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AN OUTSIDER'S LOOK AT FLIGHT INSTRUMENTATION*

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Abstract

The author has a varied background in medical and nuclear instrumentation, large particle accelerator control, and detonation diagnostics. He has recently been involved in hazard instrumentation for solid-propellant-motor ground tests.

This paper presents his ideas and speculations on possible diagnostic instrumentation for use in missile flight testing. A plea is made for increased instrumentation efforts. There is some discussion of telemetry methods.

I. General Impressions and Author's Philosophy

I believe the instrumentation needs for a field are best determined by those individuals working in that field. Conversely, through my limited exposure to the solid-motor field, I have formed opinions critical of the quantity of existing instrumentation efforts in that field. I want to share these opinions in a spirit of helpfulness, knowing that I am an outsider whose knowledge may be too meager to reach accurate conclusions.

Lord Kelvin's statement that knowledge not expressible in numbers is "of a meager and unsatisfactory kind" expresses an essential aspect of engineering. In the real world, it is measurement instrumentation that must supply the numbers. John Cage of Hewlett Packard has said, "I think it is axiomatic that the instrumentation art must grow faster than the science and engineering activities in which measurement is necessary."¹

Judging by the number of papers published, that deal with propellant and combustion science, the knowledge base necessary to develop improved solid propellant motors is growing at a healthy rate. At the engineering design end of the spectrum, I believe the performance history of solid motors and the performance of recently designed motors such as the Space Shuttle boosters and the Trident I motors, indicate a mature technology with the developed "rules of thumb" so necessary to any engineering technology. There seems to be an understanding gap however, in going from laboratory propellant experiments to engineered motors. At this point, I suspect significant improvement in solid motors, taking advantage of advances in combustion and materials science, is going to require detailed knowledge of what goes on within large motors during burn. Chamber pressure, thrust, and outer case temperatures

are not enough to optimize designs. Computer modeling must periodically be verified in the real world. Detailed knowledge of instantaneous temperatures, gas and particle velocities, densities, chemical composition, and stress throughout the motor during burn would seem highly desirable.

To obtain this data will require a significant effort in the development of transducers and new instrumentation techniques. Although this session is primarily concerned with flight instrumentation, the development of required techniques and transducers would strongly impact ground testing and basic propellant and combustion science experiments. The instrumentation need in these areas may be even greater. The National Research Council 1979 High Temperature Science report² states:

"The competition between analytical and experimental abilities to characterize combustion systems and processes shows experimentalists in danger of lagging behind modelers in their general capabilities for probing hot, turbulent chemically reacting gases. The basic problem has been a lack of measurement skills for the rapidly fluctuating variables to be monitored."

Although the problems are obviously difficult, they do not seem overwhelming in comparison to many of the instrumentation problems being dealt with today. Furthermore, the national energy situation is forcing attention to related instrumentation requirements in such areas as synthetic fuels processing and gas turbine efficiency improvement.

Looking at instrumentation activity another way, one notes that most high technology research and development areas are also supporting significant instrumentation development efforts. (The instrumentation art must grow faster than the science and engineering activities requiring measurement.) Astronomy, particle physics, and molecular biology, as well as applied areas such as fission reactors, geothermal power, medicine, and high-explosive technology, all support large instrumentation development efforts. In all of these areas people are working directly on development of instrumentation techniques and transducers in laboratories well equipped for such work and in close proximity to the facilities where such techniques and transducers will be applied. It is my impression that such activities go on only in a very limited sense within the solid motor development community. I believe that the new instrumentation development that does go on in this field is mainly applying new commercially developed products.

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Another comparison might be made between flight testing an ICBM and an underground nuclear weapons test. I am guessing that the overall total cost of these activities is of the same order of magnitude. (I acknowledge that flight testing an ICBM involves much more than just flight testing the motors.) The instrumentation development budget for nuclear weapon tests appears to be very large in comparison to that for instrumentation development for flight testing. (Lord Kelvin and reasonable engineers would ask for budget numbers here. I have been unable to obtain them.) In nuclear weapons test instrumentation development, the "state-of-the-art" is actively being advanced in such areas as high-speed oscilloscopes, high-speed analog to digital converters, fiber optic data transmission, image intensifiers, high-framing rate video cameras, wide bandwidth coaxial cables, high-speed light detectors, laser diodes, and charge-coupled-device analog shift registers. In what areas of general instrumentation applicability is flight testing advancing the "state-of-the-art?"

