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John Cardone on Designing Flex for Spacecraft p.12

Flexdude Abides: PCB Design for Satellites p.24

Much More!

THE AEROSPACE ISSUE

John Cardone on Designing Flex for Spacecraft

by Andy Shaughnessy

If you watched footage of the Mars rover driving all over the red planet, you're familiar with some of John Cardone's handiwork. He's been designing rigid, flex, and rigid-flex circuitry for spacecraft since he joined JPL in the early '80s, and he's worked on some of the more ground-breaking flex circuits along the way. Now John runs his own design service bureau, JMC Design Services, and he continues to design circuitry for things that blast off. I caught up with John recently and asked him to give us the straight scoop on designing boards for spacecraft.

Andy Shaughnessy: John, give us a little bit of background about yourself, and how you got into PCB design.

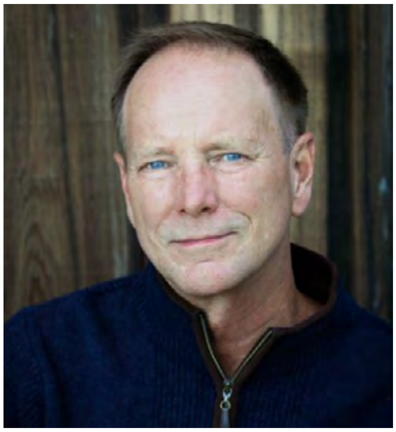
John Cardone: My first engineering jobs were with Raypak, where I designed hydronic deicing systems (which looked very much like film heaters on a larger scale), and then Medical Communication & Instrumentation (which coincided with my start at Cal State, Northridge), where I designed my first electronic enclosure, PWBs and flex cable, all on the drafting and light tables with pencil and red/blue tape from Bishop Graphics.

The product I redesigned at MCI (later Biocom Inc.) was a medical communicator, the Biophone 3502, which was a feature of the old '70s TV series "Emergency." You can see the old unit by clicking here. It had miles of wire, stack pole switches, and a gutted Motorola radio behind the front panel. The attached pdf is of the manual for the replacement radio. The second pdf is a copier scan that shows only a portion of the panel flex cable (focal length issue). I took this with me on my CSUN job fair interview with JPL, and as it happens not too many other students had comparable show-and-tell items.

After graduating from CSUN I went to JPL as a mechanical design engineer. At that time JPL was just getting into CAD design and they had three seats of Computer Vision Cadds3 that were kept in a dimly lit closet. My first task (after listening to Cadds3 training tapes, and reading the manuals) was to layout a two-layer PWB used in a PAP smear analyzer. From there I worked in a support role for most of the flight projects that came through our mechanical design group from Galileo on. The drafting tables were slowly replaced by more CAD stations; we transitioned through software revisions, flirted with ProE (until the designer revolt), and settled on Unigraphics NX and Solidworks. PWB design moved from Computervision to Protel, Mentor and Altium. My work focused on electro-mechanical design. This might include light structure, electronic enclosures, schematic capture, PWB design (rigid, flex, rigid-flex), and cabling.

***Shaughnessy:** Tell us about JMC Design Services, and what led you to start your own company?*

Cardone: I worked at JPL from 1983-2005. At that time factors all converged to allow my family to make the move to Grenada where we have a small ranch, for the purpose of raising horses. If I could have done that and stayed at JPL I would have, but it's 650 miles away. The next best thing was to contract to them as a remote associate, and this I've been doing for JPL and a number of other clients since 2005.



John Cardone

***Shaughnessy:** So you were at JPL for 22 years, when they were just getting into EDA tools. What were some of the biggest challenges you faced (technical, bureaucratic, etc.) during that time?*

Cardone: When I started at JPL in the design room, they were just getting started in MCAD with CV CADDS3. JPL is a matrix organization, and I am not certain of the state of EDA tools in the sections with an EE focus. It may have been very rudimentary as I do recall creating many schematics and PWBs for the Galileo S/C.

CV was a unique platform because it did it all. You could create an electronics enclosure, add a PWB to it, link the PWB to a schematic net-list from a schematic created in CV, and then place and route the PWB. CV is still being used in the ship-building industry because it is very adept at large assemblies. It was later purchased by ProE, hence its decline and JPL's search for a replacement. I believe that the fact it was being used at the time of my start at JPL fostered my inclination to cross the boundaries that typically exist between mechanical, electrical, systems, thermal, etc. On the MER (Mars Exploration Rover) project I was a member of the mechanical, systems, and electrical engineering teams.

