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Plug-and-Play (PnP) Micro-Electro-Mechanical System (MEMS) Inertial Measurement Unit (IMU) an Enabling Technology for Small Satellites

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ABSTRACT

Great strides are being made toward a standardized Spacecraft PnP Avionics (SPA) protocol and, at the same time, Micro-Electro-Mechanical System (MEMS) technologies are being developed and exploited by small uninhabited aerial vehicles (UAVs). The integration of the PnP capability with the MEMS technologies, implemented at lower costs while being designed for use in the space environment, will move the spacecraft component industry toward supporting the next generation of small, highly capable satellites. Microcosm, in conjunction with MilliSensor Systems and Actuators, Inc. (MSSA) and HRP Systems, is creating a PnP MEMS Inertial Measurement Unit (IMU) for spacecraft applications that will ultimately have performance comparable to today's mid-range IMUs, such as Northrop Grumman's LN-200. The combination of low cost, low mass, low power, and high performance expected from the PnP MEMS IMU is enabling technology for accurate pointing knowledge and control for the next generation of small satellites. This paper will address the state of the technology development to date for the PnP MEMS IMU, as well as presenting an estimate of the performance that is anticipated in future design iterations.

INTRODUCTION

Responsive space and rapid response missions have become important for spacecraft to support current warfighter missions. To achieve rapid response, as well as low cost implementation, both plug-and-play (PnP) and MEMS (Micro-Electro-Mechanical Systems) technologies will need to be incorporated into the sensors of the next generation of space vehicles. The Microcosm team, consisting of Microcosm, in conjunction with MilliSensor Systems and Actuators, Inc. (MSSA) and HRP Systems, is working to create a PnP MEMS IMU with the goal of achieving LN-200 class performance. The single die, developed by MSSA, includes 9 MEMS instruments — 3 gyros and 6 accelerometers that provide high quality rotation rate and acceleration information. The SPA PnP interface is an inherent part of the sensor, and the unit is being developed with the appropriate packaging to address flight environment issues, such as vibration, g-forces, and radiation tolerance. The digital drive and read electronics, developed by HRP Systems, takes advantage of state-of-the art digital components including a field programmable gate array (FPGA) implementation for the processing. Value added flight software, developed by Microcosm, is being included to support data smoothing and filtering, and will be augmented with GPS aiding and other mechanisms for enhanced performance over long periods of operation.

Microcosm is pursuing opportunities for distribution and value-added-reseller opportunities for space applications of this PnP MEMS IMU and other low-cost attitude determination and control system (ADCS) hardware market. A combination of this PnP MEMS IMU and a Microcosm low-cost star sensor, MicroMak™, with the appropriate ADCS flight software, will create a virtually turn-key spacecraft attitude determination system for small and nano-satellites. The primary target market for the PnP MEMS IMU, in the spacecraft arena, is nano- and microsatellites that desire a low cost, high- to moderate-accuracy rate sensing, but it can easily and cost-effectively satisfy guidance and navigation requirements for larger spacecraft as well as a host of other vehicle types in different environments, most with straightforward design modifications.

REQUIREMENTS

The typical mission requirements for nano- and micro-satellites were the basis for identifying the following environmental effects in space and during launch that have been investigated as part of the research and development (R&D) effort:

Shock	Vacuum
Vibration	Solar UV degradation
Acoustics	Thermal conditions
Radiation	Dynamics
Magnetic fields	Chemical reactions
Electrostatic fields	Radio frequency transmissions
Outgassing contamination	Micrometeoroids

For shock, vibration, and acoustics, the launch environment, rather than the orbit environment, will drive the requirements for the production version of the PnP MEMS IMU.

Ground environments were not considered, but may be a factor to consider in the future (e.g., ground environment variations between Kwajelien and Kodiak represent an extreme). The effects of electrostatic or plasma fields (spacecraft charging, electrostatic discharge, enhanced sputtering and re-attraction of contamination) will be mitigated by packaging and proper spacecraft grounding. Additionally, the IMU is not sensitive to contamination due to outgassing. The IMU will be hermetically sealed within its packaging to negate the effects of the change in ambient pressure to a vacuum. Only surfaces exposed to the sun are subject to UV degradation, and therefore the enclosed IMU is protected from this effect by its packaging. Thermal conditions of the IMU will be actively controlled in the final implementation.

