AEROBALLISTICS MODULAR MODALITIES (AMM): A MODULAR INSTRUMENTATION SYSTEM FOR PROJECTILES

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ABSTRACT

Munition telemetry engineers are posed with the challenge of developing ruggedized, precision instrumentation for various projectile bodies. Much of the hardware is custom, and engineers must address numerous concurrent electrical and mechanical integration issues within a limited schedule. The Aeroballistics Modular Modalities (AMM) system is a miniaturized, modular, open-architecture platform which provides a pre-made, tailorable system for developing projectile instrumentation electronics. The system excels at capturing projectile dynamics data, where the sensors can be chosen a-la-carte. The system is highly-customizable, and can be tailored to any instrumentation package.

INTRODUCTION

The concept of a modular instrumentation system for projectiles is borne out of the need to rapidly provide hardware for precision munitions programs, when those programs are unclear of their measurement needs. New weapons programs will often need to characterize new airframes, requiring instrumentation packages to measure projectile fight dynamics (in-bore, muzzle-exit, in-flight) that are not entirely known in advance. Sometimes, multiple concurrent programs will require similar instrumentation packages, but with slightly different measurement capabilities. In other cases, programs will require instrumentation packages to support failure investigations, where various types of supporting or refuting data will need to be collected quickly to identify a root cause. All of these cases require a highly configurable sensor package that can be rapidly built.

In the process of designing these systems, the issue of how to electrically and mechanically integrate individual sensors and the encoder system within the projectile body or fuze always arises. Engineers at this point will create their own system design methodology. At one extreme, the instrumentation electronics can be fabricated all at once on a single printed circuit board, creating a boutique system designed for a limited application. Examples of such systems utilizing rigid-flex printed circuit board technology are the ARDEC developed ARRT-150 Aerofuze Rev 2 [1], and the ARDEC STEEL system [2], where all of the electronics are built on a single folding rigid-flex circuit board. This reduces fabrication costs, simplifies assembly, and streamlines component logistics, but increases yield risk. The failure of one sensor (which usually cannot be reworked) means disposal of the whole system circuit board. The labor performed on that system, and other expensive parts already assembled to the board, are wasted. Additionally, integrating new sensors onto the systems requires a redesign of the entire system electronics - every time. Extra circuitry will need to be added to the system schematic and routed on the board. Preexisting circuitry must be shuffled to accommodate the newer circuitry, and care must be taken that this does not cause interference issues or loss in functionality.

At the other extreme, the system electronics can be designed in a fully modular manner, where the individual sensors are separate, and later connected with wires, headers, or connectors to a main encoder board [3] [4]. Assembly techniques such as “bird caging” circuit boards, lap-soldering edge-plated circuit boards [6] [7], or creating fully connectorized modules [8], have been used. This increases fabrication and assembly costs, reduces the volume available for sensors, but reduces yield risk as individual sensors can be swapped out if they are non-functional. This fully modular approach also allows for specific sensor modules, which may contain parts with long lead-times, to be fabricated ahead of specific needs and put on the shelf until needed, again providing rapid responsiveness to needs through the modularity in the design. New sensors can also be integrated into the system easily, providing that they meet an interfacing specification.

The Aeroballistics Modular Modalities (AMM) system attempts to address most of these issues, by providing an open-architecture, standard mounting strategy and wiring strategy, designed for instrumentation packages with diameters between 1” and 2”. This diametric space claim allows the system to be applicable to a wide variety of munition packages ranging from 40mm to 155mm ammunition. The system was designed to support capturing data from multiple sensors measuring in-bore, muzzle-exit, and in-flight projectile dynamics, where the sensors could be chosen a-la-carte. The system is highly-customizable, and can be tailored to any instrumentation package, including utilization of sensor modules with cores developed for other applications.

AMM SYSTEM DESIGN

In an AMM-based system, individual sensors ICs are placed onto small PCB disks known as “modules”, which have standardized diameters, mounting hole locations, and electrical headers. These are then soldered to rigid tabs on a rigid-flex board called a “spine”. The disks are mechanically mounted together using four corner standoffs, as the spine board weaves through the spaces between the disks. Similar to the human spine, there is a straight run for each connection down the spine to a rigid base, which has an analog multiplexer and other extra circuitry. The base of the spine then connects to the main encoder known as a "core". The core provides power, control logic, analog-to-digital conversion, and on-board memory. The core samples the analog signals, interfaces with digital sensors, and generates a telemetry bit-stream. Finally, the core attaches to the outside world through a connector, or drives an external RF transmitter. A block diagram of this architecture is shown in **Figure** . Dimensions for a 14-pin AMM sensor module (referred to as variation AMM085_X320Y0_14PIN) are shown in Figure 2.