My final argument for higher instrumentation budgets concerns design simplicity. Many people, myself included, believe weapons systems (and other high-technology systems) should be as simple as possible, even at some cost in performance. Simplicity usually translates into being economical, reliable, and maintainable. The key to design simplicity is really understanding how something works. Often this understanding can only be obtained by using complex instrumentation during the development phase.

II. Special Conditions Concerning the Development of Flight Instrumentation

In most fields, the instrumentation engineer has full control of the instrumentation from selection of the transducer through data recording and often data analysis. In the flight instrumentation of solid propellant motors, this situation clearly doesn't exist. The instrumentation engineer at the motor contractor selects his transducers and conditions their signals to input to the telemetry system, which is probably the responsibility of the missile system contractor located a days travel time away. Here the telemetry engineer designs his system to transmit data to the flight test range receivers, which are another days travel time away. This chain is made to work by standardizing it and adequately documenting it. Still, if I were the instrumentation engineer at the motor contractor, I would want at least one channel simply to send a test generator signal that would allow me to evaluate for myself the amplitude, timing, and frequency response of the overall system.

If one wants to do something innovative, transmit video data, for example, modifying the system to accept it could become quite involved. Clearly this situation is one that can be lived with, but it complicates the instrumentation problems and sometimes limits innovation.

III. Conditions for Innovative Instrumentation Development

I believe the following conditions and attitudes tend to lead to useful innovative development:

A. The person who wants certain data should be interested in precisely how the instrumentation engineer is going to obtain it.

B. Instrumentation engineers should develop a personal concern with the complete system from "what is being measured and why" through "how the data analysis will be done." Too often, if the engineer does not have this concern, system features impose data artifacts that are falsely interpreted.

C. Variety usually leads to greater creativity. An instrumentation development engineer can frequently work on transducer development for several very different applications and can handle routine instrumentation for an upcoming test. Development engineers should not be isolated from routine real world needs.

D. Adequate laboratory space and equipment for instrument development, evaluation, and testing must be available on a permanent basis.

E. Electronics plays a key role in the majority of instrumentation work. A significant fraction of a group's instrumentation development engineers should be able to do analog and digital integrated circuit and discrete circuit design work. These people should have available basic electronic test equipment, as well as a stock of parts to allow rapidly assembling prototype circuits.

F. Other valuable knowledge that should be available includes physics, such as light and optics, acoustics, mechanics, and heat transfer; knowledge of material properties and fabrication; microprocessor application and programming; and applied mathematics including measurement error analysis.

G. Instrumentation development engineers must be able to keep up with the "state-of-the-art." This should include visits to other instrumentation development facilities, attendance at short courses and professional meetings, and availability of journals and texts.

H. Instrumentation engineers must place high priority on good communications with others. They must ferret out what new types of measurement are important to be able to do. They need to develop good communication links with their peers working in other locations within their organizations and with peers working on similar problems in other fields and in other organizations.

IV. Some Specific Technologies Apt to Be Useful in Flight Instrumentation

A. Putting Transducers Inside the Motor Case

For many measurements, it would be

desirable to have transducers located inside the motor case. While being able to pass wires or fiber optics through the case would simplify data gathering, many motor designers prefer not to risk any additional holes in the pressure vessel. In this situation, either transformer coupling through the case or radio frequency transmission could be used both to power an internal data collection system and to transmit data out. Los Alamos has designed two passive transponder systems^{3, 4} for pulsed data interrogation of cattle and vehicles, that might be applicable to very low data rate situations.

In some cases, one might want electronic instrumentation capable of surviving and operating at high temperature within the case. Various Department of Energy programs⁵ are developing semiconductor devices capable of operating at 2750 to 3500°C. The Los Alamos integrated thermionics circuit program⁶ will provide circuitry usable to at least 5500°C.

Instrumentation placed within the case will need protection from the corrosive effects of chemicals present in the propellant. Parylene⁷ coating might provide a very light weight, reliable solution to this problem.

Safety problems of electrical potentials embedded within the propellant need to be resolved. Los Alamos has had extensive experience with electrical potentials in high explosives and probably has relevant data available.

B. Fiber-Optics

Fiber-optics is a very rapidly growing field that in addition to providing communication links can also be used to construct transducers to measure temperature, pressure, sound, rotation, current, and magnetic field⁸⁻¹². Other fiber-optic transducers based on light scattering measurements² might be devised for studying the combustion process either within solid motors or via the exhaust plume. Fiber-optics can also be used to couple infrared radiation thermometers to normally inaccessible areas¹³ and to construct flexible endoscopes for using video cameras to view inaccessible areas.

