Concurrent Product Design: A Case Study on the Pico Radio Test Bed

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Abstract

*This paper presents a case study on the mechanical design and fabrication of the **Pico Radio Test Bed:** a wireless networking node produced from off–the-shelf components 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 arise, problems are noticed, and requirements change.*

Introduction – Concurrent Design

Concurrent design is also known by several other names, including simultaneous engineering, concurrent engineering (CE), and integrated product development. Even though these terms were not coined until the early 1980s, the concepts that CE embodies have been implemented as early as World War II (Ziemke & Spann, 1993).

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." (Noble 1993)

This definition, like many others, 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 (Corbett 1991), it remains a subset of concurrent design.

Perhaps a better definition is offered by Canty (Canty 1987), "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 nicely 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 (Rabaey et al., 2000). This goal is to be achieved through a three-step implementation, the first of which is the Pico Radio Test Bed (PRTB) (da Silva Jr. et al. 2001). 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 manufacture paradigms used to produce the casing for this project.

Design for Manufacturing

The benefits of DFM are well documented (Boothroyd et al. 1994). 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 meets several of the key casing requirements. These requirements included: low per part cost, complex geometry, thin walled sections, and low weight, among others. 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) (Bralla 1986, Wright 2001) could be followed. The primary DFIM rules that were considered in this design included: uniform wall thickness to avoid sink, warp, and residual stresses, no undercuts for a simple two-half mold, 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 (Lopez 2001).

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 (Montero, et al. 2001). 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 the FDM process.

Legacy Issues – The Marine Intercom Project

As with most projects, the PRTB project did not "arise in a vacuum." Some of 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 (Brodersen 1999). 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.

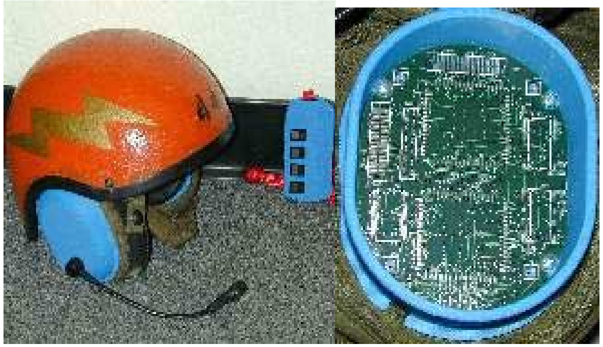

a) Helmet Assembly **b) Earpiece with PCB**

Figure 1: Legacy – the Marine Helmet Project

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). It is interesting to note that this general flat-sided oval shape was retained throughout all versions of the PRTB, even though the shape could have changed to any form after the first generation.

There are two key reasons why this shape was retained, even though it was no longer necessary for the design. First, it simply did not occur to anyone to change the board shape, even though an early change may have resulted in a simplification of the ultimate casing design. Second, everyone was overly concerned with other challenging aspects of the project to re-consider this simple aspect of the design.

About halfway through the project, someone finally thought to ask why we were still using the oval shape. At this point, however, significant effort had gone into designing both the new generation PCBs and the casing. A change in shape at this point would have essentially required starting the casing over again.

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 (Pescio, 1997).

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 other hardware. For this reason, it followed only DFM rules for the FDM process. At this point in the design, there were almost infinite options available, as the paring of the option space had not yet begun (Hazelrigg 1996).

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 possibly carry a patch-antenna. The connectors for the dummy board were to protrude from the casing to allow for connection to external sensor boards (to be designed later). The power board provided switchable power supplies to several voltages, and connectors to the radio board and external hardware. The digital board contained a complete CPU subsystem, a Codec interface, and Xilinx external RAM and ROM to support protocol research. The radio adaptor board contained connector adapters for either the Proxim RangeLAN II radio, or the Bluetooth Single

Chip radio. Additional hardware required to make the PRTB a self-contained system included: a battery, a power switch, and an antenna.

Selecting some of these components proved to be somewhat challenging. The battery used in Motorola's StarTAC cell phones was selected due to its small form-factor, its common availability, and the fact that a snap-fit mechanism is built onto it. A large, self-illuminating, case mounted power switch was selected to provide visual feedback on the state of the unit. The means for drawing power from the battery was neglected for the proof-of concept prototype.

