Challenges and Solutions for Addressing Size and Environmental Constraints In Precision Guided Munitions

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It may have all started in the cartoons or science fiction. The concept that a pyrotechnically launched projectile could be actively steered towards its target after it left the barrel and chase the hapless coyote that had fired it. Over the past 150 years we have seen simple rockets transform into precision guided missiles able to hit an aircraft traveling over 1200 miles per hour. Advances in barrels, elementary RADARs and accurate fusing technologies have increased the precision of artillery and mortar down to meters.

But both weapons systems come with a high cost, both in dollars and mobility / portability. Apart from man-portable, missiles and their affiliated launching and control systems are expensive and large. While outstanding at attacking high value defined targets, the logistics of both storage and transport, limit the amount of ammunition that can be carried and, at times, hamper mission flexibility.

And while amazing in their precision, missiles, and some projectiles, are susceptible to jamming, mechanical anomalies and the one shot, one kill strategy driven by assuming one missile successfully prosecutes one target. Depending on the system, many become ineffective at shorter ranges.

Though missiles programs will continue into the distant future due to their continually improving efficacy in prosecuting specific targets, systems evolved based on guiding pyrotechnically launched projectiles ("bullets") to hit high threat targets.

Enter the Phalanx Close In Weapons System ("CIWS"). This system, based on a rotary Vulcan cannon, fires 640 extremely dense metal projectiles per minute at incoming targets. A RADAR system, integrated into the cannon, matches the RADAR return from the incoming threat to the RADAR return of the outgoing projectiles, which creates an intercept solution if the projectile maintains constant speed, attitude and heading. An excellent system, it provides the last-ditch defense against incoming missiles for high value US Naval assets.

While the system functions as designed, it was designed to counter older threats, expends a significant number of expensive bullets and puts surrounding allied assets at risk. Other systems exist based on guidance from RADAR, InfraRed, GPS and/or Laser, and while highly effective, struggle in diverse threat environments.

The future may well lie with programs akin to MADFIRES. The Multi-Azimuth Defense Fast Intercept Round Engagement System ("MADFIRES") looks to replace systems like the Phalanx CIWS with a 30mm projectile that is guided to the target by the projectile's own internal guidance system. Though capable of a high rate of fire, this system envisions increased probability of early intercept, increased number of targets prosecuted and a great reduction in munitions expended, coupled with reducing collateral damage.

Such a system can provide close-in protection not only against enemy missiles and projectiles, but simpler attacks like a speedboat or pickup truck loaded with explosives. The aforementioned is expanded as the Defense Industry looks to provide such systems to light armored vehicles in the battlespace and the vision of creating long range hypersonic bullets & artillery to prosecute complex modern threats. The same technology will apply to the next generation of armored cavalry (a.k.a. tanks).

This paper, and related presentation, will discuss three aspects related to the design and manufacturing of the electronics to support this next generation of projectiles (including missiles). Let's start with defining a problem statement. How do you design, build, test and certify the electronics for a guided artillery shell that experiences accelerations greater that 30,000 times the force of gravity (9.8m/s2), leaves a barrel with a spin exceeding 3000 revolutions per minute, may be powered by a highly variable source and is encased in materials that quickly exceed 250°C? And this all fits inside a 26mm cylinder that needs to be maintained by a young technician in the field and most importantly, work the first time and every time. The one advantage is that longevity and repeatability will not likely be requirements.

In writing this paper, it became clear that the focus may be more to educate the design engineer as opposed to belaboring the potential solutions. In the interest of time, we will skip the Electrical Engineering design challenges that relate to higher frequencies, Doppler, cost and speed. We will instead discuss extreme g designs, high density packaging, unique geometry, thermal challenges and storage considerations.

Greatly simplified, a guided projectile is broken down into the following subsystems: Seeker, Stabilization, Guidance, Power, Detonation, Telemetry and Control. A few add propulsion control, but they are in the minority and not for consideration in the highly dense electronics problem statement.

Seekers are usually, but not always, on the front of the munition. They can be systems that either passively or actively use RADAR, InfraRed, Visual, Laser Guided, Anti-radiation, GNSS (Global Navigation Satellite System) and/or other technologies to designate an intended target.

Stabilization is primarily Gyroscopes, Accelerometers, GNSS and sensor fusion systems that determine the munitions orientation in space. A majority are electronic, but some are still based on spinning mass gyroscopes. These systems feed information to the Guidance System.

The Guidance system is the "brains" of the munition. It can range from a simple analog feedback loop linked to the control surfaces, to extremely complex systems that compare terrain data to known positions for accuracy. Digital systems are becoming prevalent but must protect proprietary software, keys and data while inflight and after mission conclusion.

The munition is powered by a multitude of technologies ranging from Lithium Hydride batteries, to chemical, to thermal, to miniature wind turbine driven systems. Though a subject for another paper, controlling and managing this highly variable power source is a sizable challenge if one is moving towards any type of standardization.

Though originally limited to testing, telemetry in munitions is becoming critical to assessing the performance of the ordinance. This can range from understanding the initial launch functioning through to terminal assessment of potential battle damage.

The control system is what drives the fins or canards on the munition to evolve it from a “dumb” bomb/bullet into a precision guided munition (aka “Smart Bomb”). Precision guided munitions started in the 1960s and have continued to evolve in accuracy in step with technology.

