WHITE PAPER

Hypersonic Flight Raises the Bar for Embedded Electronics

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SYSTEMS

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Introduction

'Hypersonic' describes a new class of weapons, maneuverable missiles that travel at Mach 5 or greater. They will soon be challenging missile defense systems, changing tactical response behaviors, and impacting global defense strategy.

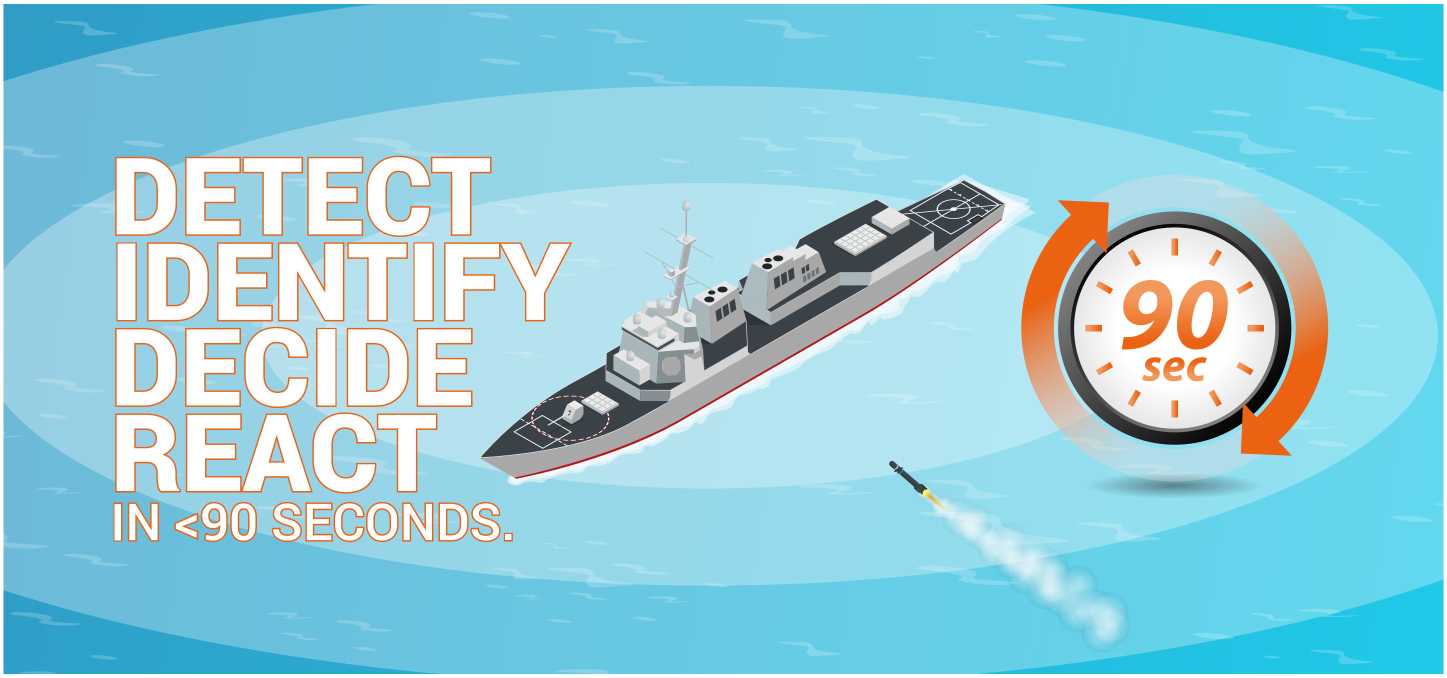


Figure 1: A ship has less than 90 seconds to detect, identify, decide, and react to a hypersonic missile threat.

Hypersonic flight introduces fundamental changes to the way today's missiles operate. Cruise missiles fly and maneuver within the atmosphere across a range of altitudes, but at speeds barely reaching Mach 1. Ballistic missiles have speeds of up to Mach 9 during re-entry from space but their trajectory is fixed. Vastly faster than cruise missiles, yet following an unpredictable and adjustable flight path, hypersonic missiles are a unique threat.