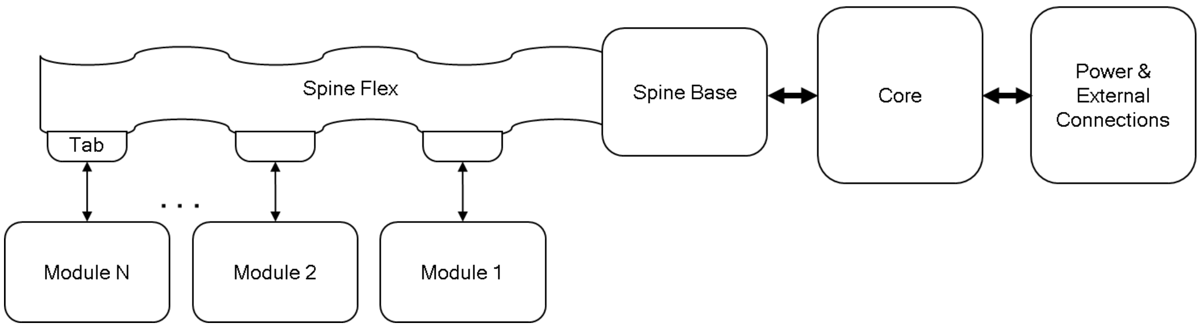
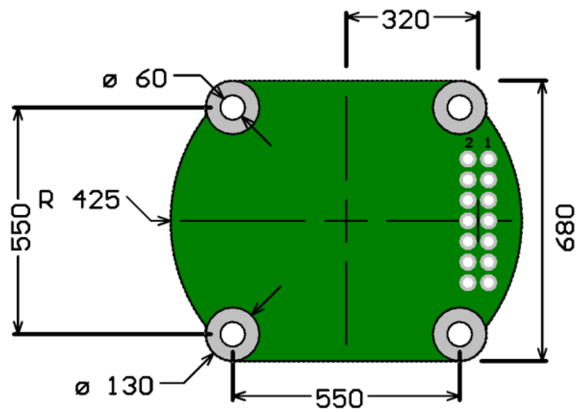


Figure 1 – System Block Diagram



Pin Descriptions	
2 - SIG	1 - PWR
4 - SIG	3- GND
6 - SIG	5 - GND
8 - SIG	7 - PWR
10 - SIG	9 - GND
12 - SIG	11 - GND
14 - SIG	13 - PWR

Figure 2 14-Pin AMM Sensor Module Dimensions (in mils)

The system follows the design spirit of several modern low-cost electronics Arduino kits for electronics hobbyists. In these systems, the Arduino main board contains a PCB with a microcontroller, with a set of headers around the outer perimeter. The pinout of the headers is standardized, supporting power, analog, and digital signals. Third-party boards known as "shields" are plugged into the headers to expand the system capability. The shield can have functionality ranging from MEMs sensors, to SD card readers, GPS modules, etc. Another similar system is the Digilent Pmod peripheral module interface for FPGA and microcontroller development kits [9]. It is this modularity that makes the system a popular choice for hobbyists, who do not wish to have to recreate an embedded system from the ground up for every project, which is also true for precision munitions developers.