Finally, is detonation. As you can guess this does not apply to “hit-to-kill” weapons that physical hit the target and transfer kinetic energy to it. Detonation sounds easy at first, but in reality, is a complex part of the electronics that assure the weapon functions as designed and minimizes collateral damage.

As an electrical engineer, when was the last time you had to consider mass models in your design? Have you ever needed to understand what force 1-millimeter gold wire puts on a pad when under a 50,000 times gravity acceleration?

Discard physics and math and let us simply say that you have a gold wire bond that on a scale measures 100 Milligrams (assuming you are on planet earth). True, this is a more accurate measure of force but since people think more in terms of “weight” let us continue the example. We know this is under normal acceleration due to gravity.

But, what happens when something is accelerated at 10,000 times the force of gravity. Now the perceived “weight” jumps to a Kilogram. With munitions looking to reach hypersonic speeds, 100,000 g (980,000 m/s^2) you could now have a 10 Kilogram wire bond inside your package.

Let’s not argue using N (Newtons) or pound force as the example is to illustrate how complex mass inside packages many become in the future. The point is, for a long time, electrical design and engineering have been shielded from such extreme physical force on designs.

To be fair, many die and packages have been demonstrated to survive and easily function through high g environments. Most packaged electronics can be modeled with little risk calculated to the substructures even when inducing temperature and vibration.

The newest generation of munitions, which require very high acceleration rates created either by pyrotechnics or technologies like electromagnetic rail guns, will stress the structures beyond what can be expected in a commercial world. I do not know many engineers that tell the flex and sheer numbers as it relates to a bare die. This compounds itself when one considers System in Package (SiP), Package on Package (PoP) or the numerous packaging techniques that exist up to gold box modules.

To be fair, the acceleration curves vary between launching systems. The time that the components or printed circuit board (PCB) are exposed to the extreme acceleration can be in the microsecond range depending on the system design. On occasion more than one acceleration spike over time may be experienced by the projectile.

During the presentation affiliated with this paper we will discuss methods and techniques required to address high acceleration. In starting the discussion, we look to orientation. People in the MicroElectroMechanical Systems (MEMS) discipline learned that mounting orientation inside of projectiles is critical to their survival.

When creating a complex package (SiP, PoP, etc.) for a high g projectile, eliminating flex for boards, interposers or wire bonds may become critical. In creating the package, rigidity needs to be in the plane of acceleration of the projectile.

Easy, right? What about if the projectile leaves the barrel spin stabilized? It is leaving the barrel at 30 revolutions per minute. Depending on the location inside the shell along with the diameter this could create some additional longer-term accelerations.

What about potting? For a long time, this was the preferred way to stabilize many devices by filling any voids with a rigid substance that would prevent flexing of the structure. While this is effective on larger assemblies, will it be cost effective for packaged die and multiple die packages?

Acceleration aside, our next challenge is the small size required to fit into the next generation of precision guided munitions. Missiles have reduced in size to 50mm in diameter but programs like MADFIRES are driving to 30mm diameters which creates ~24-25mm internal diameter to put electronics into. One can assume that 20mm may be in the future as well which will drive an increased need for miniaturization.

Oh, and the packages and the boards need to be round or cylindrical. These are easily possible but require new packaging and manufacturing techniques to move them for a hand process to an automated one. Here we can borrow from other industries, such as healthcare, which have already moved into unique geometric configurations.

Considering the environmental and geometry challenges, what physical interface do you use between these contained subsystems? How do you route data between the modules (SiPs, PoPs, Assemblies, etc.)? Remember you may need to support calculations of a munition traveling faster than 1700 meters per second.

Wow. This is tough. It is easy in theory, but how to you produce these in volumes to make it affordable?

It gets harder yet. Most of our education regarding thermal has been focused on moving heat out of the system. What about preventing heat from getting in? If your munition is only lumbering along at 800 kph then you may not be thinking about the heat generated from air friction.

However, when your vehicle is traveling faster than 6000 kph, at or close to sea level, then you have significant concerns about the heat the system is generating by pushing aside this fluid we call air. Without going into specifics, the leading edge of a larger projectile may quickly exceed the datasheet operating temperatures (85, 105 or 125°C) of most components. Hell, it may exceed the melting point of lead. And this at a time when you are turning electrons into heat trying to accurately put this round on target.

Yet, there is one more challenge. When you make a munition, it may not be used for many years. All of us in the defense industry really hope these weapons are not used for many years, if ever.

Many does not mean 3 or 4. Not even 10.

An example is the AIM-9 Sidewinder Air to Air Missile entered service in 1956. Today a variant of that missile sits on the wingtips of many of the modern F/A-18 Hornet fighters deployed around the world by many militaries. The design has not changed significantly in that time.

Storage requirements look arduous. More arduous than we can design for. Or, that we want to design for. Salt fog. Storage heat exposure. No cell phone must endure this. The military has so many old systems for old missions.

Requirements range from the RTCA DO 160 to new military specifications that require Accelerated Life Testing activities that attempt to qualify the survival of a system as it goes from storage to depot to the field and back for 20 years.

The same can be said of many of the modern systems being designed today. They may be stored, moved into and out of a theatre, dropped, banged and forgotten. But the day a 19-year-old kid needs to use one to save the life of himself and his platoon, it has to work. The first time, every time.

Please join me for my quick presentation and then lively discussion as to how we, together, solve these challenges.