So far, no hypersonic weapons have been deployed, but all major powers have advanced development projects. Russia and China have been vocal in promoting their capabilities, claiming successful tests of hypersonic missiles that will soon be able to deliver conventional and nuclear warheads at ranges over 2,000 km.

The U.S. is pursuing multiple hypersonic R&D programs, with public statements promising increased funding as efforts ramp up. It is worth noting that the U.S. focus includes both offensive hypersonic weapons and defensive systems; the defensive challenge is best illustrated by a tactical scenario that gives a ship less than 90 seconds to detect, identify, decide, and react to a hypersonic missile threat. (Figure 1)

Daunting Technical Challenges

Matching and overcoming hypersonic threats will demand technology advances across three broad areas: (1) propulsion systems, (2) airframe materials, and (3) embedded electronics. While most R&D spending is targeting the first two areas, it is clear that innovative improvements in embedded electronics are key to creating fully functional hypersonic systems.

Abaco is actively working on such innovations, bringing decades of embedded expertise to bear on the challenges posed by hypersonic flight. The rest of this white paper will examine, in broad terms, the nature of those challenges and some promising solutions.

Hypersonic Flight Raises the Bar for Embedded Electronics

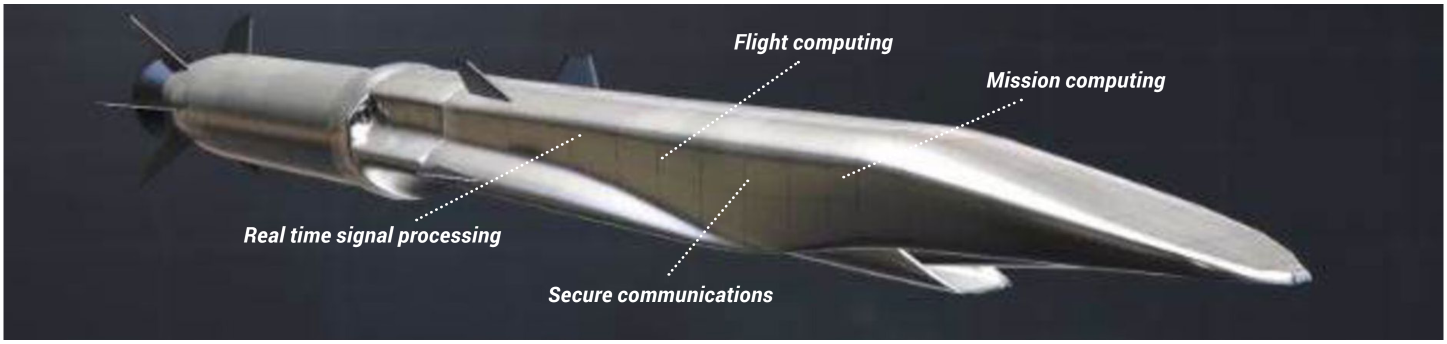


Figure 2: Embedded electronics will need to perform multiple functions for deployable hypersonic platforms.

The first thing to recognize is that embedded electronics will need to perform multiple functions for deployable hypersonic platforms. (Figure 2) The primary functions are:

- Mission computing, focused on responding to commands, adjusting to changing conditions and ensuring that all subsystems work in concert to accomplish a platform's mission
- Flight computing, controlling the path of the platform, monitoring the outputs of sensors, and controlling the operational employment of sensors
- Real-time signal processing for radar, EO/IR sensors, and Electronic Warfare (EW)
- Flawless and secure communications with command and control networks

The electronics to perform these functions may exist in a single computing enclosure, or be spread across several. The system may even be designed so that a subsystem of electronic components can perform multiple functions, switching between them based on the mission situation. But: regardless of the configuration, hypersonic flight will present the electronics with an intimidating set of environmental challenges, taking conditions already faced by airborne electronics and raising the bar to an entirely new level of difficulty.

The most obvious environmental hurdle is the incredible heat generated by air friction at 3,800 mph. Hypersonic air frame designers are responding with new materials, so that much of this heat will be managed at the platform's surface. Still, hypersonic embedded computing systems must be ready to endure temperatures exceeding those faced by currently deployed airborne systems. They must also be able to withstand the extreme G forces experienced as a platform accelerates to hypersonic speed.

