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VEHICLE MOTION MEASUREMENT TECHNOLOGY

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16. Abstract

Vehicle motion measurement technology is addressed on three fronts, viz.: (1) motion transducers, (2) digital data acquisition, and (3) optimal state estimation. A wide range of position, velocity, and acceleration transducers, of both linear and angular form, are identified and reviewed. A digital data acquisition system design philosophy particularly appropriate for the mobile vehicle environment is articulated, and existing and potential systems ascribing to that philosophy are described. Three commercially available data acquisition systems which might also be used in vehicles are reviewed. Optimal state estimation techniques are discussed, with emphasis on Kalman filtering methods. References are given. Three appendices contain literature on transducers, literature on digital data acquisition systems and components, and references on the applications of optimal state estimation techniques.

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CONTENTS

1.0 INTRODUCTION

This document is the final report by the Engineering Research Division of the University of Michigan Transportation Research Institute to the General Motors Corporation on the project "Vehicle Motion Measurement Technology."

The purpose of this project was to review the state-of-the-art in the technology of vehicle motion measurement. In doing this, three broad subject areas were addressed, viz. (1) motion transducers, (2) digital data acquisition systems, and (3) data reduction techniques. Sections 2.0 through 4.0 consider these subjects, respectively.

Section 2.0 discusses position, velocity, and acceleration transducers available on the market today and applicable to the measurement of sprung and unsprung mass motions.

Section 3.0 considers digital data acquisition systems applicable to road vehicle motion measurement. In this section, we present discussions of (1) a system previously developed by UMTRI (where the goal is to put forth our view of the desirable qualities of such a system, as derive from our own experience); (2) potential systems that could be developed by GM from available hardware and that would possess (what we see as) the desirable qualities of the UMTRI system but would have hardware configuration particularly suited to GM's needs as well as current and projected computer hardware environment, and (3) prepackaged, commercially available systems that could serve GM's purposes.

Section 4.0 presents a brief discussion of optimal state estimation, concentrating on Kalman filtering techniques. This general method is used broadly in the aircraft and aerospace fields for treatment of vehicle motion measurement data. Although it has not generally been applied to road vehicles, we believe that it holds significant potential of improving the quality of measured vehicle motion time histories in this field. Similarly, it may be useful in obtaining good quality measurements from "non-traditional" transducer sets. Section 5.0 lists references applicable to the discussion of

Section 4.0.

Appendices A through C, contain materials associated with Sections 2.0 through 4.0, respectively.

2.0 SENSORS

A search was made for sensors that may provide improved measurement of dynamic vehicle motions. The following measurements, for which greater accuracy is desired, were identified: (1) ground clearance, (2) pitch and roll angle, (3) wheel angles, (4) sprung-to-unsprung mass displacement, and (5) slip angle. Also, the sponsor expressed an interest in obtaining new servo accelerometers and angular rate sensors. Thus, data on such devices are included.

All of the device specifications and literature received from the manufacturers contacted is included in Appendix A, even though many of these devices may not be applicable to the sponsor's immediate problems. Appendix A is divided into five sections: (A-1) accelerometers, (A-2) noncontact distance sensors, (A-3) noncontact velocity sensors, (A-4) non-gyro angular rate sensors, and (A-5) gyroscope-based sensors. Section A-5 includes information on rate gyros, rate integrating gyros, free gyros, vertical gyros, and directional gyros. Conventional distance-measuring devices, LVDT's, linear potentiometers, and string potentiometers are not included.

The following is a general discussion of some of the sensors included in Appendix A. The discussion is intended to call attention to attractive features and possible applications of certain sensors, to compare similar devices, to give a brief explanation of their operation, or to provide information obtained from the manufacturer which is not included with the literature in the appendix. This section concludes with a list of all manufacturers contacted for information on gyro-based instruments, together with comments on their response to our query. We feel that there may be other possible sources of applicable gyro devices which were not found in this search. For example, suppliers of navigational equipment for private and/or light aircraft were not contacted.