Finally, the performance goals associated with the PnP MEMS IMU are shown in Table 1. Additional packaging goals include a final enclosure size of a 2 to 3 inch cube, weighing less than 0.3 kg and requiring less than 2.5 watts of power.

Table 1. PnP MEMS IMU Protoflight Performance Characteristics.
(dph -> deg/hour and dps -> deg/sec)

	Current Goal
Angle Random Walk (deg/sqrt(hr)	0.1
Bias Stability (dph)	1-10
Scale Factor (mV/dps)	8

When these goals are met, the PnP MEMS IMU will provide a spacecraft with high-quality inertial navigation information in a much smaller, lower-power and lower-cost package than is typically used today.

PNP MEMS IMU DEVELOPMENT

The on-going development of the PnP MEMS IMU has required many independent efforts focused on the development of the MEMS IMU instrument, the design of the digital drive/read electronics to replace the existing analog components, and the integration and testing of the two. Additionally, there is the creation of inherent PnP capabilities within the digital electronics, as well as the development of interface software that meets the intent of PnP in terms of self-discovery and reconfiguration. Finally, the algorithms that enhance the performance of the stand-alone MEMS IMU as well as those that add value to IMU information for attitude determination, navigation, and guidance must be tailored and matured for the specific characteristics of the MEMS IMU instrument.

MEMS IMU Instrument

The development of a MEMS IMU instrument includes many challenges, not the least of which is packaging. Because MEMS IMU instruments are so diverse in nature, packaging must be customized for each type and implementation. Thus, packaging is virtually a new activity, for each type, and this can be extremely costly. Additionally, because of the nature of the environmental concerns associated with space applications, packaging becomes even more complex, and thus more daunting. MEMS IMUs are currently not, for the most part, designed for use in space system applications, they have much higher errors (i.e. bias, scale factor) than space-qualified non-MEMS devices, and they can have much lower tolerance for shock.

The MEMS IMU chip structure, developed by MSSA, consists of silicon instruments fabricated onto a rugged Pyrex substrate for mechanical and alignment stability. The instruments are aligned to the precision of photolithography, on the order of 5 microradians. The Pyrex substrate also provides electrical isolation between instruments and provides a stable physical platform for maintaining the inter-alignments of the devices as well as reducing the stress imparted to the devices by the package.

The IMU instrument is a 3 by 3 array of cells containing 3 gyroscopes and accelerometers, one instrument per cell. This planar form factor enables great flexibility for insertion into packaging and system concepts. The die is a vacuum encapsulated single chip with pads for wire bonding. The vacuum encapsulation is done at the wafer level and eliminates the need to vacuum encapsulate the package. A getter is included for long-term vacuum stability and flight-worthy implementation. As shown in Figure 1, the MSSA integrated MEMS IMU is a single chip containing all the gyroscopes and accelerometers necessary to sense motion in six degrees-of-freedom. The instruments are single degree-of-freedom designs. Low cross-axis sensitivity of the gyros and accelerometers has been demonstrated. Current gyro bias instability is 100 deg/hr. Accelerometer bias instability is 0.5 mG. The current gyro design will produce 10-30 deg/hr stability with 1-10 deg/hr stability expected in future versions. The shock survival at the die level is 10 kG and greater survival capability is expected to be included at the package level. The three gyros are located on the diagonal, from top left to bottom right. The planar Z-gyro is in the center cell. There are two accelerometers for sensing along the horizontal, vertical and out-of-plane (Z) axes. The two matched pairs are used to take out unwanted sensitivities of the accelerometers to rotational motion.

