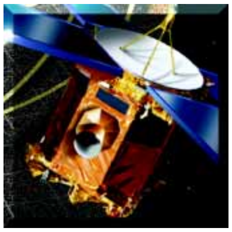

Cooperative Fabrication of the NEAR Spacecraft

Jay R. Dettmer

Cooperative fabrication was a key factor in building the Near Earth Asteroid Rendezvous (NEAR) spacecraft within the cost and schedule constraints dictated by the NASA Discovery Program. Because many of the traditional barriers between the engineering and the fabrication teams were avoided on NEAR, APL reaped the benefits of cooperative planning, design for ease of fabrication and assembly, and team problem solving. The result was a unified and high-spirited team focused on accomplishing the task. That teamwork, in combination with many of the enabling technologies within the fabrication organization, allowed APL to meet NEAR's cost, schedule, reliability, and performance goals.

(Keywords: Concurrent engineering, Design for fabrication, Hardware fabrication, NEAR, Teams.)

INTRODUCTION

As the first spacecraft to be launched in the NASA Discovery Program, the Near Earth Asteroid Rendezvous (NEAR) spacecraft had to stay within a $150 million budget (in 1992 dollars) and had to be launched within 3 years (Cheng et al., this issue). These constraints directly challenged the Engineering and Fabrication (TSO) Branch in APL's Technical Services Department to perform the detailed design, fabrication, and assembly (referred to henceforth as the fabrication) of a major spacecraft in less time and for less money than ever before. To meet this challenge, the staffs of the TSO Branch and the NEAR Program set about establishing relationships that enabled them to work better together. With the help of the engineering team and the Program Office, the TSO Branch engaged in cooperative planning, design for ease of fabrication and assembly, and team problem solving. The result was a unified and high-spirited team focused on accomplishing the task. That teamwork, in combination with many of the enabling technologies within the TSO Branch, allowed APL to meet NEAR's cost, schedule, reliability, and performance goals.

To put the overall fabrication effort in perspective, consider that it took 118 flight printed wiring board (PWB) assemblies and 36 major flight mechanical assemblies to create the in-house fabricated portion of NEAR (Hartka and Persons, this issue). Behind that hardware were 596 electrical drawings, 532 mechanical drawings, and 335 specifications. It took approximately 107,000 man-hours (about 53 man-years) of TSO

Branch labor to create those detailed drawings and to build the hardware. Including materials, but not the electrical parts, those in-house drawings and hardware cost about $6.4 million, or under 7% of the total program's cost. An additional $3.8 million of parts were purchased for the in-house electronics effort.

COOPERATIVE PLANNING

From the very beginning, the TSO Branch and the NEAR Program Office realized that cooperative planning was essential. Because the TSO Branch had reduced its workforce after the Midcourse Space Experiment (MSX) satellite was completed in early 1993, the Branch had to determine if the remaining skill base was adequate to meet the technical and capacity demands of NEAR. A miscalculation would either make it impossible to meet NEAR's schedule demands because of inadequate capacity or make the resulting costs too high as a result of excess capacity. Because a variety of skills are needed at various phases of the fabrication effort (e.g., designers, fabricators, assemblers, and other specialists), the entire workforce needed to be balanced.

In October 1993, months before any fabrication work was ready to begin, a representative from the TSO Branch began attending NEAR team meetings and holding discussions with the subsystem lead engineers. Those discussions enabled the TSO Branch to thoughtfully plan the acquisition and training of additional short-term personnel. In addition, those early meetings and the continued Branch presence enabled the leader of the fabrication effort to become a part of the NEAR team and to establish good working relationships.

As the overall effort became more defined, schedules were developed detailing the handoff from engineering design to detailed design to the start of fabrication. Those detailed schedules led to further refinement of the staffing plan for the various skill areas. Staff were hired in a slightly anticipatory method instead of a delayed reactionary method. That planning resulted in balanced budgets and on-track schedules.