2.1 Accelerometers

A variety of accelerometer types are available. These include potentiometric, strain gage, piezoelectric, piezoresistive, and servo accelerometers. Although piezoelectric and piezoresistive accelerometers are typically smaller, the servo, or force balance, accelerometer excels in overall performance and ease of use. Therefore, only the servo accelerometer is included in this report.

The typical servo accelerometer has an accuracy of about 0.1% of full scale range, very low offset or bias, and very low scale factor and bias temperature coefficients. Standard units are available weighing from over eight ounces down to as little as 0.7 ounce, and in a variety of mounting configurations. Shock survivabilty, which is important with regard to long service life in field test operations, ranges from 100g to 1500g in different models with full scale ranges of one or two g's required for vehicle dynamics testing. Prices range from about $400 to $2000 in single unit quantities.

Data sheets from four major manufacturers of servo accelerometers, covering over twenty different models, are included in Appendix A-1. Table 1 (3 pages) shows a comparison of the specifications and price of several models selected from these data sheets. These "examples" in Table 1 illustrate the differences in the way manufacturers specify their accelerometers as well as differences in the accelerometers. In critical applications, beware of "specmanship."

Columbia lumps together the effects of hysteresis, non-linearity, non-repeatability, resolution, and threshold in a quantity called composite error, while other manufacturers specify each of these quantities separately or not at all. Frequency response is typically specified only by natural frequency and damping. However, in some cases the frequency response is specified as an error band over a range of frequencies from zero to a frequency less than the natural frequency (for example, see the Sunstrand QA-800, QA-900, and QA-1400 data sheets). Most manufacturers supply a calibration sheet on each individual accelerometer, but this may not include all calibration data the user may desire for a given application. Additional calibration data usually can be obtained with the accelerometer for an additional charge. The Sundstrand Model QA-2000 is temperature modeled over its operating temperature range by computerized test equipment. The accelerometer has a built-in precision temperature sensor; its output together

Table 1

Specifications and Price of Selected Linear Servo Accelerometers

	Sundstrand Mini-Pal	Sundstrand QA-900	Sundstrand QA-1400
Range-Full Scale	±1g to ±50g	±30g, ±12 Vdc max.	±60g, ±12 Vdc max.
Output	±5 Volts	±1.3 ma/g nom.(1)	±1.3 ma/g nom.(1)
Natural Freq.	150 Hz min.	500 Hz min.	500 Hz min.
Damping	0.3 to 1	0.3 to 0.8	0.3 to 0.8
Linearity	5 mg or 0.05% F.S.*	0.03 mg/g^2	0.02 mg/g^2
Threshold	0.005% F.S. max.	0.005 mg min.	0.001 mg min.
Resolution	-	0.005 mg min.	0.001 mg min.
Hysteresis	5 mg or 0.02% F.S.*	-	-
Repeatability	5 mg or 0.02% F.S.*	-	-
Composite Error	-	-	-
Cross-axis Sen.	5 mg/g max.	2 mg/g max.	2 mg/g max.
Bias	±10 mg max.	±10 mg max.	±10 mg max.
Bias T.C.	±0.05 mg/°C max.	±0.09 mg/°C nom.	±0.09 mg/°C (2)
Scale Factor T.C.	±0.02%/°C max.	±0.018%/°C nom.	±0.018%/°C max.
Shock	200 g, 5 ms	250 g, 6 ms	250 g, 6 ms
Weight	0.7 oz	2.3 oz	2.3 oz
Price	$1250	$990	$1810

* Whichever is larger

(1) Current output. Range set by external resistor

(2) As low as 0.01 mg/°C on special order

Table 1 cont.