At JPL these were few bureaucratic challenges. It's a marvelous place, and more of a campus environment than a commercial engineering firm. The one challenge I felt is that the vast majority of funding is tied to a specific project, so we could not be a Bell Labs where you have the luxury of playing around until you hit on something. An axiom is that technology used on flight projects must have a high TRL (technology readiness level), and how do you get a high TRL? By being demonstrated on a flight project, of course!

I cannot complain about the progress that EDA tools have made over the years. Having started on a light table, being able to insert or delete a trace with a few clicks is amazing. Even in the early '80s, CV had gate and pin swap, and back annotation. But it was certainly slower. There were many times I babysat a computer overnight as it chugged along. At that time (and today) we were limited in our selection of components because of their fault tolerance and radiation hardness. It was very rare that we spent the mass to radiation-shield a component. It had to arrive at the dock hardened. So, for example, Galileo PWBs were designed with robust CMOS logic in flat packs. We still occasionally use flat packs, and even some DIPS.

The environment: One major concern in both mechanical and EDA design is the severe thermal cycling seen by both earth orbiting and space probes. With mechanical design (which includes printed flex cabling) attention has to be given to the CTE of all dissimilar materials with an interface. This effects bolted joints, necessary machining tolerances, selection and use of potting materials, and on and on. As you know, the X-Y CTE of polyimide has been tuned to be close to that of aluminum, but since it has a ~constant bulk CTE, plated through-holes that see large delta T can crack due to the large difference in the CTE of CU and CTE-Z of polyimide.

Let me focus on PFC (printed flex circuit) for a moment. Its optimal design isn't necessarily the same as in a rigid, or rigid-flex design. Here are a few examples: First, in a PFC, for controlled differential impedance, an off-set broad-side coupled configuration is much more space efficient, and gives a better transition at the connector interface (less reflection) than using edge-coupled. And in a PWB design edge coupled is most common. This creates challenges that need to be resolved at the PFC-to-PWB interface (it's all about interfaces).

Second, every guide you will see on PFC design will warn that I-beam construction is a no-no. The problem is that a staggered design adds impedance where you may not want it, reduces common-mode noise rejection, and it uses more cable width or allows increased crosstalk between functions. To validate our designs, we conducted life tests with at least 2x needed cycles, under vacuum and temperature extremes. I have five rovers on Mars (one Pathfinder, two MERs and two MSL rovers) and each has far exceeded its required life.

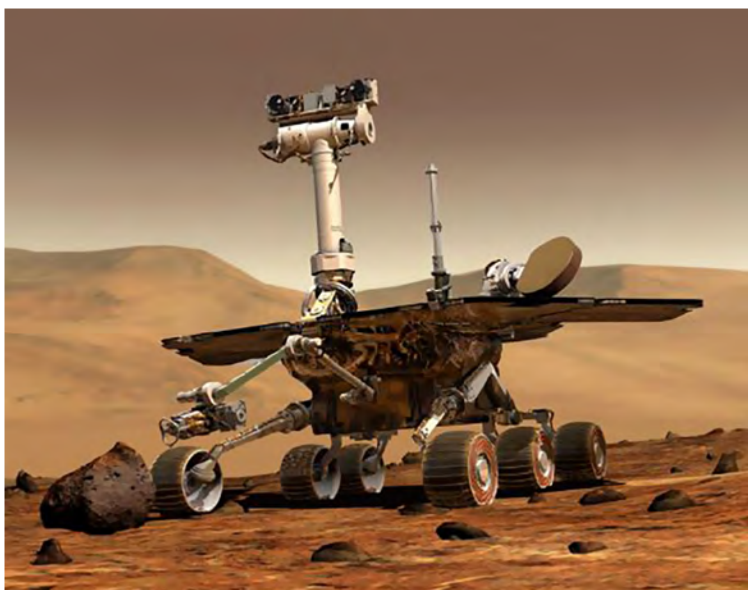
Third, as the Mars rover designs have progressed, the PFC challenges have gotten increasingly more strident. From Pathfinder to MSL, PFC cable lengths have increased to more than 10m, with full end-to-end cable lengths of ~15m. The longest cable runs transition from PFC inside the rover, to round wire outside, to flex over a 5 DOF (degree of freedom) robotic arm, back to round wire for a transition at the arm end, then to flex in a rolling loop on the drill mechanism, to a final wire segment to the motor. In this example of the drill rotation motor, the requirement was <0.8 ohm one-way. We met the requirement, and for the upcoming M2020 project we're on track to improve upon it (and to reduce the trace-to-chassis capacitance which was found to introduce some noise into the encoder reading). Oh, there's another challenge. How do you put noisy motors, heater, brakes (yes there are holding brakes) and quiet encoder, temperature, and data telemetry on the same cable? By the way, there are more than 4.5 miles of printed flexible circuitry in the rover's arm alone.