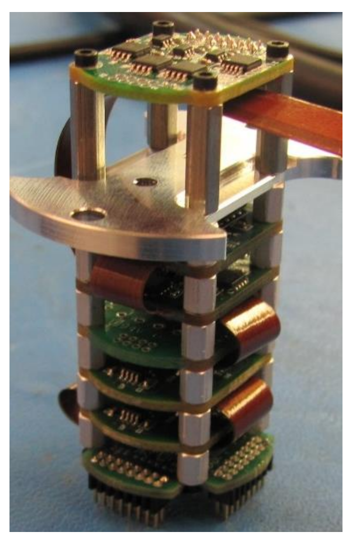


Figure 3 –Assembled AMM modules and spine

The mechanical interfacing strategy, illustrated in Figure 3, consists of four 0-80 x 1/8" OD standoffs on all four corners of the sensor board. Using four standoffs helps ensure that the boards are flat and parallel to the horizontal axis of the projectile, which helps ensure reliable sensor data by establishing a common system datum to which all sensors maintain orthogonality to. This is especially important when using multiple sensor measurements in order to verify measurements through redundancy, or to generate a full state vector using multiple sensors in an extended Kalman filter. The electrical interconnection strategy is equally simple – a dual row, 14-pin, 0.050"-pitch header on the right side of each board, mounted on the bottom. The pin assignments are designed to be symmetric, so that accidentally installing a module upside down will not cause a short circuit - just a mismatch of signals. For testing purposes, 0.050"-pitch sockets can be attached. However for flight integration, the headers are soldered directly to the spine tabs, creating robust connections during high-g shock events.

By utilizing both rigid-flex circuitry and headers, the AMM system gives a balance of high-integration and modularity. It should be apparent that multiple sensor modules, should they be commonly used together, could be pre-combined into a single rigid-flex circuit board, with the exact same mounting and header strategy as aforementioned. This eliminates the spine as a separate PCB. It's an example of integration, and is up to the system designer. By already having the mounting and wiring strategy in mind, the AMM system allows for this flexibility.

AMM SENSOR MODULES

Several sensor modules were created during development of the initial AMM system, based upon sensor ICs that are commonly used for measurements of projectile dynamics [10] [1].

The AMM085_2XMAGFLEX magnetometer, shown in Figure 4, is used to estimate projectile flight dynamics including roll, pitch, and yaw, by measuring the geomagnetic field vector. Magnetometers are especially effective on spin stabilized munitions because they possess the necessary bandwidth to measure the pitching and yawing angular motion of a platform in flight while it is spinning at rates upwards of 300 Hz [11]. In this case, dual Honeywell HMC1053 magnetometer ICs are used to increase reliability through redundancy, and for capturing the magnetic field vector around the spin axis at two slightly-offset locations. Each magnetometer has set/reset hysteresis control circuitry. Two four-channel digital-to-analog converters are used to calibrate sensor offsets. The output is filtered with 6 two-pole anti-aliasing filters, and passed through a small compensation resistor before connecting to the spine header.

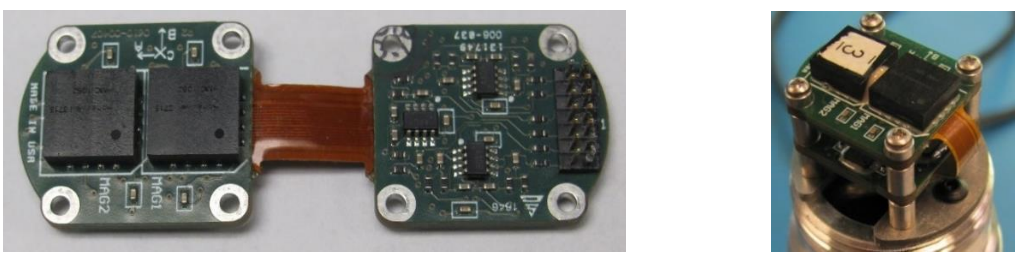


Figure 4 – 2XMAGFLEX, Dual Magnetometer Module (Left); Folded (Right)

The AMM085_377_326Z accelerometer, shown in Figure 5, is used to capture lower frequency muzzle-exit tip-off induced rigid body radial accelerations, and in-flight drag deceleration. A tri-axis Analog Devices ADXL377, +/- 200g MEMs accelerometer is used, along with a tri-axis ADXL327 +/- 16g accelerometer. Each output is filtered with a single pole 1-kHz antialiasing filter, followed by a compensation resistor, before connected to the spine header. These sensors are adequate for measuring in-flight, but not in-bore projectile dynamics.