Specifications and Price of Selected Linear Servo Accelerometers

	Sundstrand QA-1200	Schaevitz LSB	Systron-Donner 4384
Range-Full Scale	±60g, ±12 Vdc max.	±0.25g to ±50g	±1g to ±40g
Output	1.3 ma/g nom. (1)	±5.0 volts	±7.5 volts
Natural Freq.	800 Hz min.	50 to 200 Hz (2)	>100 Hz (2)
Damping	0.3 to .7	0.3 to 1	0.7 ±0.1
Linearity	0.02 mg/g^2	0.05% of F.S.	0.05% of F.S. max.
Threshold	0.001 mg	-	-
Resolution	0.001 mg	0.0005% of F.S.	0.001% of F.S. max.
Hysteresis	0.001% of F.S.	0.02% of F.S.	0.02% of F.S. max.
Repeatability	0.003% of F.S.	-	0.02% of F.S. max.
Composite Error	-	-	-
Cross-axis Sen.	2 mg/g max.	2 mg/g max.	0.002 g/g max.
Bias	±10 mg max.	±0.1% of F.S. max.	0.1% of F.S. max.
Bias T.C.	±0.135 mg/°C (3)	±0.002%/°C	±0.0018%/°C max.
Scale Factor T.C.	±0.018%/°C max.	±0.02%/°C	±0.018%/°C max.
Shock	250 g, 11 ms (4)	100 g, 11 ms	100 g, 11 ms
Weight	2.3 oz	3 oz	3 oz
Price	$1775, $1860 (4)	$860	$1350

(1) Current output. Range set by external resistor

(2) Dependent on g range

(3) As low as 0.01 mg/°C on special order

(4) 1000 g, 0.5 ms on special order

Table 1 cont.

Specifications and Price of Selected Linear Servo Accelerometers

	Columbia SA-127	Columbia SA-120R	Columbia SA-120
Range-Full Scale	±2g to ±10g	±1g to ±50g	±1g to ±100g
Output	±7.5 Volts	±7.5 Volts	±7.5 Volts
Natural Freq.	30 to 300 Hz (1)	30 to 300 Hz (1)	30 to 300 Hz (1)
Damping	0.7 nom.	0.7 ±0.2	0.7 ±0.2
Linearity	-	-	-
Threshold	-	-	-
Resolution	-	-	-
Hysteresis	-	-	-
Repeatability	-	-	-
Composite Error	±0.25% of F.S.	±0.15% of F.S.	±0.2% of F.S.
Cross-axis Sen.	-	-	-
Bias	±0.15% of F.S.	±0.2% of F.S.	±0.1% of F.S.
Bias T.C.	±0.002% of F.S./°C	±0.001% of F.S./°C	±0.001% of F.S./°C
Scale Factor T.C.	±0.03%/°C	±0.025%/°C	±0.03%/°C
Shock	100 g, 1 ms	1500 g, 0.5 ms	1000 g, 0.5 ms
Weight	4 oz	1 oz	1 oz
Price	$400	$995	$1250

(1) Dependent on g range

with the calibration data permits computer compensation of the accelerometer output. This extreme is normally required only for demanding aerospace applications. The price of the QA-2000 ranges from about $2000 to $2800, depending on the extent of the calibration modeling.

The servo accelerometer is inherently a current output device, where the output current is that required to obtain an internal force balance. This current is passed through a load resistor, producing a voltage across the load resistor proportional to acceleration. Voltage output accelerometers have this resistor built-in, and the accelerometer output impedance equals the resistor value, typically one to five kilo-ohms. Thus a low-impedance load placed on the accelerometer output will change the output scale factor. A low-impedance output option is available in the Schaevitz accelerometers.

Data sheets on angular accelerometers manufactured by Schaevitz, Columbia, and Systron-Donner are also included in Appendix A-1. Current prices (for estimating only) have been added to the data sheets where a price schedule is not provided by the manufacturer.

2.2. Noncontacting Distance Sensors

Appendix A-2 contains data sheets and literature on two noncontacting distance sensors that may be suitable for measurement of the vehicle body to ground distance. One is a low cost ultrasonic pulsed ranging module, and the second is a high cost solid state laser/optical device. Either device would permit operation at higher vehicle speeds than is possible with the Polaroid distance sensor.

2.2.1. The Ultrasonic Ranging Module. Data on several ultrasonic ranging devices, manufactured by Massa Products Corporation, are included in Appendix A-2. The Massa model E-201 appears particularly suitable for vehicle body to ground measurements. It is a pulse ranging device wherein an output latch is set by the transmitter trigger pulse and reset by the first return echo. Thus the output pulse width is proportional to the target range, approximately 148 microseconds per inch, determined by the velocity of sound in air. This model employs separate transmit and receive transducers, each approximately one inch in diameter. Cables connect the transducers to a small

(2 x 4 x 0.75 inches) electronic module weighing only 3 ounces. Detection range is 2 to 24 inches with a resolution of 0.001 inch. The maximum transmit pulse repetition rate, and thus data sampling rate, is specified in the data sheet at 100 pulses per second. At a vehicle speed of 60 mph this provides measurements at intervals of 10.5 inches. Operation at pulse rates up to 200 pulses per second may be possible. Power required is 8 to 15 volts at 30 ma. Cost is about $200 per unit in small quantities.