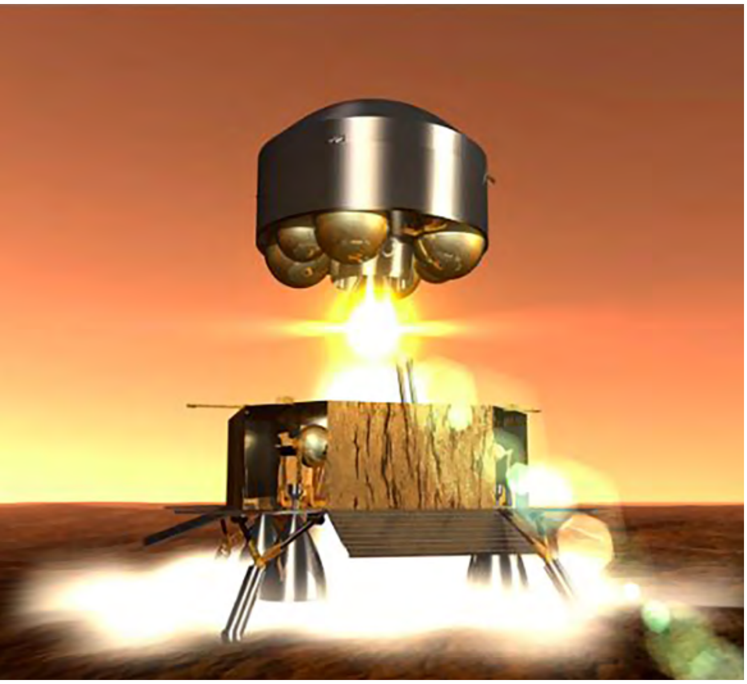
***Shaughnessy:** Tell us a little more about your work on the MER. What were some of the unique issues you encountered on that project?*

Cardone: To tell you about MER, I'll need to start with MSR (Mars Sample Return). I was part of a small pre-planning team that was outlining the configuration for this mission. At some point NASA decided that returning a sample to Mars orbit, by a rover to be eventually picked up by another spacecraft, was too ambitious. As a side note, M2020 will be preparing and packaging samples, for eventual return to earth. I haven't looked into how they plan to do this but the plan might be up on jpl.nasa.gov.

From that context MER began. A number of mechanical designers were co-located. Designers do little "engineering" and they generally work for many Cognizant Engineers. A CogE would be responsible for an element of a project, attend budget meeting, contract design, analysis, fabrication people, etc., while the designer drives the development of the CAD model and the documentation. I managed the design of all things inside of the Rover body, another managed the rover exterior, another the mobility system, robotic arm, mast cam, etc.

Because I started with the MSR team, I came into the MER project with a viable configuration concept. The MER rover body is essentially an ice chest. Inside it is something like a 6U VME chassis. The front and back of this chassis supports stuff like the UHF and X-band components, the redundant batteries, inertial measurement units, and the cable tunnels. The cable tunnels are insulated serpentine pathways that provided thermal isolation for the rover's wiring between this chassis and the





rover exterior. From there the wiring goes to all of the actuators and instruments.

For the rover's internal wiring, I developed a 4-layer printed flex cable construction (two conductors, two Faraday shields) with edge launched micro-d connectors. I think there were 50 flex cables in the front and rear cable tunnels, each about 1m in length. The only round wires exiting the rover were a couple of RF lines to the antenna, ~20 pyrotechnic lines, and a couple of others due to last-minute changes. This saved considerable mass, volume and, most importantly, it reduced our thermal leakage. The thermal leakage related directly to needed heater power and solar panel size, and operational constraints; for example, how long to heat up before we can do science?.

