the external power connector and power board connector to the battery board to provide strength (see Figure 11). However, this board rested on a planar surface in the casing. The pins of these connectors protruded from the backside of the battery board and prevented it from sitting in the proper position. This caused interference between the battery and radio boards, and prevented the battery connectors from seating properly with the battery. To remedy this, these connectors were replaced by surface mounted (SMT) connectors with no pins protruding through the PCB. These changes, among other electrical changes required a second iteration of the battery board to be designed and fabricated.

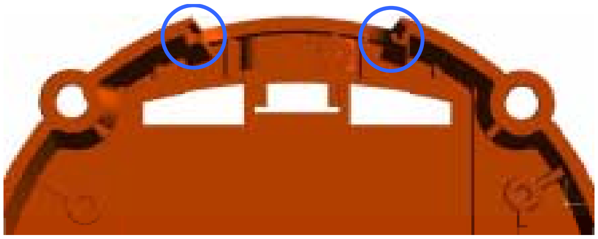
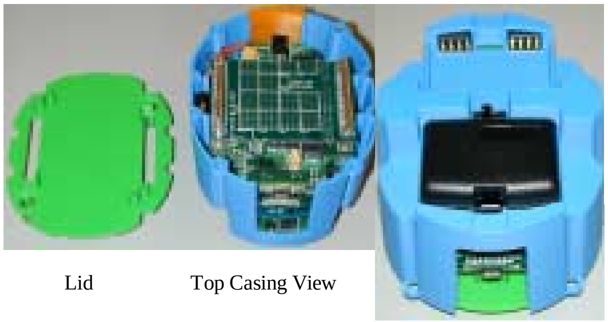


Figure 12: Capture Redesigned – No Undercuts

The remedy for the window undercut shown in Figure 9 caused a different problem with the battery board. To fix the undercut, a thicker rib was added to accommodate the larger opening for the properly drafted window capture (see Figure 12). In addition, the capture rib was only run down two-thirds of the length of the window (see Figure 13) to limit the width of the drafted rib. The addition of these thicker ribs created an interference with the battery board. Therefore, the second board iteration contained cutouts to avoid this interference.



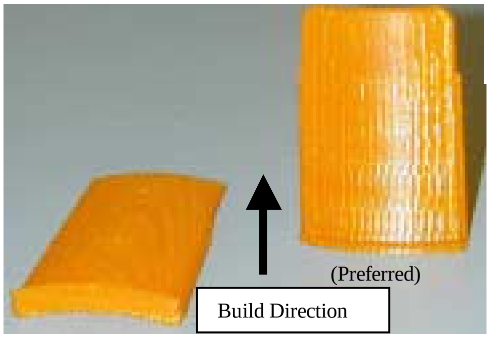
Lid Top Casing View

Figure 13: PRTB Third Generation Prototype

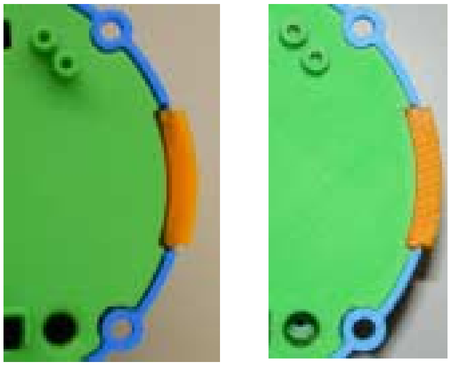
The final problem with the PCBs was on the radio board. Specifically, the antenna connector was not placed on the window side of the casing! This meant that it would be impossible to use the external antenna option without design changes. This change was made by the electrical engineer to avoid a collision between the antenna connector and the serial port, but was not communicated to the mechanical designer. This represents the major communication breakdown in this case study. After much discussion, it was decided to add a second window to the casing design (see Figure 13). This option did not generate a new mold, and provided slightly better access to screws for easier assembly. On the downside, it weakened the casing to cut out both sides, and it added an extra part to the assembly. However, this trade-off was considered to be the best available option, as it would be too costly and time consuming to modify the PCB.