Consider an illustrativeinstallation of this sensor with the transducers mounted in a plane parallel to the ground and their centers on an axis parallel to the longitudinal axis of the vehicle. Each transducer (transmit and receive) has a beam width of 10 degrees. With an appropriate spacing set between the transducers and with the transmitter located ahead of the receiver in the direction of travel, the reflected signal is within the receiver beam width over a band of velocities and of sensor heights. Relative to the road, the location of the receiver when the echo arrives is exactly the same as the location of the transmitter when the pulse was transmitted only for a unique set of values of (1) the spacing between the transducers, (2) the vertical distance between the sensors and the ground, and (3) the vehicle velocity. For example, the "optimal" spacing between transducers is 1.9 inches when the ground distance is 12 inches and the vehicle velocity is 60 mph. The minimal spacing between transducers, determined by their size, is 1.12 inches.

Errors inherent in ultrasonic ranging devices in general and in this particular application of this device result from:

- The change in the velocity of ultrasonic waves in air with change in air temperature, air pressure, and relative humidity.

- Variation of the output pulse reset time with the power in the echo pulse.

- Triangulation errors due to non-optimal transducer spacing and due to vehicle pitch and roll.

- Air turbulence.

Velocity of ultrasonic waves in air. The effects of temperature, pressure, and humidity on the propagation of ultrasound in air are well known, and these parameters are easily measured. Thus, correction of data for errors due to changes in the propagation velocity are possible. The approximate velocity change for each quantity with the other two constant is:

- Temperature: +0.95 % per 10 deg. F. rise.

- Pressure: -1.7% per inch of mercury increase.

- Humidity: +0.035% per 10% increase in relative humidity.

Echo power. The output pulse is reset when the received echo amplitude exceeds a preset threshold. The echo pulse rise time is finite. Consequently, the time at which the echo signal exceeds the threshold varies with the echo amplitude. Variations of the echo power or amplitude may result from changes in range, surface reflectance, and signal attenuation in the air. This error may be negligible.

Triangulation errors. Triangulation error is defined as the difference between the vertical height from the transmitter to the ground plus the vertical height back to the receiver, and the shortest triangular path from the transmitter to the ground and thence to the receiver, where the distance between the transmitter and receiver is the base of the triangle. Thus the triangulation error is zero only when the transmitter/receiver spacing is "optimal" (as described above) for the sensor height and vehicle speed, and the pitch and roll are zero. The triangulation error is less than one per cent of the reading over the following range of conditions with zero pitch and roll angles.

Transducer spacing	1.7 inches
Measurement distance range	12 to 22 inches
Velocity range	0 to 60 mph

Given the spacing between transducers and the vehicle velocity, the triangulation error is a predictable function of distance. Thus, a first-order correction can be made on the measured distance data to decrease triangulation error. Vehicle pitch causes a predictable error as a function of measurement distance resulting from a change in height of the receiver relative to the transmitter. Five degrees pitch results in an error of about one percent of reading at a distance of twelve inches and less for longer distances. Given a measure of the pitch angle, this error is correctable. Roll angles up to about five degrees cause negligible error. Unpredictable errors will occur when the power reflected from the point on the surface corresponding to the shortest triangular distance between the transmitter and receiver does not exceed the receiver threshold. Power exceeding the threshold may be received from a different point , but in this case the error on the indicated distance is not predictable. With the 10 degree beamwidth of the transducers, this should occur only at pitch and/or roll angles somewhat greater than 5 degrees. Operation of this sensor may be practical at angles greater than 5 degrees. However, experiments would have to be performed to determine the actual practical pitch and roll angle limits within which the errors are predictable and thus correctable. Of course broader transducer beam width would increase this limit.