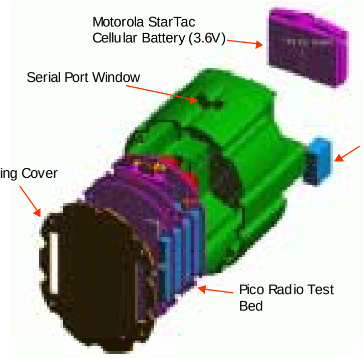


Figure 2: CAD model of PRTB version 1 assembly

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 to the casing with #4 screws. 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. The depth and position of these ribs was designed to accommodate either the Proxim or the Bluetooth radio boards. 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 casing was modeled in SDRC I-DEAS Master Series 8. 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 also featured two rectangular cutouts for the connectors on the dummy board, and a hole to access the reset switch on the digital board. These can be seen clearly in Figure 3, a photograph of the completed prototype. Note that the board stack is missing the dummy board, and shows the Proxim radio (the topmost board shown on the stack).

Figure 3: Prototype Components for PRTB version 1

It was recognized early on that the casing (and as a result, possibly the boards) would have to change when the design was updated to follow the DFM rules for injection molding. Figure 4 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 large sink marks to appear on the outside of the casing. Second, the large bosses would no longer fit through the existing cutouts in the first version of the PCBs.

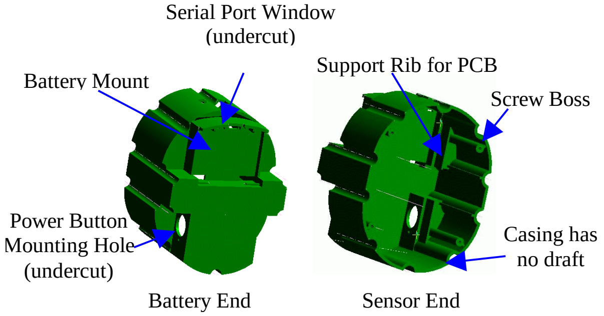


Figure 4: CAD model of PRTB version 1 casing features

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 and would have to be removed in the final design.

Note that at this point, there was no active fastening between the board stack and the casing. The design of the stack left no access for a screwdriver to the screw holes in the bottom PCB (radio board). As a result, a high tolerance fit was used to capture the boards on all sides and hold them in place.