In addition to this, I also created the rover wiring diagram, and the flex cable designs for the robotic arm (seven cables up to 3m in length), panoramic camera mast (seven cables up to 1m in length), high-gain antenna (HGA—three cables up to 1m in length), and the mobility system (six cables up to 1.8m in length). The mast used a COTS twist capsule, the arm and the HGA used its continuous flex in custom twist capsules, and the mobility had a one-time deployment of a rolling fold for the telescoping structure.

The biggest challenges were:

A) There was some bias against flex because it is considered too costly, impossible to modify and comes with a long lead time. Our first big use of flex was two impossibly complicated and expensive 30+ layer rigid-flex circuits that I designed for the first rover, Pathfinder. I still hear the same bias on each successive program, and on each program printed flex cables are an enabling technology that allows them to meet the mission goals.

B) I spent a great deal of time negotiating with instrument and electronic designers over pin-out designs that would enable efficient use of flex. For the 100 ohm differential stuff, it means talking them into broad-side instead of edge-coupled (not a huge deal for them since the electronics generally used wire between the connector and PWB. This gives thermal compliance between the PWB and the chassis, and doesn't overly constrain or stress the solder joints). We also segregated noisy stuff to one edge, and quiet to the other and placed shield line between.

C) Controlled impedance. The flex cables used Dupont AP material and acrylic adhesive. To hit the 100 ohm differential I can reduce trace width, but I need to stop at some point to maintain the robustness of the trace (12 mils), increase the offset distance, but this needs to be kept as small as possible or the coupling will shift to through the shield layer and it eats up finite cable width resources (~24mils), and I can increase the distance between the trace layers and the shield layers, but this increases cable stiffness, increases needed twist capsule diameters, and static bend radii (~12 mils).

D) I created flat patterns for each of the cables by modeling them in their flight configurations, and then flattening each design using the sheet metal module in CV Cadds4.

When it was all done, I think it came together pretty well. Its original mission was supposed to be 90 sol (one Martian day). I don't recall exactly how long they ran them. I think it was over five years, and that they were still mostly operational when they decided to stop the operational funding. You will always need to check me on mission facts. I'm a design mercenary, and have moved on to a new project by the time something has launched. I'm one of 20 JPL engineers listed on a patent (USD487715) for the "ornamental design" of the MER.

***Shaughnessy:** It's interesting that you designed everything inside the Rover body, and your patent is for "ornamental design." Do you have any other patents?*

Cardone: I managed the rover interior design, meaning that I took the designs of others and configured them within the rover. The electronic packaging concept was in a large part mine, but I did not do the detail design of the PWBs, chassis, RF components etc. The only detail design I did inside the rover was the wiring, flex cables, a few pieces of secondary structure, and the cable tunnels. I'm not a lawyer, so don't know the ins and out of patent law, but I think a partial reason for the patent was so that it could be licensed to LEGO.

I'm a co-author of one other patent for a novel electronic packaging method (US 6206705 B1) which I helped develop for a micro-spacecraft study at JPL, and that I used on the JASON spacecraft. There was some interest in it, but I don't think it was ever licensed. At least I never received any checks in the mail. It used AMP elastomeric connectors, which were a piece of flex with parallel conductors on it, which was wrapped around a piece of silicon. All connectors are composed of a spring and a contact. With these the flex was the contact, and the silicon is the spring.

***Shaughnessy:** You mentioned a "bias" against flex. It was like that until recently, but now we're seeing flex everywhere. Why do you think flex has become so popular lately?*

Cardone: Projects have review hurdles they all have to cross (early peer reviews, preliminary design review, critical design review, and detail design review), and without fail someone will submit an action item to justify the schedule impaction, cost, etc., of using flex over traditional cabling. The fabrication cycle of a typical JPL PFC is about six months. And on the surface this is longer than a typical round wire harness, but it doesn't account for the downstream time savings. Another weak link for us is the limited vendor pool for fabrication. Because of the panel size needed we get a lot of no-bids. We have one vendor that's been working with us since Pathfinder (that >30 layer rigid-flex I mentioned before), and they have been great. So the bias I mentioned is at a project level where they are looking solely at project risk.

I've been using flex, rigid-flex throughout my career, and I consider it just one tool in the box. If I think it's the right tool I push for it, and if not I don't. If it is becoming more popular then this would have to be due to improvements in fabrication, and resulting cost reductions. Some of it may also be due to reduced end-item assembly costs. Perhaps skilled labor, for end-item assembly, is less available or more expensive.