Another challenge directly related to hypersonic speeds is extreme levels of mechanical vibration. Uncontrolled energies at resonant frequencies can rapidly destroy components and connections throughout an embedded computing system. Some hypersonic platform designs further complicate the mechanical vibration challenge by using an engine that varies its combustion behavior based on altitude. This innovative propulsion solution also means that the engine vibration characteristics will vary, further complicating embedded electronics designs.

Other environment considerations are not related to hypersonic speeds but must still be accounted for, based on a given platform's mission profile. One is severe swings in humidity caused by changes temperature between sea level and a 90 km altitude, an operational range proposed as a target for some projects. There is also the pyrotechnic shock generated when a missile is released from an under-wing support - clearly an issue for air-launched platforms. Both of these situations create added stresses for electronics.

Moving Forward With Solutions

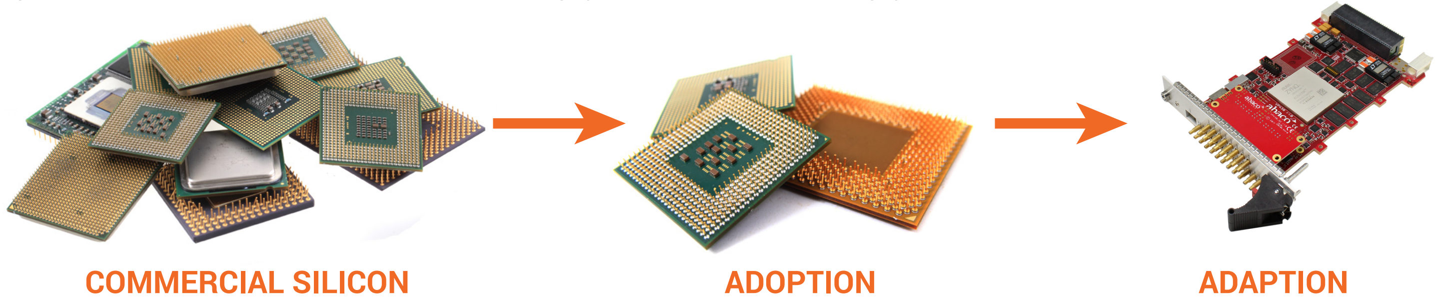
At the foundation of embedded electronics designs, there must be a general technology strategy for providing powerful, multi-function embedded computing that can meet hypersonic mission requirements and also deal with the hypersonic environmental challenges.

The first step is creating a computing system that is powerful enough to manage increasingly large and complex data systems and still respond in real-time. That can only be accomplished by using the latest commercially available computing and communications silicon. The broad general market drives performance advances at the chip level much faster than any application-specific development project can possibly move.

The next step is to ruggedize the systems in which the selected commercial chips will be deployed. Ruggedization is achieved by using a range of techniques and technologies at the computing board and enclosure level to make the commercial silicon survivable in the harshest conditions.

Hypersonic Flight Raises the Bar for Embedded Electronics

Figure 3: Adoption and adaption has been used to develop highly capable, advanced computing systems.



The two-step approach of adoption and adaption has been used to develop highly capable, advanced computing systems that enable most of the DoD's latest deployed systems. (Figure 3) It is the only viable way to meet the needs of deployed, hypersonic systems, because hypersonic platform technology is going to advance rapidly under conditions of intense global competition.

Abaco implements this approach, bringing deep experience in embedded computing ruggedization and a track record of success to this critical effort. The approach starts with a continual process of tracking and evaluating all the trends in commercial processing and communications technology. The evaluation leads to adopting the best examples of commercial technology across multiple processor types.

Today's processing silicon is segmented into technology types, including multi-core general purpose processors (GPPs), general purpose graphics processing units (GPGPUs), field programmable gate arrays (FPGAs), digital signal processors (DSPs),and communications processors (CPs). As the name suggests, a GPP is not specialized – and yet, for the purposes of embedded computing, it is. A GPP is the best processor type when decision-making and context-switching is important; for example, when responding to commands.