DESIGN FOR FABRICATION

The old practice of "throwing a design over the wall to fabrication" has been replaced with design for fabrication (also known as concurrent engineering[1]). In design for fabrication, the engineering team (circuit engineer, thermal engineer, and stress engineer) works with a fabrication team (packaging engineer, reliability engineer, designer, fabrication specialist, and assembly specialist) to reach agreement or consensus on each electronic or mechanical assembly.[2] By working together when the subsystem is still in the conceptual and detailed design phases, they avoid many problems that may not become apparent to the engineering team until the subsystem is actually being built. Because changing a problem at the design stage is much easier than changing the hardware later, the program saves money and prevents rework delays and schedule delays caused by increasing the fabrication workload.

The NEAR team practiced design for fabrication by holding fabrication feasibility reviews, making extensive use of packaging engineers, and using multidisciplinary product teams to monitor subsystem fabrication. All of these methods forced the engineering and fabrication teams to focus on issues and to communicate more frequently. The result was a significant reduction in hardware changes during the actual building phase.

A major result of the design for fabrication was the dramatic reduction of integrated circuits that had to be mounted on heat sinks (Fig. 1). Previous practice tended to put every integrated circuit on a heat sink or heat spreader, regardless of its power dissipation, to ensure

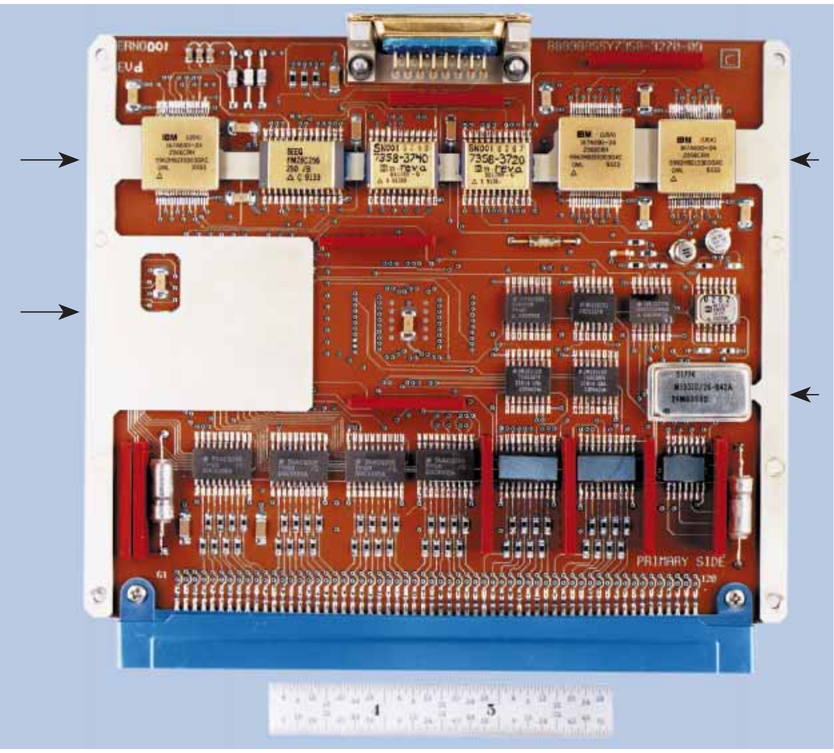

Figure 1. Printed wiring board with selective heat sinking (arrows point to the heat sinks). The large rectangular portion of the heat sink penetrates the board to cool a component on the hidden side of the board.

that there was adequate conductive heat transfer in the vacuum of space. This old practice increases the complexity of the board layout and the weight, cost, and schedule. In contrast, the NEAR team took the time to perform a thermal analysis for each component on each board. The thermal analysis determined if a particular component had to be on a heat sink, or if its leads would transfer enough heat, or if the addition of a thermal compound between the component and the board would be sufficient.