Prototyping Issues

The injection molding issues raised in the second prototype were resolved successfully. However, an interesting prototyping issue arose around the manufacture of the third generation windows. As previously mentioned, these windows required a very high tolerance press fit with the case. However, the prototypes that were initially generated through FDM were ill fitting, and stressed the casing when inserted into the window capture feature. Upon closer observation, it was revealed that the build orientation of the FDM part was causing this problem. FDM is able to perfectly reproduce contours in two dimensions. However, three-dimensional constructs are approximated linearly through the stacking of two-dimensional layers. The thickness of the slices determines the accuracy of the approximation. In this case, the high tolerance capture ribs had been built in the least accurate direction. By altering the build orientation of the window, as recommended by Montero, et al. [11], so that the two-dimensional contours reproduced the critical areas, the fit of the window was improved dramatically without altering the design (see Figure 14).



Build Orientation of Two Windows



Poorly Fitting Window Fit Improved

Figure 14: Effects of FDM Build Orientation

RESULTS

All three components were successfully produced by injection molding, with no redesign necessary in the tooling to get good parts (Figure 15). No dramatic sink marks, or other defects that might be caused by improper design were evident. This fact underscores the power of following DFM rules. However, as with most projects, there was a little “fine tuning” required to get the first articles to match the intended design.

Figure 15: Injection Molded Final Product

For instance, one minor problem that appeared was that blush marks formed in the windows due to inherent moisture in the material. This was ameliorated by altering the gate geometry (Figure 16).

a) Initial Part b) Blush improved with gate change

Figure 16: Blush Marks on Windows

Translation Issues

The final deviation of the injection molded part from the design was an irregularity in the wall thickness at the upper edge of the casing (Figure 17). A comparison of the designer's CAD model and the manufacturer's CAM model revealed that a translation error had occurred. The model had originally been generated in I-Deas MS8, and exported as an IGES file to the MasterCAM software being used in the mold house. The file was then exported to an out-of-house shop using SurfCAM. Somewhere along this chain, a software translator altered some of the splines representing this top wall. Fortunately, this problem was fairly simple to correct, although at the cost of some of the surface draft. The fact that translator errors occur between mechanical modeling tools underscores the difficulties faced in developing translators and standards for all tools, particularly cross-domain tools.

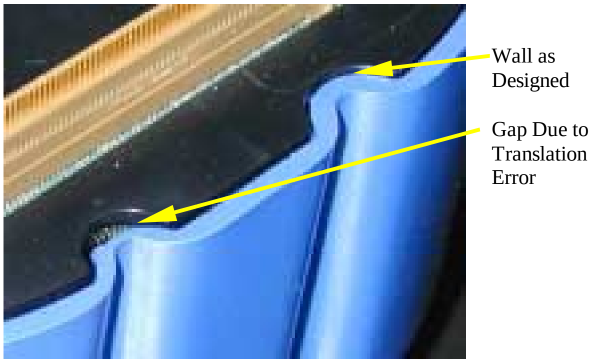


Figure 17: Irregularities due to Translation Errors

Figure 18: Casing Mold Core

CONCLUSIONS

The project was successfully completed, with the mechanical and electrical systems interfacing in the desired manner. In addition, experience and insight were gained into the process of concurrent product design. This experience has allowed us to target the areas in the design process in which improvements may be made.

Part of the design challenge lies in the fact that no good bridge currently exists between ECAD and MCAD systems. This makes it difficult to verify that designs properly match. The development of STEP AP 210 promises to ameliorate this problem by providing a cross-domain standard for model data.

Additionally, the careful identification of constraints and couplings between domains early in the design process was found to be a useful tool for identifying crucial interface points between the domains. DUCADE, a tool to assist in the identification of these constraints and to document design decisions and specifications is currently being developed at UC Berkeley's Manufacturing Institute to assist in this process. Feedback, comparison, and frequent prototyping were also found to help identify conflicts early in the design process.

One other key observation is that errors in design seem to usually occur in the areas *between* domains, rather than *within* the domains of which designers are experts.