Other processor types are specialized for different types of data movement or specific types of mathematical processing. They also have different characteristics regarding the amount of electrical power they require and, directly related, the amount of heat they generate during operation.

There are even new types of semiconductors that combine multiple functions on one chip, focused on specific types of application. For example, Radio Frequency System-on-Chip (RFSoC) technology integrates Analog to Digital Conversion (ADC), Digital to Analog Conversion (DAC), specialized logic, and multiple processing cores onto a single silicon component. Developed for commercial radio frequency communications, RFSoC technology is also ideal for radar and EW.

Continually evaluating all types of commercial semiconductors is just the first part of a design at Abaco. The evaluations are then used to select the optimal processing technique for each specific mission function, sometimes combining processor technologies to move a data steam through a processing pipeline with the lowest possible latency. Other types of silicon, including data switches, memory, and memory controllers, are also used to form a system architecture, though processors represent the bulk of the power and heat budget.

In the commercial world of climate-controlled computer rooms, this would pretty much complete the system design process. Take the selected processors, join them together in a high-performance architecture, then blow enough air through the system to take away the heat. For embedded defense electronics, the design process moves on to another demanding phase – ruggedization.

Designing Electronics That Will Survive

Ruggedization covers all the design practices and techniques used to ensure embedded electronics survive a harsh environment. We described this environment earlier for hypersonic platforms as consisting of extreme heat and high energy mechanical vibration, with the additions of rapid humidity changes and pyrotechnic shock in some situations.

Heat

Dealing with heat is generally considered the biggest challenge, driven by two forces. First, there is the temperature surrounding the electronics within the platform, and second, the heat generated by the operation of the electronics. Modern processors, of all types, are delivering geometric increases in performance with each new generation, and the heat generated has increased in lockstep with the performance.

Figure 4 illustrates this trend over recent years. Heat flux measures the heat that must be dissipated per unit of chip area; it can be seen that the current heat flux levels of around 100 W/cm^2 exceed the heat flux level of a cooking heat plate. At the same time, most types of commercial silicon have well defined maximum operating temperatures, also referred to as maximum junction temperatures, that have remained fairly constant over the years, typically in the 95°C-105°C range.

Hypersonic Flight Raises the Bar for Embedded Electronics

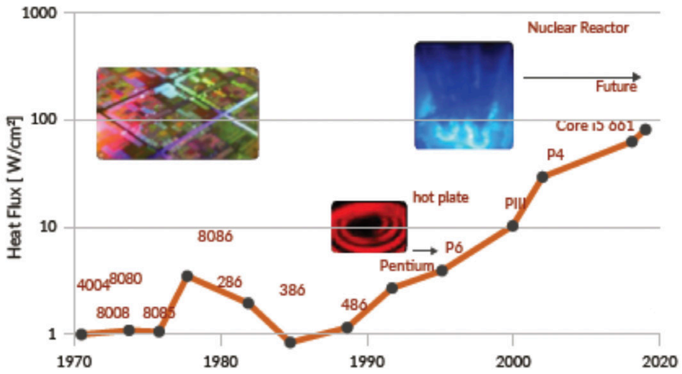


Figure 4: The heat generated by modern processors has increased in lockstep with their performance.

There is no magic bullet, no uniquely effective technique for getting the heat out of an embedded system so the silicon stays below its maximum junction temperature. In situations where the external temperature is not extreme, forced air over customized heat sinks can be effective. This is, however, not an option for hypersonic platforms, leaving designers with two other primary techniques: conduction cooling and heat pipes.

Conduction cooling and heat pipes can be combined within clever system level designs. Conduction cooling is implemented with a heatframe that encloses a circuit board where the processors are connected, and wedge locks that firmly attach the heatframe/circuit board assembly to a system chassis wall. See the sidebar description 'Illustrating Conduction Cooling'.

Heat pipes are used to move heat directly from a surface with significant heat load, such as a multi-core GPP, to a cooled surface, often inside the finned outer surface of a chassis enclosure. A heat pipe's effectiveness is dependent on a number of variables but they are often an efficient way to deal with difficult hot spots in a system.