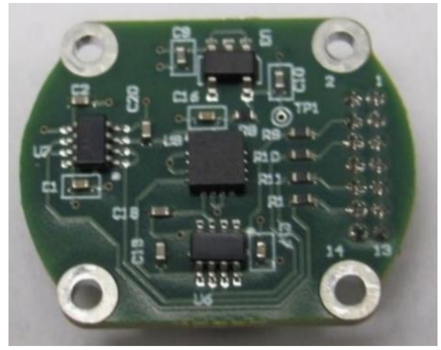


Figure 5 - AMM035_377_326Z module

The AMM085_3XAD623 board, shown in Figure 6, is a three channel signal conditioning board for bridge-circuit pressure gauges, or piezo-resistive accelerometers. Pressure gauges are often used to measure the base pressure seen on the back of a projectile as it travels down the gun tube or to measure the radial blow-by pressure profile seen forward of the obturator and rotating band [5]. Piezo-resistive accelerometers, such as the Endevco 7274 are used to capture higher frequency, high g-force in-bore projectile accelerations, including set-back, set-forward, and balloting loads. The frequency content of interest for a particular application is not always known ahead of time, therefore, utilizing an accelerometer with a higher frequency response and a greater resonance or natural frequency is advisable for capturing in-bore dynamics. In many applications, the acceleration on the frame or a primary structural component is of particular interest, in which case the sensing unit would not be physically attached to the board. Pressure transducer sensing elements are remote from the board in most instances as well. The AMM085_3XAD623 board is specifically designed to accept soldered leads from remote sensors with the gauges being connected to a separate 8-pin header on the left-side of the board. Each channel incorporates an instrumentation amplifier, second stage gain, offset, and four-pole 50-kHz Butterworth filter. The offsets are generated by a digital-to-analog converter and can be pre-programmed to offset or modify gauge imbalance.

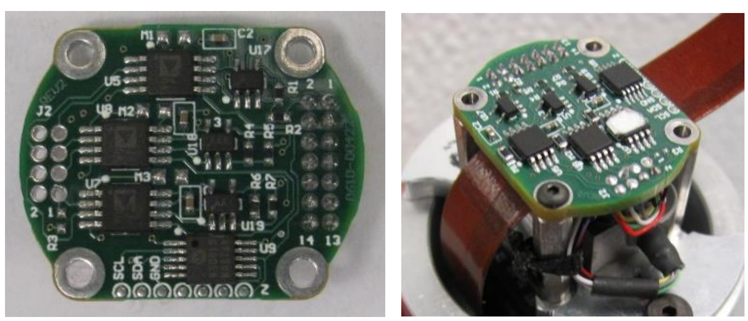


Figure 6 – AMM085_3XAD623 module (Left); Assembled AMM085_3XAD623 with Endevco 7274 accelerometer gauge attached (Right)

The AMM085_1521L accelerometer board, shown in Figure 7, is used to capture in-flight axial acceleration/deceleration events due to rocket motor thrust and drag respectively. A single-axis Silicon Devices 1521L, +/- 400g MEMs accelerometer is used. The output is filtered with a single pole 1-kHz antialiasing filter, followed by a compensation resistor, before connected to the spine.

Figure 7 - AMM085_1521L module

AMM CORES

The Aerocore is an Actel flash FPGA based PCM telemetry encoder and on-board recorder. It utilizes four independent external SAR A/D ICs, and includes 64Mbit SRAM and 128Mbit NOR-based Flash RAM as non-volatile memory. The circuit card assembly, shown in Figure 8, allows for up to 16 digital I/O, and 4 analog inputs. External analog multiplexers can be attached to increase the number of analog channels. The board delivers power to its constituent sensor modules, including 5V regulated, 3.3V regulated, and raw battery power.

The head of the Aerocore contains the headers along the outer perimeter which attach an AMM spine. The tail contains a small tab which attaches to an external power board. The power board provides a connector to the outer chassis, and additional circuitry such as an RF transmitter power regulator and pre-modulation filter. Utilizing an extra inexpensive board allows the external connections (such as the type of connector) to vary with application, while always using the same Aerocore main rigid-flex board internally.