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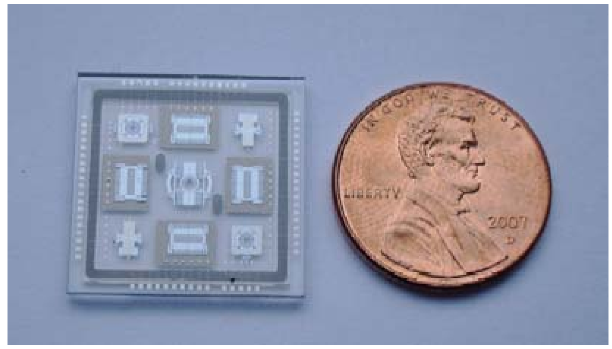

Figure 1. MSSA MEMS IMU Sensor chip with 6-degrees of freedom based on 3 gyros and 6 accelerometers in a small package.

After initial problems with yield, the IMU instruments are now designed to be larger and thicker, on the order of 3 mm and 40 microns thickness, for optimum performance and to enhance consistent repeatable quality. In order to achieve the required, very high fabrication yields, all instruments are based on a set of highly produceable common components. All instruments were designed for the process and are proprietary. The planar Z-axis gyro is built around a proprietary single degree of freedom design. The wafers are fabricated by a standard process in a commercial MEMS foundry. As shown in Figure 2, at least 12 dies can fabricate on a 4 inch wafer.

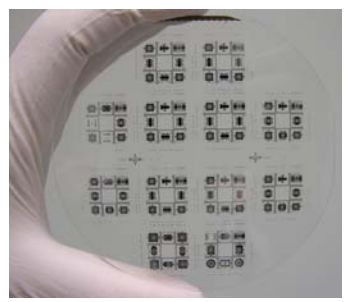

Figure 2. MEMS IMU fabrication wafer with 12 dies, each with all the gyroscopes and accelerometers necessary to sense motion in six degrees-of-freedom.

The efficiency of the single chip means that although the smallest size is obtained for the IMU, IMU-level advantages are derived from the great commonality in the instrument designs and the use of the same materials, same process and same batch. Because they are fabricated at the same time, from the same materials, and with the same process, the devices have inherently common mechanical, thermal and electrical characteristics. All the instrument sensitivities to the environment are highly correlated which simplifies compensation techniques. The small integrated IMU chip is convenient for thermal control and the application of vibration and shock damping within the package to which the chip is mounted.

Digital Drive/Read Electronics

In support of the PnP MEMS IMU, risk reduction digital drive/read electronics were prototyped to replace all of the current analog electronics, with the exception of the pre-amplifier circuitry. There are separate analog electronics for the gyro and accelerometer instrument. Figure 3 shows an initial delivery of the MSSA developed analog electronics boards for the gyro instruments. The high frequency demodulation board contains all of the high frequency electronics and the oscillator while the control electronics board manages the overall operation.

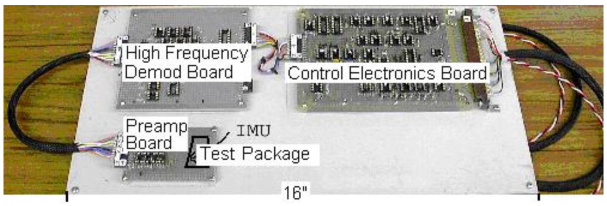

Figure 3. The initial analog electronics for the gyro function is 16" long and 8" wide and includes the pre-amplifier board, the basic control electronics, and the high frequency demodulation board.

The prototype digital electronics, shown in Figure 4, makes use of custom components as well as vendors' development kits and tools so that the prototyping process is optimized. Risk reduction of key elements of the digital design was the focus of this path-finding effort.

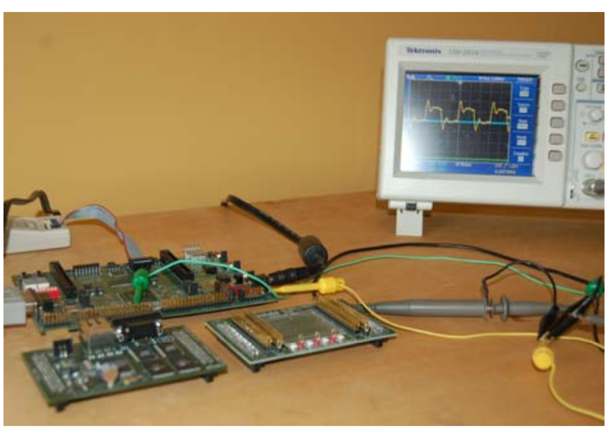

Figure 4. Shown in a test configuration, the PnP MEMS IMU brassboard digital electronics for risk reduction of elements not available as COTS, as well as COTS implementation of those that are available for evaluation.