Vibration, acceleration, shock, and humidity

Wedge locks used in a conduction cooled design have the added benefit of vibration-resistant rigidity. Vibration effects, as well as acceleration G forces and pyrotechnic shock, can all be mitigated by using damping materials at physical connection points, both within a system chassis and where the chassis is attached to the airframe.

The solution for changes in humidity is the most straightforward; conformal coating of electronics is easy and effective.

Illustrating Conduction Cooling

The components of a typical ruggedized embedded computing system include processing circuit boards enclosed within heatframes, which are installed inside a sealed chassis (see Figure 5). The circuit board can host a single GPP, GPGPU, FPGA, DSP, or CP or some combination of them, along with switches, memory chips and memory controllers.

A heatframe and wedge locks provide mechanical support to the circuit board and also conduct heat from processors to the chassis walls. Typically, multiple circuit board/heatframe assemblies are installed inside a rugged chassis to deliver mission critical functions in a harsh environment.

The typical heat transfer path in a conduction cooled system consists of three main components, as shown in Figure 6.

Figure 5: Boards are enclosed in heatframes and installed in a sealed chassis.

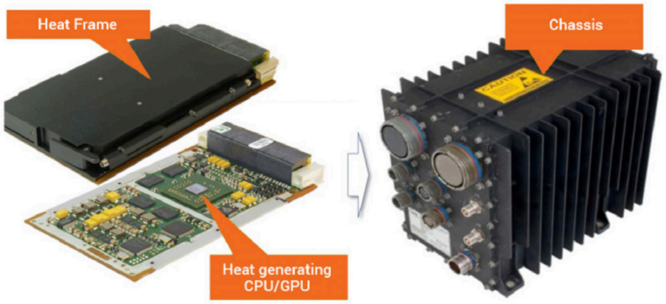
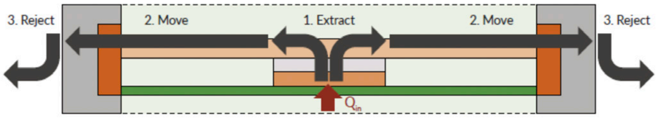


Figure 6: The typical heat transfer path in a conduction cooled system sees heat extracted, moved and rejected.



*1. **Extract.** Efficient heat connection between a mechanical heat spreader and a processor mounted on a circuit board. As the heat flux, Q_{in}, is highest near a processor, the performance of this part of the thermal path has significant impact on the overall system thermal performance. Note that some heat will move into the circuit board, which is a less efficient thermal path.*

*2. **Move.** Heat moves through the spreader into the heatframe and is conducted to its edge, where it moves through the heatframe-wedge lock interface into the chassis. The chassis wall spreads the heat to fins on the exterior surface or to a platform cold wall.*

*3. **Reject.** At the chassis' exterior surface, a coolant, usually air, removes the heat using forced or natural convection.*

Hypersonic Flight Raises the Bar for Embedded Electronics

Using Adoption and Adaption for Rapid Deployment

Abaco has streamlined internal processes that make the adoption-adaption cycle move quickly, for rapid deployment. Continual evaluation of trends and innovations in commercial semiconductor development is a key component. So are continued improvements to already world class ruggedization practices. A third component supporting rapid deployment is a software framework for developing high-performance, real-time embedded applications.

The AXIS Software Tool Suite from Abaco includes modules supporting the accelerated development of algorithm implementation, data movement, inter-process communications, image processing, event analysis and more capabilities. At the platform level, programs need powerful embedded electronics that can support all aspects of a mission, making software development a critical function.

Conclusion

The hypersonic technology challenge is already here. The challenge can broadly, from a computing point of view, be divided into two: deployment of advanced subsystems that leverage heterogeneous (i.e. processors of multiple types) compute platforms that respond appropriately to the range of application requirements – and the requirement for those platforms to operate with robust reliability in extremes of heat, shock and vibration.

Abaco has an extensive track record in both, and is uniquely placed to support the development of embedded computing for hypersonic applications.

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