Air turbulence. Qualitative effects of air turbulence are unknown. The data sheet warns against placing the sensor in areas of air turbulence. However, the manufacture could not provide any qualitative data or even rough estimates of the expected errors resulting from air turbulence. Experimentation is required to qualify this error source. It is of interest to note, however, that K.J. Law Associates in Farmington, Michigan, market a road roughness meter using a proprietary ultrasonic pulse ranging sensor operating at a pulse rate of 200 Hz, for which an accuracy of 0.02 inch is claimed at speeds of 0 to 60 mph.

If the maximum permissible pitch and roll angles are about 10 degrees, the Massa ultrasonic distance sensor may provide a low-cost method to measure vehicle pitch and roll. Of course, this would require mounting at least three sensors at separate locations on the vehicle, and the pitch and roll would be calculated from the known locations of the sensors and the corrected ground distance measurements.

2.2.2. Solid State Laser Distance Sensor. The Selcom Optocator is a precision distance sensor manufactured by Selective Electronics Inc. This device measures distance by a triangulation method utilizing scattered light from a small spot of infrared light projected on the target surface. Specifications and details of the operation and performance of this device are given in the literature in Appendix A-2. The literature includes a copy of an article from the January, 1984, premiere issue of Sensors Magazine, which describes the Opticator and a number of applications.

In overview, the Opticator consists of an optoelectronic sensing head, or gauging probe, and a power supply/signal processing unit. Probes are available providing sensor stand off distances from 4 to 12 inches and measuring ranges from 0.3 to 10 inches. Accuracy is 0.1% of the measuring range with a resolution of 0.025% of the measuring range. The basic measurement rate is 16 kilohertz. Several data processing and data output boards are available, providing either digital or analog outputs or both, and other display and control functions. For example, the Receiver Averaging Board (see the literature) provides both digital and analog outputs. Jumper selectable output updating frequencies are 8kHz, 4kHz, 2kHz, etc., down to 31 Hz. for both the digital and analog (D to A) outputs. The data rate is reduced by forming the average of several measurements. Thus, at an update frequency of 8kHz, two measurements are averaged to form the output data value, at 4kHz four measurements are averaged, etc. The maximum analog output bandwidth is 2kHz.

The Opticator is claimed to maintain the specified accuracy on a wide variety of target surfaces, but it will not work on specular reflecting surfaces because it operates on scattered light. It has been applied in a road profilometer, cross profile, and road texture measurement system developed in Sweden. Excellent performance of this system has been reported with operation at highway speeds. Brief tests were conducted at UMTRI with an evaluation unit on loan from the local representative. This unit performed to the manufacturer's specifications. Addition of a 0.03 inch film of water to a jennite-like surface produced no change of indicated distance, even though distance changes of 0.01 inches could be resolved.

Excellent accuracy should be obtained using the Opticator to measure vehicle body to road heights or, with multiple sensors, measuring body pitch and roll angles. The Opticator measures distance, along the line of its narrow projected beam, to any surface, flat or curved, that scatters sufficient light back to the detector. A flat surface can be oriented at an angle of 20 degrees or more from an orientation normal to the beam without loss of distance measurement accuracy. Thus the distance measurements from three Opticators projecting beams perpendicular to a reference plane established in the vehicle body would accurately define a plane on the ground and its orientation with respect to the body reference plane. Having established these two planes, it is then straightforward to compute the distance between these planes along any line perpendicular to the ground plane (body to ground distance), and the angle between any line in the ground plane with respect to any line in the body plane (pitch and roll angles, for example). Considering the accuracy of the Opticator, the limiting error sources for this system would probably result from compliance of the vehicle body and the sensor mounting brackets.

Dynamic measurement of wheel angles is another possible application of the Opticator. In this application three gauging probes would be mounted outboard of the wheel by brackets attached to the vehicle body, thus establishing a reference plane in the vehicle body. A flat target plate would be mounted to the wheel. The three perpendicular distances from the body plane to the target plate, measured by the Opticator probes, uniquely define the orientation of the wheel plane with respect to the body plane. Therefore, wheel angles with respect to reference lines in the body plane can be calculated. Furthermore, given the orientation of the body plane with respect to the ground plane, as described above, the actual steer and camber angles can be calculated. Of course, a thorough analysis would be required (which was not attempted here) to qualify the effects of sprung mass to unsprung mass displacements on this measurement system to determine its actual practicality.