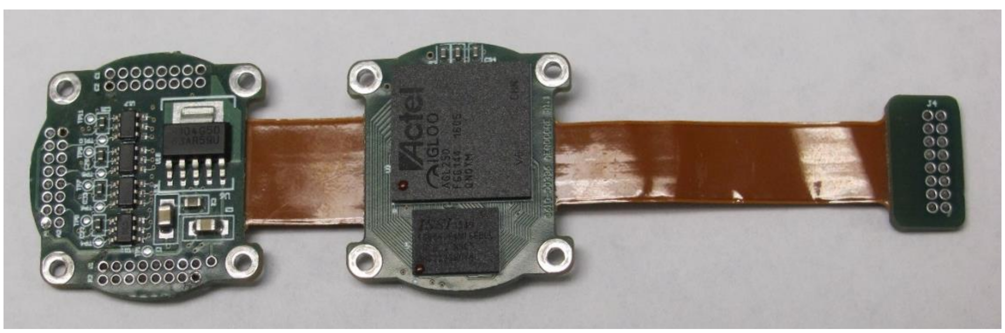


Figure 8 - Aerocore Rigid-Flex Circuit Card Assembly

AMM SPINES

A rigid-flex PCB ("the spine") is used to interface the Aerocore with the sensor suite. One implementation, used on the ARRT-174 Instrumented Precision Guidance Kit (PGK), is shown in Figure 9. At the extremities of the spine are rigid tabs with 14-pin through holes headers, where the sensor modules attach. At the spine base, there is circuitry for an analog multiplexer, and additional analog sensors. Headers are arraigned along the base perimeter to connect to the Aerocore circuit board. The multiplexer drives one of the core analog-to-digital converters, and is meant for multiplexing in-flight sensors that typically require 3-10 ksps sampling rates. The remaining three Aerocore analog-to-digital converters are used to capture in-bore sensor data, such as high g-force accelerometers, that typically require much higher sampling rates per channel, such as 500 ksps – 1 Msps.

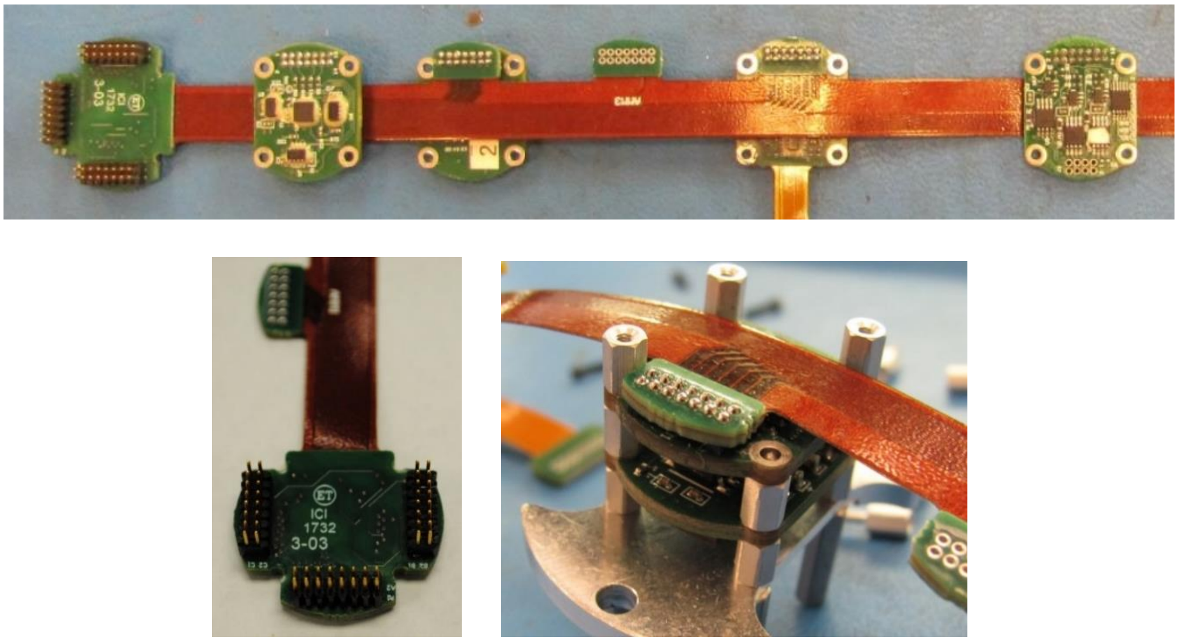


Figure 9 - Rigid-flex spines with AMM modules attached. (Top) Assembled and Unfolded; (bottom-left) Spine base; (bottom-right) Spine tab

MECHANICAL INTERATION INTO PROJECTILE PLATFORM

The most common way that an AMM electronics package can be mechanically integrated into its packaging (such as either a projectile or projectile fuze) is to mount the sensor package first to a primary metal plate via the four corner standoffs. This metal plate is then fastened to either the fuze housing directly, or to a secondary mechanical assembly, that is packaged into the final system. Benefits of mounting the system first to a metal plate is that it provides stability, alignment, and an area for hard-mounting sensors such as accelerometers which is critical to ensuring that the proper system dynamics generated are accurately transferred to any high frequency accelerometers. This mounting concept can be integrated into a variety of fuze housings and form factors.