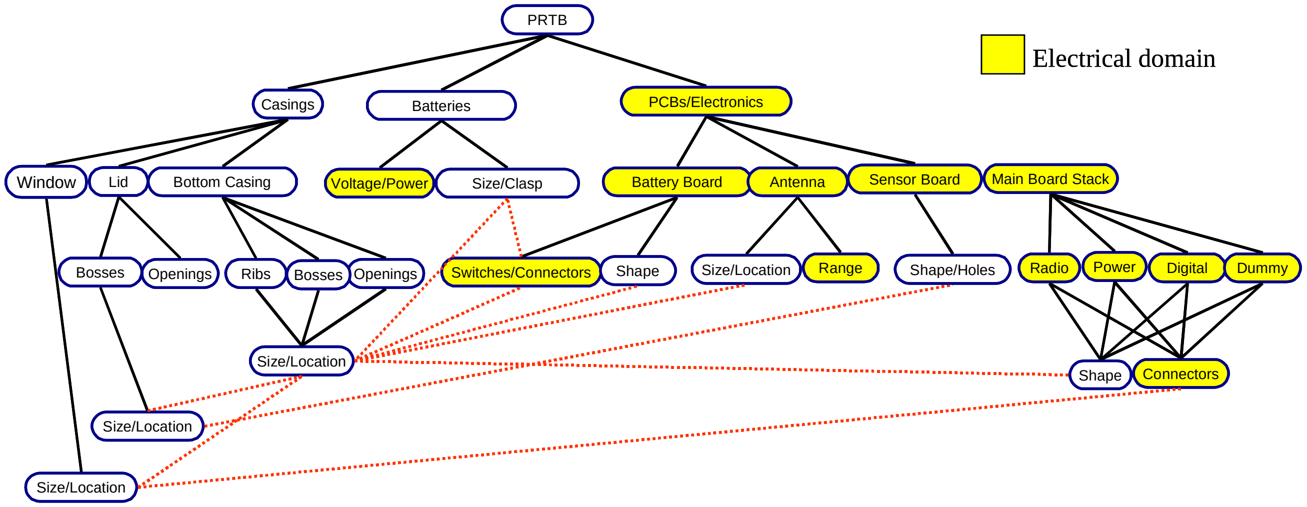


Figure 5: High Level Design Constraints Between Electrical and Mechanical Domains

PRTB – Second Generation

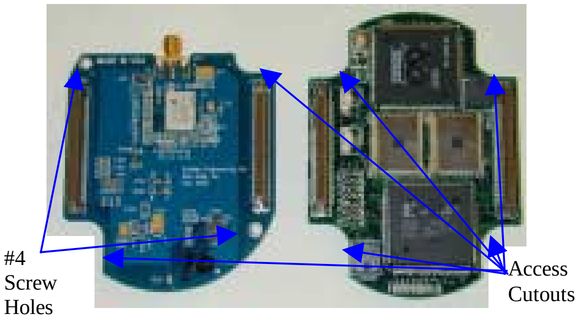
It was at this point that true concurrent design began. This is because the PCBs needed to be redesigned for electronics functionality reasons, allowing input and feedback from the mechanical disciplines to also be considered. Additionally, the DFM rules for the design became much more stringent at this 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 (Wang, et al., 1998). These coupling design constraints required particular attention from the different engineers involved, as well as concerted communication between them. The key areas that were identified were: PCB stack mounting, battery and battery connectors, antenna, sensor board mounting, port access, and wire routing. Figure 5 graphically shows some of these high-level constraints and couplings.

Printed Circuit Board Stack Mounting

Some of the issues revolving around PCB stack mounting were realized with the completion of the first generation prototype. As previously mentioned, 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 the tight tolerances that were 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.

Two approaches were taken in order to address these two issues. First, the board shapes were altered to allow larger bosses to pass through them, and to allow screwdriver access to the bottom board (see Figure 6). 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. Once again, this trade-off slightly increased assembly difficulty as the screws now were threaded down a blind hole. The use of guiding chamfers at the bottom of these holes and a self-aligning lid somewhat ameliorated this issue. Guiding ribs were included in the case interior to help position the PCB stack in the casing (and onto the screw bosses).



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

Figure 6: PCB shapes for PRTB Generation 2

The double stacked radio adaptor board coupled with an off the shelf radio board was abandoned in favor of a single radio board of our own design, using a Bluetooth radio chip. This integration allowed for a reduction of approximately one quarter of an inch in the stack height, as well as a simplification in assembly. The mounting method was also simplified (to two screw bosses) as the mounting scheme no longer had to accommodate two different radio board combinations (see Figure 7). As the Bluetooth radio board showed potential for lower power consumption, this technology was selected for inclusion into the second-generation radio board.

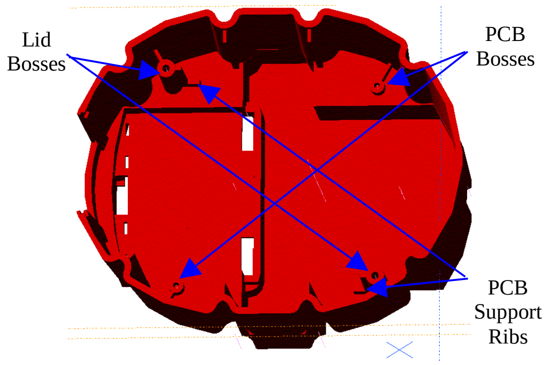


Figure 7: CAD model of Casing Mounting for Main PCB S

Battery and Battery Connectors

The Ni-MH battery (for Motorola's StarTAC cell phones) 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 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 do 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 directly 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 8). 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 cantilever that resulted from their required position on the PCB.