The desire to reduce the weight of the NEAR electronics enclosures also led to the following interesting example of design for fabrication and engineering trade-offs. We wanted the enclosure sidewalls to be as thin as possible to reduce their weight; however, they needed to be structurally rigid and able to be machined. As seen in Fig. 2, these conflicting requirements led to enclosures that had large numbers of strengthening ribs and very thin sidewalls, all made out of lightweight magnesium. The use of magnesium saved approximately 36% of each enclosure's weight but required special procedures to avoid the fire hazard during machining. Since the cost of the wasted material is insignificant with respect to the weight-savings benefits for a satellite, the preferred way to make such an enclosure is from a solid block of metal so that internal stresses are minimized while the thermal and structural properties are maximized. With only a few design limitations, the TSO Branch was able to fabricate these enclosures from a solid block of magnesium using a combination of conventional machining and two types of electrical discharge machining, one of which is shown in Fig. 3.

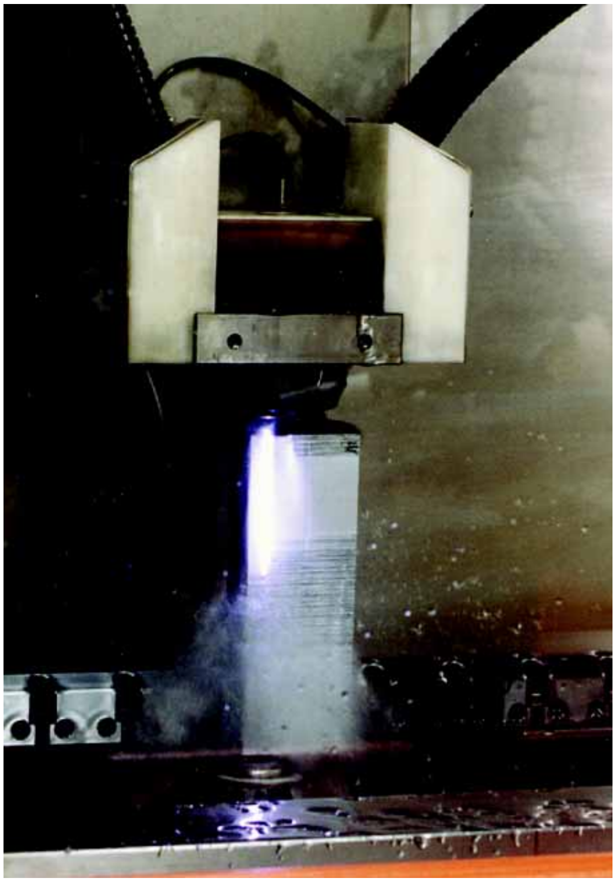

Figure 3. Wire electrical discharge machining for complex shapes. The bright glow is where the charged wire is burning away the metal.

NEAR made extensive use of rigid-flex PWBs (rigid, or conventional, PWB sections connected by flexible conductor sections) to solve many issues of design for fabrication while exploiting their inherent benefits of saving weight, reducing volume, eliminating assembly steps, and minimizing human error.[3,4] NEAR's most effective example of the use of rigid-flex PWBs was the detector electronics assembly for the Near-Infrared Spectrometer. Two of these assemblies required a modest amount of electronics to be packaged in a small enclosure. Such packaging would have previously required the use of multiple PWBs connected by a wiring harness in a small enclosure, which is a difficult task. NEAR used a rigid-flex PWB consisting of four rigid PWB sections connected by four flexible conductor sections (Fig. 4). Figure 5 shows how the resulting single assembly was folded up to fit in the required space after its components were attached to the board in its flat state.