C. Acoustics and Ultrasonics

Acoustic detectors mounted on motor cases might be useful for diagnosing malfunction conditions¹⁴⁻¹⁵. The major problem would probably be interpretation of the data. Acoustic signals as high as 300 kHz have been recorded from burning propellant and probably result from high-speed chemical reactions, gas phase effects, and beating of signals from crystal breakup and rearrangement¹⁴.

Active ultrasound echo techniques similar to those used medically and for nondestructive testing probably could be used to detect case bond separation and insulator flap closure with pressurization in spite of the high-attenuation coefficients of the materials.

D. Transient Data Recording

Sometimes it is desired to record short duration transient signals that are too fast to transmit via the telemetry system. An example might be sudden shocks lasting 10 to 20 μ sec during stage separation.

A solution to this problem is to output the signal to a charge-coupled-device (CCD) analog shift register¹⁶ running at 5 mega-samples/sec. Typical chips have about 1000 stages so $\approx 200 \mu$ sec of data can be held. A level discriminator at the input looks for any signal exceeding a preset threshold level. If a signal exceeds the preset level, the clock rate, after a preset delay (say 100 μ sec), is shifted to a low frequency, say 8 kHz. The data can now be transmitted over the telemetry system, having had its frequency shifted down by a factor of 625. A very compact transient frequency shift package with a weight of <150 grams can be built. CCD shift registers with a signal to noise ratio of >55 db are being built by Fairchild Semiconductors and EG&G Reticon.

E. Video Systems

High-quality video cameras have decreased markedly in size in recent years. A color camera designed for surgical applications is now available in a package weighing 172 grams, and 14 cm long by 3.8 cm in diameter¹⁷. Extremely rugged and compact CCD cameras are also available¹⁸. Various intensified cameras for low-light conditions and infrared sensitive cameras are available.¹⁸ Los Alamos has used a moderately small, high-sensitivity (0.05 foot-candles), high-resolution (700 lines) ruggedized camera (Edo-Western Model 1831) inside nuclear reactors. This unit is rated for operation from -30°C to 65°C, 150 g shock, and has no altitude limitations. The unit weighs 510 g and is 2.8 cm in diameter by 13.1 cm long. Variations on available video cameras include frame rate, resolution, image storage time, sensitivity, and signal format.

One application for a video camera would be to look at the forward dome through a wide angle lens to show dome rupture, should it occur. For this application, one would have to use a low resolution, high-frame-rate camera (maybe a 64x CCD with a 5 MHz clock giving 1220 frames/sec) to allow recording and transmitting a frame before hot gas hits the lens.

The major difficulty in using video cameras is getting a telemetry channel with wide enough bandwidth. This would probably require both a separate telemetry transmitter and dedicated receivers in the tracking stations. Further discussion is given in Section V. Telemetry and Data Acquisition.

Extensive airborne video work has been done by a group at McDonnell Aircraft Company in St. Louis headed by J. E. Soller¹⁹. He is familiar with a number of options for implementing video systems.

F. Detonation Diagnostics

Los Alamos has had extensive experience in implementing detonation diagnostics on ground tests.²⁰ Pin switches that are activated by the arrival of a detonation wave can in principle be used on a flight vehicle. If several pin switches are mounted on the motor case and one accurately records the time (100-ns resolution) of arrival of the detonation wave at each switch, one can then calculate the origin of the detonation by triangulation. Implementation on a flight vehicle would be difficult because of the wide bandwidth (≈ 10 MHz) telemetry channels that would be required to transmit adequate timing data. Data probably could not be encoded and sent back at slower rates because in a detonation scenario, the entire motor would be consumed <500 μ sec and telemetry failure would probably occur very quickly thereafter.

Unless a wide-bandwidth dedicated telemetry channel were available, there doesn't appear to be any sure way to implement detonation diagnostics on a flight test.

(i. Special Strain Transducer Needs:

There is a need for strain gauges that could be embedded within the propellant. Another need is for ultra-high temperature (1900°C to 4200°C) strain measurement techniques which could be used on exit cones made from composite materials.

V. Telemetry and Data Acquisition Systems

Historically, the data acquisition systems used for aerospace telemetry were analog frequency-division-multiplex (FDM) systems based on transducer signals frequency modulating (FM) sub-carrier oscillators (SCOs) operating in the 400-Hz to 180-kHz frequency range.²¹ The outputs of as many as 20 SCOs, each operating on a different frequency, were combined to drive a FM transmitter operating in the VHF or UHF frequency range. On the ground the output of the telemetry receivers fed magnetic-tape FM instrumentation recorders. The Range Commander's Council (RCC) Inter-Range Instrumentation Group (IRIG) did impressive work in promoting standards for such FM-FM telemetry systems and for ground-based FM instrumentation recorders.