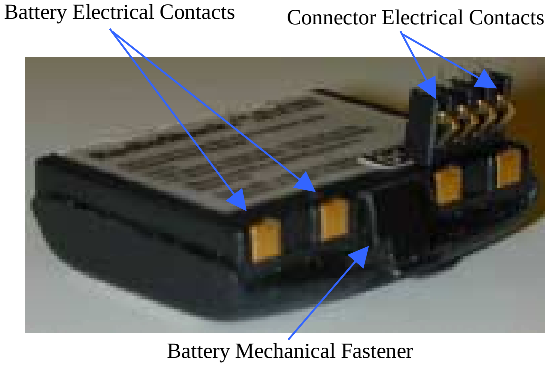


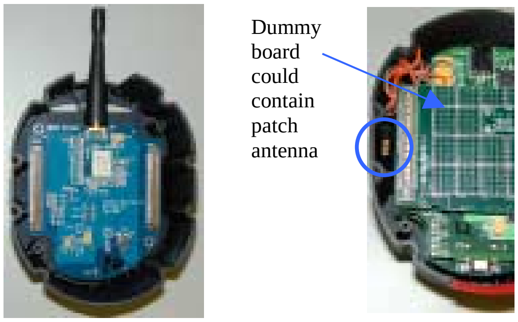
Figure 8: Battery and Battery Connector

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. This is because without an existing design, there were many unknowns. For this reason, the key to designing for the antenna was incorporating versatility.

Most of the nebulous issues revolved around the quality of the antenna reception, and how other components would affect it. For instance, it was unknown how the plastic casing or the other electrical components might affect reception. Similarly, the ideal orientation of the antenna within the casing was unknown.



a) External on PCB b) Internal on Harness

Figure 9: Antennae and Mounting Schemes

To account for these issues, three separate possibilities were created for antenna placement. First, the antenna could be affixed directly to the radio board, sticking out through the casing horizontally (i.e. parallel with the bottom of the case) (see Figure 9). Second, a smaller antenna could be located to fit internally into the casing, standing vertically. Finally, a patch antenna could be incorporated onto the dummy board at the top of the PCB stack. These three options were later tested to investigate which one provided the best reception for the radio board.

Sensor Board Mounting

The sensor board was to be external to the PRTB casing. This allowed it to be rapidly exchanged with replacement sensor boards containing different sensor packages. In addition, it exposed the sensors to ambient conditions, away from any noise generated by the main PCB stack. Unfortunately, exposure to the environment also brings about a risk of physical damage, water and humidity exposure, and other hazards. This risk was deemed acceptable, as the sensor board was the second least expensive board in the stack, next to the dummy board, and easy to exchange.

Connecting the sensor board to the main stack was to be accomplished through the use of the same board-to-board connectors used in the main stack. These protruded through the lid, providing a friction fit mechanical connection to the sensor. The sensor board was to use the same form factor as the radio board. This shape accommodated several functions. First, it provided two screw holes, so the sensor board could be attached to the lid via screw bosses in case the friction connection was insufficient (see Figure 10). Ribs were also added to the lid to support the corners of the board not attached to screw bosses. Second, the cutouts on the board provided screwdriver access to the screws that attached the lid to the casing. Finally, the cutouts allowed access to the reset switch through a hole in the lid.

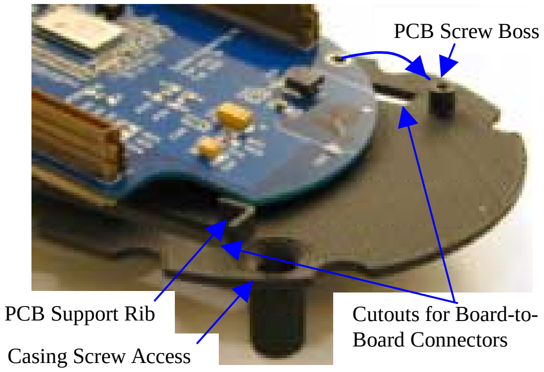


Figure 10: Sensor Board and Mounting Scheme

Port access

Several components in the casing needed to be easily accessible from the outside. The first generation casing simply provided a cutout in the side of the casing for serial port access. This access was necessary to provide debugging and data collection facilities for the node. The second generation casing also required access to the serial port, but the more stringent Design for Injection Molding rules prohibited a side cutout with a simple two half mold.