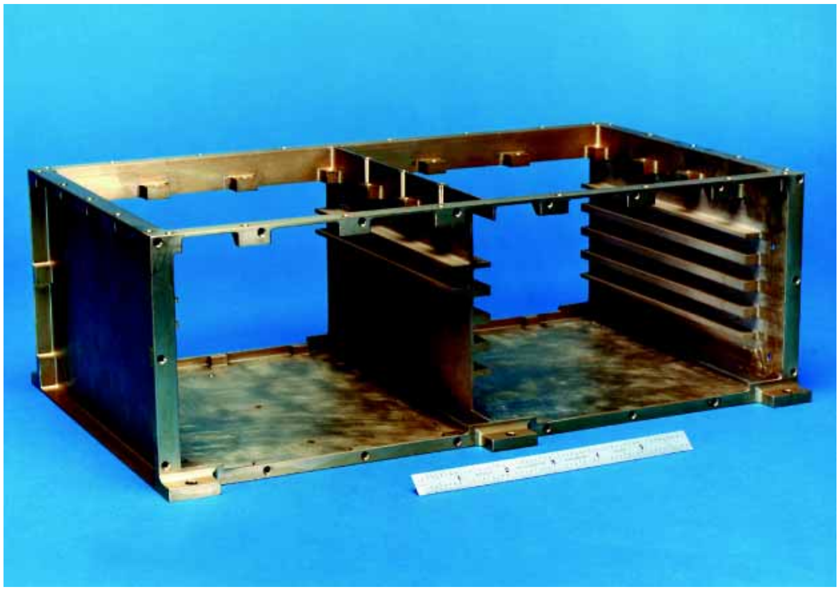

Figure 2. Electronic enclosure made from a solid block of magnesium.

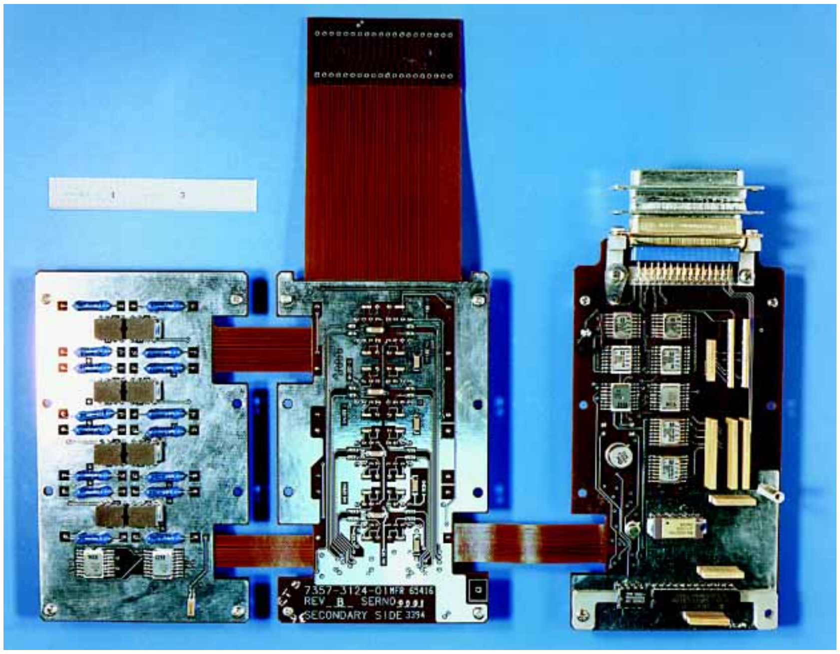

Figure 4. Rigid-flex printed wiring board in a flat configuration.

TEAM PROBLEM SOLVING

A number of factors led the NEAR Program to an environment of team problem solving without the "finger pointing" and hard feelings that so often occur when things go wrong in a fast-paced program. Key factors that led to this good working environment included the "just the facts please" attitude of the program manager and the system engineer, open communication of problems and progress by the fabrication leader, cooperative working relationships of the engineering and fabrication teams, and shared common purpose of the project. Team problem solving paid off in the quick and fair resolution of resource and technical issues and the correction of errors.

The most striking demonstration of team problem solving was the NEAR Program's weekly fabrication-focus meetings. Each Wednesday, several members of the engineering, program, and fabrication teams would meet for an hour to focus on specific subsystems with which they were having difficulties. Discussions were open and fair, with the supervisors, hands-on engineers, and technicians all presenting their viewpoints. Compromises and decisions were made on the spot and implemented within hours. These businesslike meetings flushed out the issues and solved them without creating bad feelings.