I suspect that IRIG standards for the FM instrumentation recorders have had a greater positive effect on the overall instrumentation effort in this country than any other aspect of flight instrumentation. These recorders have been important in biomedical instrumentation, mechanical engineering research, and many other areas.

The advent of integrated circuits and low cost computers resulted in most data acquisition systems switching to digital techniques. The standardized computer interfaces that resulted, (General Purpose Interface Bus, GPIB-IEEE-488, CAMAC-IEEE-593, STD Bus, etc.) were bi-directional, making it easy to build combined data acquisition and

control systems with real-time modification of data taking parameters based on real-time analysis of the data. In many applications single-channel data recording bandwidths now exceed 1 GHz and computer interfaced transient digitizers allow short burst data recording of these bandwidths.

Flight instrumentation also went digital, but in a somewhat different fashion.²² In the time division multiplex (TDM) systems, transducer signals are fed through analog multiplexers to analog-to-digital converters, the outputs of which drive pulse-code-modulation (PCM) encoders. The serial or parallel output from the PCM encoders modulates the telemetry transmitter. On the ground, the output of the telemetry receivers feeds the PCM data to PCM magnetic-tape instrumentation recorders, which have evolved from the IRIG standard FM tape recorders. Indeed, one can buy instrumentation recorders that by the simple change of plug-in modules can be converted from analog direct, to analog FM, to digital PCM recording. The data recording rate of these systems is quite impressive; a single instrumentation recorder may record data at >80 Mbit/sec. The tapes from the PCM recorders are played back into computer systems for data reduction and output.

The PCM digital telemetry systems were developed under IRIG standards. Most missile telemetry transmission is now done at S-band (2200 to 2300 MHz). Tracking parabolic dish antennas with low noise preamplifiers, and diversity receiving systems based on right-hand circular and left-hand circular polarization directions are used.

The conversion of the FM-FM analog telemetry systems to the TDM digital systems is most impressive to me. These systems seem to be very flexible, and the input subsystems are designed identically to common ground based computerized data acquisition systems. The recent incorporation of microprocessors in the missile data system allows data sampling rates and channel gains to be varied according to preprogrammed instructions, and could even vary parameters in accordance with the real-time incoming data. This should greatly expand the number of useful data acquisition channels. The range of data sampling rates programmable on one system currently under design include: 700 measurements at 1000 samples/sec, 100 measurements at 8000 samples/sec, and one measurement at 192,000 samples/sec (all at 3-bit accuracy).

For most applications, the above data logging rates are impressive. If, however, one needs to transmit data on explosive phenomena in real-time or to transmit video data at normal video rates (30 frames/sec) or higher, the system simply does not permit it. The 192,000 samples/sec rate corresponds to an analog bandwidth of 96 KHz and a risetime of 3.6 μ sec. In an era where general purpose oscilloscopes have bandwidths of 50 to 250 MHz and home television a bandwidth of 4.5 MHz, the system seems very limited.

In most cases, data does not need to be

transmitted in real time, and analog CCD shift registers or more complex on-board transient digitizer techniques using storage in digital memories could easily record wide bandwidth data. Subsequent transmission at reduced speed could be done on the standard PCM telemetry system. Probably a high percentage of video applications could be satisfied by transmitting only a few frames at low speed, provided those frames were initially recorded at high speed. The electronics to do this exists now and will rapidly shrink in size, weight, and cost with the advent of large-scale integration.

Techniques exist to transmit video data or other wide bandwidth data in real time. Both White Sands and Cape Canaveral have some capability to receive and record video data on standard video tape. In a system used at Edwards AFB, a separate S-band telemetry transmitter on an aircraft is FM modulated with a deviation of 16 MHz by the signal from two video cameras. On the ground, a standard telemetry receiver, with an added wide bandwidth detector, outputs the signal to a standard video recorder. All components are commercially available. At Cape Canaveral, TV data from a chase plane transmitting on C-band using satellite TV format is recorded during Space Shuttle launches.

Many people feel that there is little need for wide bandwidth data or video while others think that it would be useful. I cannot judge the usefulness, but it is possible to transmit such data now (with some difficulty), and it will become increasingly easy to do so in the future.

I believe the solid motor development community could profitably increase its instrumentation efforts. As an outsider, I do not see many developed instrumentation techniques which can simply be plugged in to solve existing flight instrumentation problems. I do see a number of technologies, however, that seem potentially very useful with relatively small effort for both flight and ground test applications.