In addition, a few more requirements were added 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 the external antenna option (Figure 9).

To address these needs, it was decided to add a window to the one side of the casing (see Figure 11). 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 an expensive slider as 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 easily removable to provide access to the board stack components.

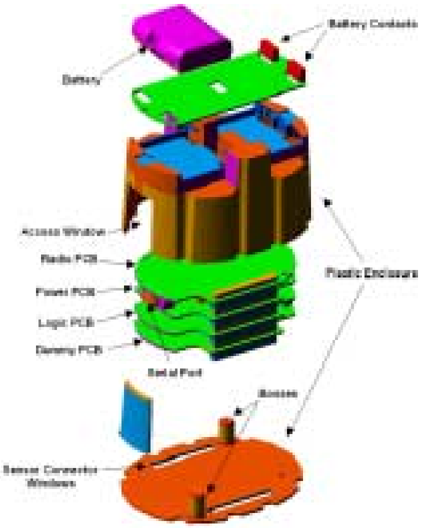


Figure 11: CAD Model of PRTB Version 2 Assembly

Wire Routing

Wire routing is often an overlooked aspect of design. This is because it is a design issue that is often 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 it. This can lead to major delays and cost overruns. Some of these issues are addressed in the literature (Billsdon, et al., 1998). 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 the internal antenna option.

Only two wire harnesses (and possibly only one) were required for the PRTB. 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.

A small coaxial wire was also required to run from the radio board to the antenna for the internal antenna option. 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. For instance, the antenna required two right angle connectors to turn the tight corner in the available space.

CAD Issues

As previously mentioned, all mechanical CAD (MCAD) work for this project was performed 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. 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 (Wang et al., 1996). In fact, of the three ECAD systems, only OrCAD was capable of exporting a format compatible with MCAD systems, DXF, without additional software.

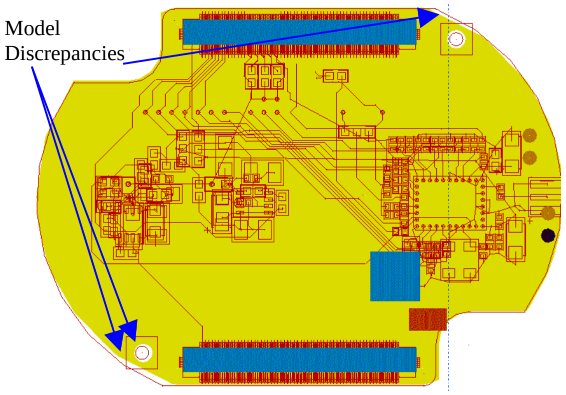


Figure 12: Comparison of ECAD and MCAD Radio PCB Shape

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 12 shows the mechanical radio board model in a light solid fill, the electrical model in dark lines, and the slight misalignment 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 can require hours of modeling individual electrical components for the mechanical designer, particularly if there is a potential for an interference with one of these components. This work must be completely re-done every time an ECAD design change occurs to insure that the models match.

Another issue facing communication between different design domains 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 requires 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.

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 (Kemmerer 1999).

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 verify that the part contained no undercuts.

Upon close inspection, the mechanical designer noticed a significant undercut created by the window capture feature of the bottom casing. Figure 13 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 13 are circled.

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.

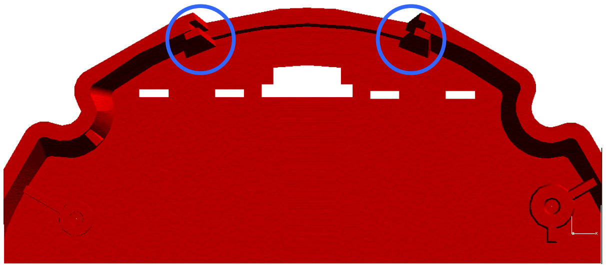
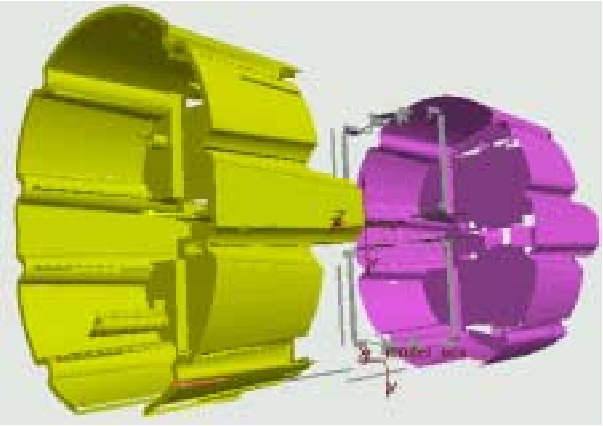