The digital electronics development was significantly more involved than originally anticipated because of the high bandwidth (MHz) frequency required to excite the instrument read-out. However, commercial off the shelf (COTS) components were leveraged in unique ways to rapidly build up the capability needed. COTS components were selected for the phased loop lock (PLL), the mechanical drive of the accelerometers, and the processor soft core for both electronics and value-added navigation processing.

Again, a path-finding approach was used to evaluate multiple techniques and parts to find the best design for the digital electronics interfacing to the accelerometer instrument (i.e. Sig/Delta modulation techniques, various ADC/DAC speed and bit widths, filters opamps, and power supply components). Currently, the read-out of the output member of the gyroscope is excited at 0.5MHz while the drive member for each is excited at 1MHz. Mechanically, the drive member is oscillated at 5 kHz, nominally. It is possible, because the excitation frequency for the accelerometer read-out (about 100 kHz) is lower than that of the gyro, that a chip based on sigma/delta modulation techniques rather than drive D/A channels can be used. This will greatly reduce the complexity and maintain acceptable performance.

When possible, the COTS components have been selected to maximize upward mobility within the family of chips and for compatibility with space qualified chips within the family to reduce design modifications for the space environment. For example, the original processing core was based on a VRTX2 chip which is no longer available but can be seamlessly replaced with a VRTX4. There is also a version of the VRTX4 chip that is radiation tolerant for space environments. The A/D device that was initially used could not support the high speed data collection required for the multiple axis of information. An upgraded device, in the same family, allows for the integration of 9 channels of data. When selecting parts that are available from multiple vendors, the availability of a cost effective path to flight ready components is a strong factor.

The digital electronics board is currently an 8-layer board that includes I/O pins for 3 gyro instrument and 3 accelerometers, with no redundancy provided by the IMU chip itself. The other 3 accelerometers will be accommodated with the next revision of the board. The pre-amplifier board is being developed with 3 analog circuits for the first 3 accelerometers and 3 by-pass interfaces for the sigma/delta chip to interface directly to the other three accelerometers. Additionally, this configuration can be used to directly compare the results using the analog driver circuits as opposed to the sigma delta modulation technique. Additionally, this prototype design includes embedding the basic FX12 (big chip) OEM board that provides the VRTX 4 functional element, as a daughter board in the initial incarnation(s) of the digital electronics board. Approaching the design this way allows for testing of the gyros and accelerometers, without adding unnecessary complexity of the FPGA circuitry and creates a "quiet" board with good connectors to be used for evaluating performance.

Future risk reduction efforts will include evaluating the timing and synchronization of the multiple signals (gyros and accelerometers) as well as providing protection from the radiation and environmental effects. Synchronization of the multiple signals, as well as allowing all gyro and accelerometer functions to operate simultaneously without degradation, are still potential risk areas. TMR software, as well as redundant hardware, are candidates to meet the radiation environment or protection from environmental events.

Creating a PnP Component

PnP implies the ability to insert a component into a system and have it become an operational element within the system, automatically. This implies the need for components to announce their existence to software that understands, augmented with information about the type of data required and provided by the component. To meet this challenge with respect to spacecraft systems, the Air Force Research Laboratory (AFRL) in Albuquerque, New Mexico has developed a standardized Spacecraft PnP Avionics (SPA) protocol. The SPA paradigm includes not only mechanisms for discovery and announcing of new components, but also includes a structure to transmit this information. The extended transducer electronic data sheets (xTEDS) interface specifies a process for defining data element, data representation and packaging, as well as power-up procedures, sensor-to-body coordinate transformations, and calibration information for the specific device.