The ARRT-174 Instrumented PGK - Over Determined Navigation (ODN) variant is one telemetry system that utilizes the AMM system for its electronics package. The sensor suite is assembled onto to a metal plate that is part of a mechanical sub-module. This sub-module has an RF S-band transmitter installed to its top, and a 15-pin MDM connector on its bottom for battery power. The module is then loaded into the fuze housing. 3D CAD renderings are shown in Figure .

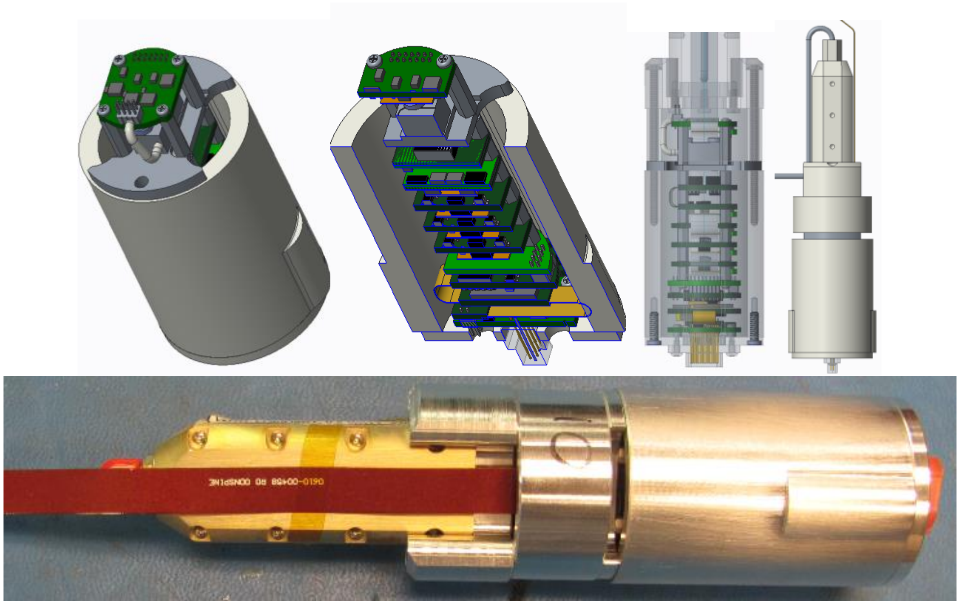


Figure 10 - Creo models of the ARRT-174 Instrumented PGK AMM System mounted inside of an ODN Module (Top). Assembled ODN Module with AMM System secured inside (Bottom)

APPLICATIONS

One use case for the AMM system was for its characterization of the M1156 Artillery Precision Guidance Kit (PGK) for U.S. Army Armament Research Development and Engineering Center's (ARDEC) Affordable Precision Technologies (APT) Science & Technology program. The program had a need to characterize the in-flight dynamics of a 155mm projectile with an M1156 PGK-like course correcting fuze. The scope of APT was to develop the enabling technologies for indirect fire precision munitions to operate in GPS denied environments. One of the enablers being investigated under APT was how to utilize magnetometers, specifically in novel mounting configurations, along with low cost commercial accelerometers, in order to enable accurate state estimation on spin stabilized precision guided munitions. The APT program additionally sought to obtain acceleration measurements associated with setback (in-bore) and set forward (muzzle exit) dynamics at specific locations within the PGK.

In order to obtain physically relevant sensor measurements, the PGK housing and canard system needed to remain intact in their tactical configuration to preserve representative mechanical and aeroballistics characteristics. The internal tactical guidance electronics system however could be removed while still ensuring a representative dynamic response to a reasonable extent. The AMM system was utilized to provide the necessary instrumentation within the tactical representative PGK airframe to capture commercial magnetometer and accelerometer in-flight data, as well as in-bore and muzzle exit high-g data. The Instrumented PGK is shown in Figure 11.