I want to express my appreciation to the people in the solid-propellant motor and telemetry communities who spent time discussing various instrumentation problems with me. However, I want to stress that I take full responsibility for the opinions expressed in this paper. Furthermore, the opinions expressed should not be considered representative of the Los Alamos National Laboratory or the Department of Energy.

1. Bernard M. Oliver and John M. Cago, Electronic Measurements and Instrumentation, McGraw-Hill, 1977, p. xvii.

2. Committee on High-Temperature Science and Technology, The National Research Council, High-Temperature Science: Future Needs and Anticipated Developments, published by the National Academy of Science, Washington, D. C., 1979, p. 48-52, 105-15.

3. A. R. Koelle, J. A. Landt, R. E. Bobbett, and P. H. Salazar, "Technical Aspects of Electronic Identification and Temperature Monitoring System," LA-7641-MS, March 1979.

4. J. A. Landt, R. E. Bobbett, A. R. Koelle, and P. H. Salazar, "The Los Alamos Scientific Laboratory Electronic Vehicle Identification System," LA-7818-MS, May 1979.

5. Anthony F. Veneruso, "High Temperature Technology Potential, Promise, and Payoff," Electro/80 Conference Record, May 13-15, Boston, Massachusetts, p. 16/0, 1-6.

6. Byron McCormick, et al., "Development of Integrated Thermionic Circuits for High Temperature Applications," Proceedings of the Conference on High-Temperature Electronics, Tucson, Arizona, March 25-27, 1981, p. 49.

7. Parylene is a Union Carbide Corporation developed vapor-deposited conformal coating with good electrical and mechanical properties from -200° C to 275° C.

8. G. B. Hocker, "Fiber-Optic Sensing of Pressure and Temperature," Applied Optics, Vol. 8, No. 9, 1 May 1979, p. 1445-8.

9. W. B. Spillman, Jr., "Multimode Fiber-Optic Hydrophone Based on a Schloren Technique," Applied Optics, Vol. 20, No. 3, 1 February 1981, p. 465-70.

10. W. C. Goss, R. Goldstein, M. D. Nelson, H. T. Fearnhaugh, and O. G. Ramer, "Fiber-Optic Rotation Sensor Technology," Applied Optics, Vol. 19, No. 6, 15 March 1980, p. 352-8.

11. A. Papp and H. Harms, "Magnetooptical Current Transformer," Applied Optics, Vol. 19, No. 22, 15 November 1980, p. 3729-45.

12. S. C. Rashleigh, "Magnetic-Field Sensing with a Single-Mode Fiber," Optics Letters, Vol. 6, No. 1, January 1981, p. 19-21.

13. Anthony J. Intrieri, "Optical Fibers Look Around Obstacles to Measure Temperature," Control Engineering, December 1977, p. 42-44.

14. A. J. Saber, M. D. Johnston, L. H. Caveny, and M. Summerfield, "Acoustic Emissions from Burning Propellant Strands," Proceedings of 11th JANNAF Combustion Meeting.

15. John L. Eisell, "Vibration Response Spectroscopy-Extension of Acoustic Emission Techniques to Combustion Diagnostic Use" Technical Memorandum 3070, Naval Weapons Center, China Lake, California 93555, April 1977.

16. A. G. Shepherd and P. Descure, "Charge Coupled Devices," Electronic Engineering, December 1980, p. 37-40.

17. News Release NR81-1R, (1981) Circom Corporation, Santa Barbara, California 93111, 1981.

18. Charles F. Freeman, Editor, "Recent Advances in TV Sensors and Systems," Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 203, August 27-28, 1979, San Diego, California.

19. J. E. Soller, "Airborne Video Instrumentation/Data Reduction," Society of Flight Test Engineers, Proceedings of 10th Annual Symposium, Las Vegas, Nevada, September 4-6, 1979.

20. A. S. Lundy, J. B. Ramsay, A. L. Criscuolo, A. D. Martin, J. A. Montoya, and J. R. Parker, "Temporal and Spatial Location of the Transition-To-Detonation Point in Propellant Grains," presented at 16th JANNAF Combustion Meeting, Monterey, California, September 1979, unpublished (LA-UR-79-2960).

21. Harold J. Jeske, "Performance Characteristics of Telemetry Transmission Systems," Tutorial Proceedings of the 22nd International ISA Instrumentation Symposium, May 25-27, 1976, San Diego, California (Fundamentals of Aerospace Instrumentation - Vol. 8) p. 109-119.

22. Charles S. Johnson, "An Introduction to Telemetry Data Systems," *ibid*, p. 127-39.