ACKNOWLEDGMENTS

The authors wish to thank our colleagues at the BWRC for assistance, support, and collaboration throughout this project: R. Brodersen, J. Rabaey, S. Mellers, F. Burghart, and G. Kelson. We also thank MetalCast Engineering Inc. for their fabrication services and advice. This project was largely funded through grant number F29601-99-1-0169 from DARPA ITO entitled, "Communication/Computation Piconodes for Sensor Networks."

REFERENCES

1. Ziemke, M.C. and Spann, M.S., 1993, "Concurrent Engineering's Roots in the World War II era," *Concurrent Engineering, Contemporary Issues and Modern Design Tools*, edited by Parsaei, H.R., and Sullivan, W.G. 1st ed. London: Chapman & Hal, pp. 24-41

2. Noble, J.S., 1993, "Economic design in concurrent engineering," *Concurrent Engineering, Contemporary Issues and Modern Design Tools*, edited by Parsaei, H.R., and Sullivan, W.G. 1st ed. London: Chapman & Hal, pp. 352-371

3. Corbett, J., 1991, "Design for Manufacture: Strategies, Principles, and Techniques" edited by John Corbett et al., *Addison-Wesley Series in Manufacturing Systems*, Addison-Wesley

4. Canty, E.J., 1987, *Simultaneous Engineering: Expanding scope of quality responsibility*, Digital Equipment Corporation White Paper.

5. Rabaey, J., Ammer, J., da Silva Jr., J., Patel, D.(2000), *"PicoRadio: Ad-hoc Wireless Networking of Ubiquitous Low-Energy Sensor/Monitor Nodes"* WVLSI April 2000

6. Da Silva Jr., J., et al., 2001, *"Design Methodologies for PicoRadio Networks"* DATE March 2001

7. Boothroyd, G., Dewhurst, P., and Knight, W., 1994, *Product Design for Manufacture and Assembly*, New York: M. Dekker

8. Bralla, J., 1986, *Design for Manufacturability Handbook*, 1st ed. New York: McGraw-Hill pp: 6.21-6.44

9. Wright, P., 2001, *21st Century Manufacturing* 1st ed. New Jersey: Prentice Hall, pp. 330-345

10. Lopez, S., Wright P. 2001, "The Role of Rapid Prototyping in the Product Development Process: A Case Study on the Ergonomic Factors of Handheld Video Games" *Journal of Rapid Prototyping*, in press

11. Montero, M.G., Roundy, S., Odell, D., Ahn, S., Wright, P.K., 2001, *"Material Characterization of Fused Deposition Modeling (FDM) ABS by Designed Experiments,"* Proceedings of Rapid Prototyping and Manufacturing Conference, SME, 2001.

12. Brodersen, R., 1999, "A Design Environment for Single Chip Digital Radio Systems", DARPA Final Technical Report # F30602-97-2-0346

13. Pescio, C., 1997, **"**When past solutions cause future problems [Year 2000 problem]." *IEEE Software*, vol.14, (no.5), IEEE, Sept.-Oct. 1997. p.19-21.

14. Hazelrigg, G.A., 1996, *Systems Engineering: An approach to Information-Based Design*, New Jersey: Prentice Hall, pp. 21-30

15. Wang, F.C., and Wright, P.K., 1998, "Concurrent Product Design and Manufacture: A Case Study on Infopad, a Wireless Network Computer," *Proceedings of the ASME 1999 International Mechanical Engineering Congress &Exposition November 15-20, 1998 – Anaheim, California*

16. Billsdon, R.; Wallington, K.**,** 1998, "Wiring harness design: can a computer help?" *Computing & Control Engineering Journal*,vol.9, (no.4), IEE, Aug. 1998. p.163-8

17. Wang, F.C., Richards, B., and Wright, P.K., 1996, "A Multidisciplinary Concurrent Design Environment for Consumer Electronic Product Design," *Concurrent Engineering: Research and Applications*, Vol. 4, No. 4, pp. 347-359

18. Kemmerer, S. , 1999, "STEP: The Grand Experience," (Editor of) *NIST Special Publication 939*, National Institute of Standards and Technology.