During any effort the size of NEAR, mistakes in engineering, design, and fabrication are bound to be made. On configuration-controlled hardware for space, exact records need to be kept of the errors and their corrections. To resolve these problems efficiently, several members of the engineering, program, and fabrication teams met every day at 1:00 p.m. The issues of the day and their corresponding documentation were discussed and approved or denied. This meeting, which typically lasted for 30 min, approved 344 drawing change notices and 260 material review discrepancy forms during the fabrication effort.

The resolution of technical issues also benefited from the team problem-solving approach. A large number of purchased DC-to-DC power converters used on a variety of NEAR boards were found to have problems that required last-minute circuit changes. One circuit change required the addition of three diodes in series on some of the converters' output leads. Since the NASA specifications required that each end of a component be firmly attached to the circuit board, it seemed at first that the boards would have to be rebuilt, or that a waiver would have to be granted to accept the non-

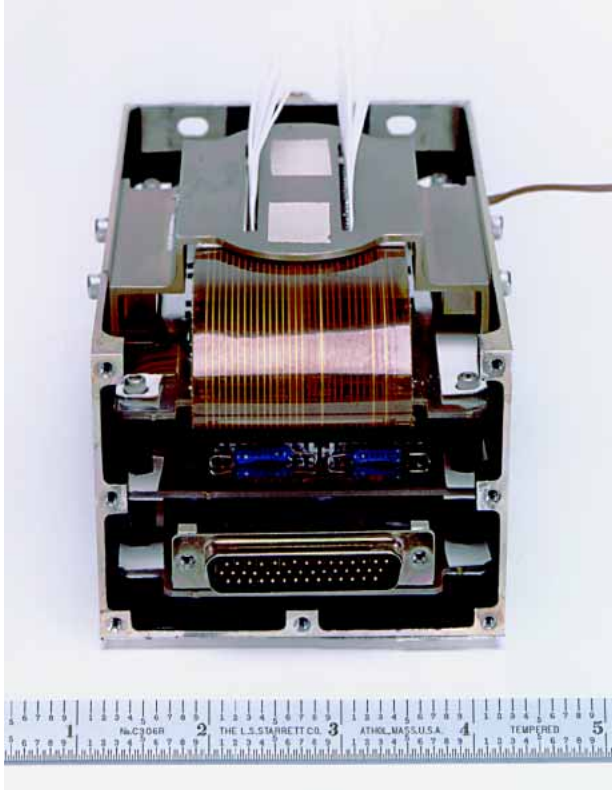

Figure 5. Rigid-flex printed wiring board in a folded configuration.

standard practice, or that another engineering solution would have to be found. To solve the problem, the fabrication staff quickly developed a method of gluing additional solder pads (Fig. 6) to the existing printed circuit board that would withstand the high soldering temperatures.

ENABLING TECHNOLOGIES

Even with the cooperative efforts described, the NEAR satellite could not have been built were it not for a number of enabling technologies and the skilled workers in the fabrication groups. Some of the enabling technologies are highlighted next.

Computer-aided engineering tools[5] were used by many of the electrical engineers for schematic capture and circuit simulation. These tools enabled them to define a circuit and then to test that circuit in a simulated environment within a few hours, without actually building the hardware. The tools made it easy for the engineering team to identify and correct errors before the hardware was ever built, thus saving money and time.

Computer-aided design (CAD) tools[5] were used in the detailed board layout to ensure that the circuit board exactly matched the engineering schematic diagram. CAD library parts, including the parts' package descriptions and board-mounting information, were defined and verified centrally. These CAD library parts were then shared among all of the board designs, avoiding duplication of efforts. CAD tools resulted in circuit boards that were correct by construction.

Advanced mechanical CAD tools were used extensively to design enclosures and mechanisms in three dimensions. Working in three dimensions avoided the problems created by trying to represent physical mechanical objects with only two-dimensional drawings. This method resulted in fewer errors and oversights.