Figure 13: Undercuts Created by Window Capture Feature

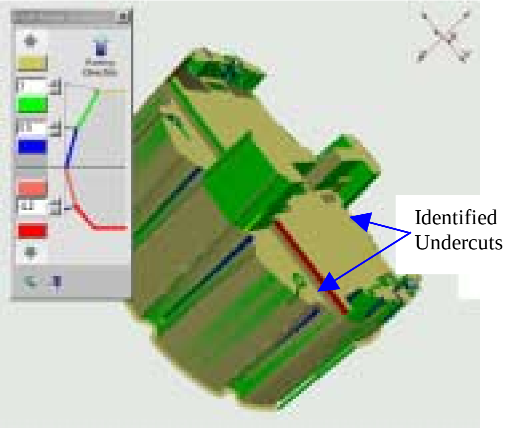
Quick Concept is a software package offered by Cimatron that performs automatic parting plane detection and undercut analysis. The bottom casing geometry was analyzed using this software, and the results are shown in Figure 14.

Areas identified by the arrows in Figure 14 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 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 13. From this experience, it seems that Quick Concept can be a useful tool, but should not be relied upon.

Material selection for the casing components was essentially left to industry standards. No special properties were required from the materials, except transparency for the window. Therefore, ABS was selected for the casing and the lid as it is commonly used in casings of consumer electronic equipment. It also has good impact and corrosion resistance. PolyCarbonate was selected for the window for its transparency.



Parting Simulation



Undercut Analysis

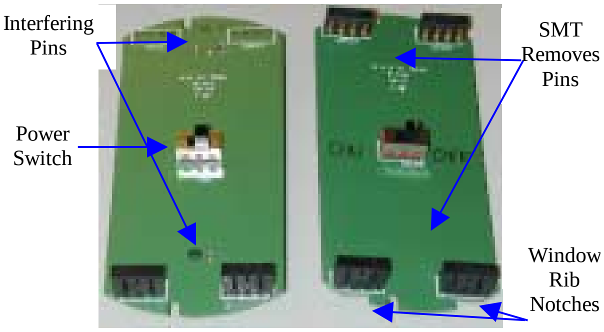
Figure 14: Bottom Casing Analysis in Quick Concept

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 on the FDM 1650. 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. As a result of this, errors found in the geometry of the PCBs were often compensated for by changing the mechanical design because of the much quicker turnaround.

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 17). This was accomplished by adding a second set of screw bosses to the lid for either screw configuration. The reset button access hole was also removed as the old sensor board shape covered it. Instead reset access was provided through the window. 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 primary cause for concern worked perfectly, while other, seemingly simple, design aspects caused 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. The screw slot was shifted in the PCB, as was the related screw boss in the casing, to accommodate this connector. This resulted in an asymmetrical board, but the fasteners were kept close to the battery connectors to provide proper support.



First Iteration Second Iteration

Figure 15: 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 15). However, this board rested on a planar surface in the casing. The pins of these connectors protruded from the backside of the battery and prevented the board 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.