***Shaughnessy:** What were the smallest and largest flex designs you've done? What was the most interesting?*

Cardone: The smallest flex I've designed was an R&D project to interconnect 4 MEMS accelerometers. The line widths were 0.025mm, leg widths are 3mm, and the overall size is about 9mm x 8mm. The three legs allowed the unit to fold up in to a pyramid shape so that it could measure acceleration in all three axes.

The largest flex designs I've done are probably the robotic arm cable for the MSL rover. They are on the order of 10m in overall length, and they are three cables designed to 24" x 85" fabrication panels (limitation of the lamination press) that are spliced together. Another very large flex I did was a phased array antenna that was designed to deploy on an inflatable frame on orbit.

Another large flex circuit design was a prototype heater for HP. It wasn't huge, but it was jam-packed with eight heater zones and over .23 miles of conductors. The goal on this design was to maximize distribution, and then adjust the trace width for the desired resistance.

My most interesting flex design was probably a rigid-flex I did for Panavision. The center segment supported the CCD sensor, and four legs folded down, enveloping the lens stack to support the other electronics. Or it may have been some circular phased patch array antennas I did at JPL. These were about 3m in diameter and were filled with tuned RF elements on about a 1/4" grid. Each element was "tuned" by adjusting the length of the two RF stubs that came out of it. Each element's stub length depended on its location on the array. I designed these with Computervision Cadds4 by constructing an executable file that placed polygons at each location based on an input file from the antenna engineer. It doesn't sound interesting, but when it was done, you could discover some beautiful patterns.

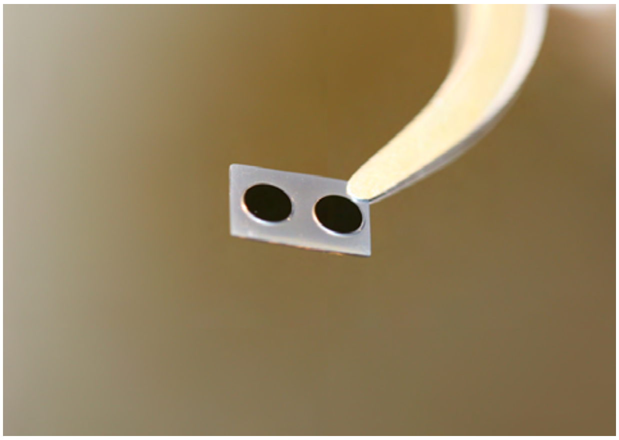
Shaughnessy: I understand that you may have designed the first flex ever used at JPL. Can you tell us about that?

Cardone: I am not certain this was the first use of flex at JPL. It is the first one I was aware of. For the Cassini mission we designed a flex that adapted a sub-d connector to surface mount interface at the PWB. Its construction was a 3 oz. layer of Cu or BeCu sandwiched between polyimide layers. The connector interface was through-hole, and the PWB interface was unsupported flying leads of the BeCu that exited the sandwich. The flex exited the connector pin array in both directions to allow maximum trace width, and keep the flex to one layer. The flex leg near the PWB had a 90 degree turn, the leg away from the PWB had a 180, and then a 90 degree turn. The end result was that we only took up about .55" of PWB area, while a round wire interface might have taken twice that.

Shaughnessy: Thanks for talking with us, John.

Cardone: Thank you. **PCBDESIGN**

New Breed of Optical Soliton Wave Discovered



Applied scientists led by Caltech's Kerry Vahala have discovered a new type of optical soliton wave that travels in the wake of other soliton waves, hitching a ride on and feeding off of the energy of the other wave.

Solitons are localized waves that act like particles: as they travel across space, they hold their shape and form rather than dispersing as other waves do. They were first discovered in 1834 when Scottish engineer John Scott Russell noted an unusual wave that formed after the sudden stop of a barge in the Union Canal that runs between Falkirk and Edinburgh. Russell tracked the resulting wave for one or two miles, and noted that it preserved its shape as it traveled, until he ultimately lost sight of it.

The microcavities that Vahala and his team use include a laser input that provides the solitons with energy. This energy cannot be directly absorbed by the Stokes soliton—the "pilot fish." Instead, the energy is consumed by the "shark" soliton. But then, Vahala and his team found, the energy is pulled away by the pilot fish soliton, which grows in size while the other soliton shrinks.