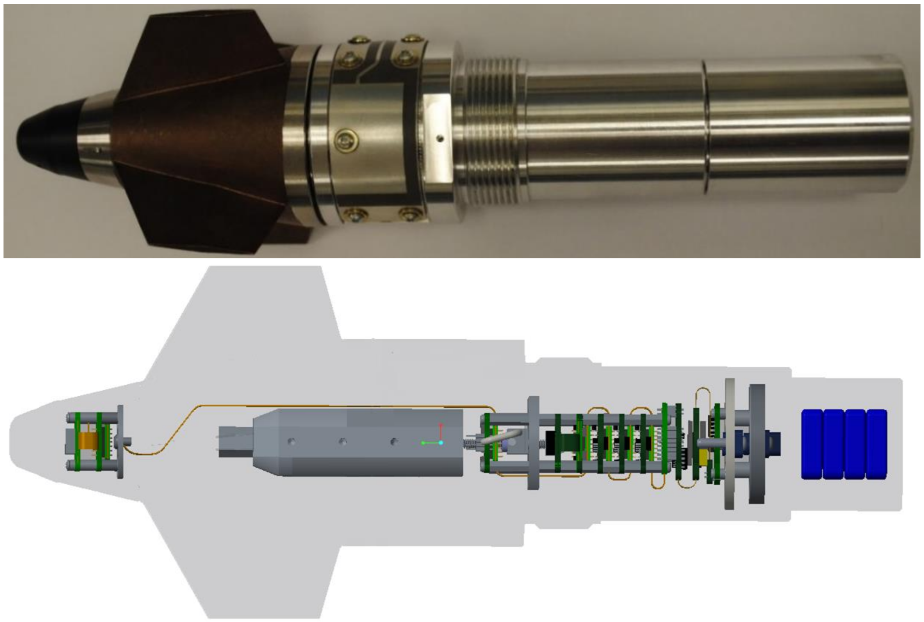


Figure 11 - ARRT-174 Instrumented PGK (top) with 3D internal rendering (bottom)

A second use case for the AMM system was for the ARRT-150 Aerofuze Revision 3, an instrumented NATO-standard fuze. The Aerofuze system is a projectile aeroballistics diagnostic telemeter for mortars and artillery [1]. Developed to collect in-flight dynamics including spin, pitch, yaw, and three-axis acceleration in real-time, data is relayed to a ground station using an integrated S-band transmitter. The electronics were designed to be packaged as either a standard mortar M734 fuze or NATO standard artillery fuze, providing a single system capable of measuring complete interior and exterior ballistics during the development of new mortar and artillery projectiles. The ARRT-150 Aerofuze Rev 3, shown in Figure 12, utilizes the AMM system as its electronics package and through modularity, it allows for the sensor package to be customized for each customer's testing needs, and allows for new sensors to be included on the platform with minimal effort.

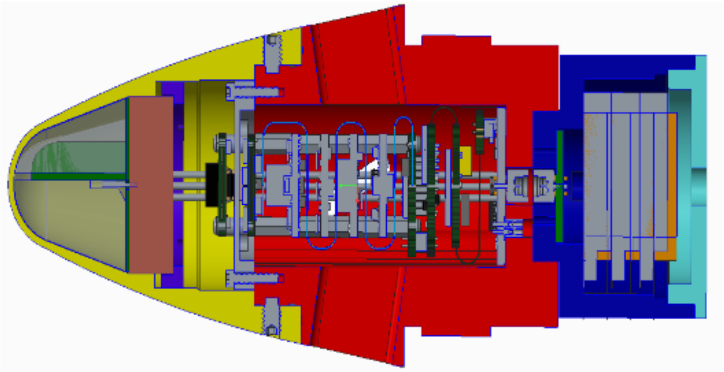


Figure 12 - ARRT-150 Aerofuze Revision 3, 3D rendering with cross-section

CONCLUSIONS

The AMM system is a modern interpretation of a modular and tailorable telemetry system for precision munitions applications. It provides developers with a platform to meet a wide range of projectile measurements needs. Its open-architecture design, low cross-sectional area, and customizability provides a flexible, low-cost, and schedule effective solution for a multitude of instrumentation applications and developmental efforts.

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