Rigid-flex PWBs[3,4] were used in certain applications that required electronic circuits to fit into complex enclosures without a wiring harness (Figs. 4 and 5). The volume of the electronics was thus reduced, and the additional weight that would have been required by connectors and traditional wiring was avoided.

Unattended numerically controlled (NC) machining was used extensively (Fig. 7) on NEAR. Although standard NC machining provides great accuracy and eliminates human error, unattended NC machining provides additional cost savings by minimizing the amount of human labor. Each machinist was able to run multiple jobs or to set up a job to run unattended during the evening.

Process controls[6] and configuration controls[7] ensured that every item was built in a reliable, repeatable, and documented manner. They will enable us to trace failures on the spacecraft back to their components and fabrication methods.

The precision lead bending of electronic components proved to be a time-saving and enabling technology. It made the mounting of surface mount integrated circuits an exact science. Calculated, precision lead bending enabled the leads of the electronic devices to precisely mate with the solder pads while the package precisely mated with the heat sink (Fig. 8). By eliminating trial and error in mating the devices, we saved time and money while making a better product.

While it is often taken for granted today, electronic communications in the form of network-shared disk drives, electronic mail, and electronic bulletin boards

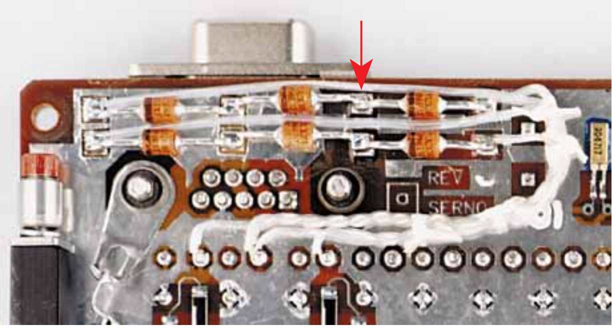

Figure 6. Glue-on solder pads allowed additions to the circuits.

Figure 7. Unattended numerically controlled machining. Note that the tool currently in use has been selected from the tool turret.

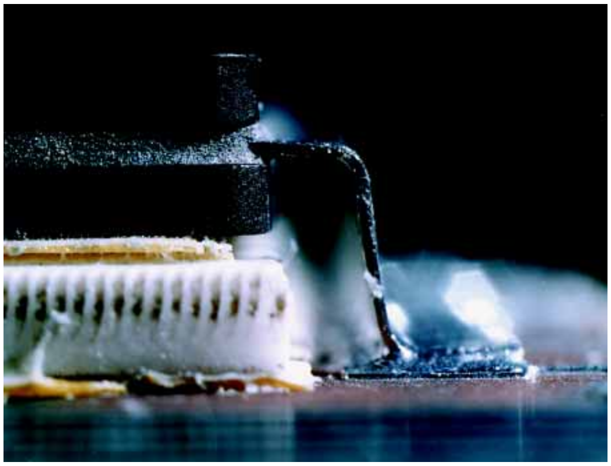

Figure 8. Precision bending of leads enabled controlled surface mounting of integrated circuits.

helped to quickly disseminate information among the program, engineering, design, and fabrication teams. This quick dissemination of information helped to build a well-informed, yet physically dispersed, team whose members could make intelligent supportive decisions on their own.

CONCLUSION

The detailed design, fabrication, and assembly of the NEAR spacecraft required many people with different skills in various organizational units to work closely together while under technical, schedule, and cost pressure. In the past, organizational, personal, and technical conflict sometimes stood in the way of getting the work done. NEAR's cost, performance, and schedule requirements would not tolerate such a loss in efficiency.

Through a variety of actions, the NEAR Program Office, engineering team, and fabrication team effectively put these potential conflicts aside and established cooperative planning, design for ease of fabrication and assembly, and team problem solving. The result was a unified and high-spirited team focused on accomplishing the task. Combined with many enabling technologies within the fabrication groups, cooperative fabrication helped APL to meet NEAR's cost, schedule, reliability, and performance goals.

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