PnP concepts are being demonstrated by AFRL in their ground-based Responsive Space Testbed (RST) and proposed for on-orbit concept verification on the AFRL PnP Satellite (PnPSat). PnP MEMS IMU digital electronics evolution included the adaptation of COTS MEMS IMUs to include a PnP front-end, as a first step. Under a Small Business Innovative Research (SBIR) program, Microcosm and HRP Systems delivered two inertial reference units (IRUs) with COTS MEMS instruments to AFRL for use in the RST and PnPSat. Figure 5 has a photograph of one of the IRUs, open so that the internal components can be viewed. The total enclosure is approximately 3 inches wide by 6 inches long and 2.5 inches high, except where the instrument extends an additional 0.75 inches.

Figure 5. Basic Elements of the PnPSat IRU include a COTS MEMS IMU, and an ASIM for interfacing with the SPA protocol as well as providing processing for value-added software.

The IRUs, contained COTS MEMS IMU instruments from Analog Devices (ADIS-16355) which include extended temperature range compensation. The instrument was augmented with a gen1 ASIM, provided by Data General, and packaged in an enclosure provided by SpaceWorks. The integration of the instrument, the ASIM, and the packaging was performed by HRP Systems. The instruments provide data that are reasonably good for an off-the-shelf MEMS IMU; however, the data are noisy and do drift. The noise in the data was taken care of in the ASIM implementation with smoothing algorithms that were developed by Microcosm. Additional “value added software” included in the ASIM took data at 100 Hz from the COTS instrument, and output a filtered solution at 10 Hz. Much of the software that is needed to make any unit PnP, such as xTEDS and SPA protocol, as well as filtering and smoothing algorithms specific to a PnP IMU/IRU, were developed, integrated and tested through the development of these two IRU units for PnPSat. This device is one of very few that has been integrated on the PnPSat that includes “value added” software as an integral part of the ASIM processing.

RESULTS AND CONTINUED WORK

The research and development (R&D) effort that has been executed to date has made extraordinary progress and many of the key risk reduction elements have been demonstrated. As with any R&D effort, there were some technical set-backs. However, at this point the MEMS IMU instrument is solid, the production approach has been established with acceptable yields, and the digital drive/read electronics have been prototyped and demonstrated in a risk reduction configuration. The MSSA die has reached TRL 4/5, including the analog electronics, with producibility and yields from the foundry reaching satisfactory levels. The drive/read electronics, dependent on the IMU instrument for actual implementation and test has reached a TRL 3, but is rapidly moving to TRL 4 with the completed design and on-going development of a single dedicated electronics board.

A PnP MEMS IMU desk-top demonstration unit is in the process of being developed by MSSA and HRP Systems. It will be the means to demonstrate the PnP MEMS IMU concept more widely. The chief purpose of the demonstration system is to allow potential customers to work with the unique characteristics of the MSSA IMU Chip. Additionally, the ability to program an IMU via the associated FPGA digital electronics, assures that users can prototype and test their own guidance and navigation solutions at their desktop. It will also allow the evaluation of instrument performance over temperature and vibration, and over time it can be easily upgraded with better-performing chips. With minor modifications, it is anticipated that the demo board will be "flyable". A more flight worthy component can be created for the cost of the space qualified parts and assembly, integration, and test of the unit

CONCLUSIONS

The PnP MEMS IMU represents a new generation of spacecraft components that are designed from the outset with small, rapid response spacecraft as the target market to provide increased performance at lower cost and impact (size, mass and power) than traditionally available for this class of spacecraft. This small, low-cost, yet high performance PnP MEMS IMU will allow development cycle time to shrink to the order of a few months instead of the usual few years, while reducing overall costs for creating space asset inventory. The MSSA state-of-the-art MEMS integrated IMU on a chip augmented with state-of-the-art digital electronics with FPGA implementation in production, will make the PnP MEMS IMU applicable to operationally responsive satellites in any orbit. The PnP MEMS IMU will prove to be one of the key enabling technologies to achieve the creation of highly responsive space systems, especially for missions with robust 3-axis pointing requirements.