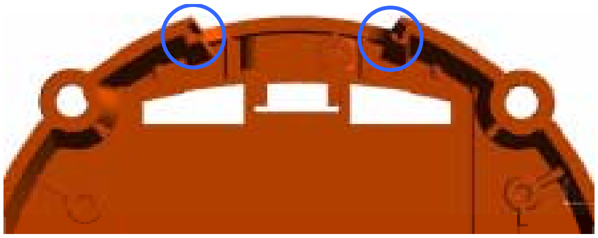


Figure 16: Window Capture Feature Undercut Redesign

The remedy for the window undercut shown in Figure 13 caused yet another 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 16). In addition, the capture rib was only run down two-thirds of the length of the window (see Figure 20) to limit the width of the drafted rib. The addition of these thicker ribs created an interference with the battery board. Therefore, the second iteration of the battery board contained cutouts to avoid this interference.

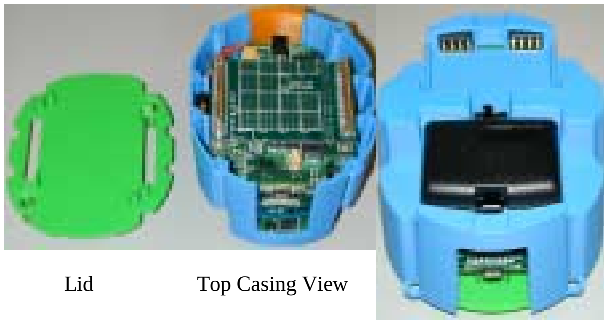


Figure 17: PRTB Third Generation Prototype

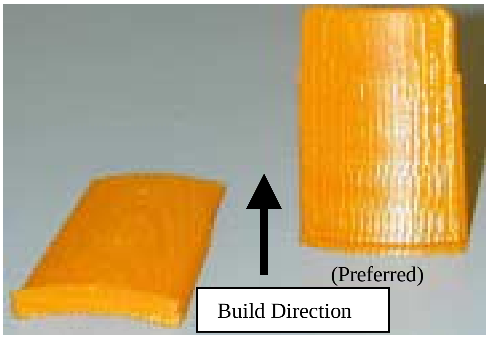
The final problem with the PCBs was on the radio board. Specifically, the antenna connector was not placed on the window side of the casing! This meant that it would be impossible to use the external antenna option without design changes. This change was made by the electrical engineer to avoid a collision between the antenna connector and the serial port, but was not communicated to the mechanical designer. After much discussion, it was decided to add a second window to the casing design (see Figure 17). 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 design. 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.

Final additions to the casing included small indents in the casing of “0” and “1” to indicate the power switch positions, and suspension loops. The casing was designed to sit on a flat surface on the battery side. Additionally, side flats were provided to allow Velcro attachments to walls. However, in experimenting with the second-generation prototypes, it was discovered that it was also convenient to hang them from the ceiling. To facilitate this, loops were provided at the top of the casing in the third generation design. These loops were essentially a bonus addition to the casing.

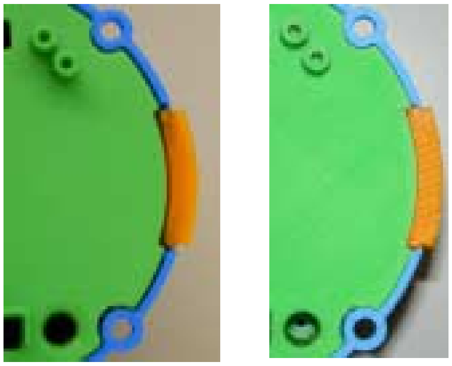
Manufacturing Issues

The injection molding issues raised in the second prototype were also resolved. The undercuts caused by reversed draft (shown in Figure 14) were corrected. More draft was added to some of the small bosses and ribs on the casing and lid to facilitate ejection from the mold. Also, as previously discussed, the window capture undercut shown in Figure 13 was removed. To verify that the final design was acceptable, it was run through the Quick Concept software once more. This time, the analysis showed no undercuts.

Another interesting manufacturing issue arose around the manufacture of the third generation window prototypes. 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. (2001), so that the two-dimensional contours reproduced the critical areas, the fit of the window was improved dramatically without altering the design (see Figure 18).



Build Orientation of Two Windows



Poorly Fitting Window | Fit Improved

Figure 18: Effect of Build Orientation on Window Prototypes

Results

All three components were successfully produced by injection molding, with no redesign necessary in the tooling to get good parts (Figure 19). 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.

Figure 19: Injection Molded Final Product

However, as with most projects, there was a little “fine tuning” required to get the first articles to match the intended design.

- The ribs on the lid measured .030” taller than the specification, preventing the sensor board from properly seating on the lid bosses.

- The “0” and “1” symbols for power designation were reversed on the casing bottom.

- The radii were missing from the casing window cutouts.

A last minute design addition was to add a small arrow to the lid to help orient the placement of the otherwise symmetric sensor board. These issues were all resolved with minor rework of the molds. Another 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 20).

a) Initial Part b) Blush improved with gate change

Figure 20: Blush Marks on Windows

Mold-Safe Design

An aspect of design for injection molding that has, until this point, been neglected in this paper is the concept of “mold-safe” design. Unfortunately, this consideration was also neglected in the design of the press-fit window ribs.

The concept of mold-safe design is simply the recognition that it is far easier to remove metal from a mold (through milling) than it is to add metal to a mold (usually through welding and grinding). Using this concept, high tolerance areas are often designed a little out of specification to allow the mold maker to make simple changes (through metal removal) to the mold for the desired effect. This leeway to the mold maker allows for simple compensation for non-uniform material shrinkage and other process variables that can affect the final geometry. This can result in significant mold cost savings.

In the case of the window rib design, the press-fit was intentionally designed with a little interference using the philosophy of, "hey, it looks great on the FDM prototype!" However, as the casing was made out of ABS, and the window out of PC, the relative shrinkage rate between the two was difficult to predict. The result was an injection-molded window with too much interference, preventing smooth assembly, and distorting the casing.

Unfortunately, in this case the mold-safe design would have been to design a loose fit, and allow the mold maker to tighten it up based upon the result. Because of this, the window mold required fairly serious rework. Fortunately, the mold maker had recognized the high-tolerance fit required between the window ribs and the casing, and had designed the window mold as a four-piece mold, with removable sections for the press-fit ribs. This was done with the recognition that this are may require re-work, and with the recognition that flash might occur on the high-tolerance ribs if a simple two-half mold had been used. This insight simplified the required changes dramatically.

Figure 21: Window Mold

Translation Issues

The final deviation of the resulting injection molded part was an irregularity in the wall thickness at the upper edge of the casing (Figure 22). After a while of the mold maker declaring that this irregularity was contained in the model, and the mechanical designer denying it, it was discovered 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 cross-domain tools.

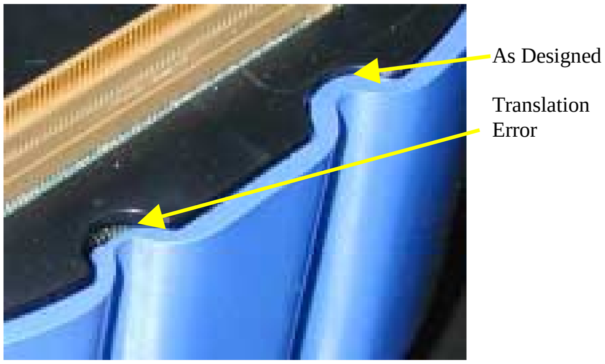


Figure 22: Wall Irregularities due to Translation Errors

Figure 23: Casing Mold Core

Conclusions

Several generalized conclusions can be drawn from the experiences of this case study.

Legacy issues can significantly increase the difficulty of a project. Basic assumptions of a project should be re-examined and questioned at each phase of a project to determine if changing requirements or conditions have rendered them obsolete.

Errors in design usually occur in the communication *between* domains, rather than *within* the domains of which designers are experts. Careful identification of constraints and couplings between domains at the beginning of a project can help avert problems. Feedback, comparison, and frequent prototyping can also help identify conflicts early in the design process.

No good bridge currently exists between ECAD and MCAD systems, making it extremely difficult to verify that designs match. The development of STEP AP 210 promises to ameliorate this problem by providing a cross-domain standard for model data.

Following Design for Manufacturability rules is critical to the success of a project. These rules can be implemented even for rapid prototyping processes, improving performance of prototypes. These rules vary from process to process, and many can be found in Bralla (Bralla 1986).

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