The Opticator is a very rugged device, designed for use in harsh industrial environments. Thus it should be reliable in the vehicle testing environment. However, it is expensive. Standard gauging probes range from about $8000 to over $12,000. Special probes are even more costly, but usually one of the several standard probes can be adapted to a given application. The nominal cost of an electronics package to interface up to 5 probes and provide digital or analog outputs is $6000 to $8000.

Regarding road wheel angle (steer and camber) measurement, Zimmer OHC, of

Rossdorf, Germany, manufactures an optical angular sensor called the Autocollina, which is applicable to this measurement problem. (We are aware that GM has initiated the purchase of a pair of these devices for this purpose, so our discussion here will be limited.) Our most useful information on this device has come through personal conversation with Dr.-Ing. Klaus Rompe of TUV Rheinland. TUV has developed a system for measuring steer and camber of all four wheels of a passenger car using four Autocollina devices. Dr. Rompe indicates that system accuracy is 0.01 deg. (However, we remain skeptical that either chassis mounting points or the instrument support structure is rigid enough to allow such accuracy. We suspect a communications difficulty here, since Dr. Rompe's English is limited and our own German is nonexistent.) TUV has applied the system in a study concerned with ride and vibration in the on-center steering condition.

2.3. Noncontact Velocity Sensors

2.3.1. Optical Velocity Sensors. The Datron Correvit-L optical velocity sensor appears to be the most successful noncontact velocity sensor development for automotive test use. This device has been available for several years and is currently marketed by D.E. Sherry Company, Rocky River, Ohio. A similar device, which operates on the same optical principle, is manufactured by Ono Sokki and marketed by Fife-Pearce Electric Co., Detroit, Michigan. The accuracy of both devices is claimed to be better than one percent on all types of road surfaces and for speeds from one mph to over 100 mph. Microprocessor electronics included with both systems provide data outputs for a variety of standard automotive test procedures: acceleration, braking, braking distance, etc. System cost is in the $20,000 range. Although the Milford Proving Ground personnel are already thoroughly familiar with these devices, data are included in Appendix A-3. Recent test data and correspondence received from D.E. Sherry also are in the appendix.

By employing two velocity sensors, the Correvit-L and Correvit-Q, sensing longitudinal and lateral velocities, respectively, Datron claims to be able to compute vehicle slip angle in the range of ±45 degrees with a resolution of 0.1 degree. (See the letter from D.E. Sherry dated April 12, 1984, in the appendix.)

2.3.2. Radar Velocity Sensors. A considerable amount of effort has been devoted to the development of radar devices for measuring vehicle velocity. The police radar, of course, is the most prominent result of this effort. While "radar fifth wheels" have been developed, they have not been adopted by the automotive test community, probably because they do not provide the accuracy of the standard fifth wheel. Several years ago, Midwest Microwave of Ann Arbor marketed a microwave velocity sensor advertised as a fifth wheel replacement with an accuracy of one mph. However, this device is no longer produced.

A radar speed sensor for locomotives, developed by RCA, is described in an article included in Appendix A-3. This article reported an accuracy of 0.2 to 0.5 mph for the device over snow, sand, open-tie bridges, road crossings, and normal track bed. Mr. Henry Johnson, the author of the article and currently with the RCA David Sarnoff Research Center, directed us to the Electro-motive Division of GM for further information on the development and applications of the device. Mr. John Lenihan, at the Electro-Motive Division in Lagrange, Illinois is responsible for current application and development of the locomotive radar speed sensor. A paper given by Mr. Lenihan at the 1981 GM Electronics Conference is included in the appendix. Mr. Lenihan informed us that it is being used to measure locomotive velocity in order to control drive wheel slip and optimize traction. The accuracy of the device is about 2% of reading, averaged over 50 sec., or 4% of reading, averaged over 1 sec., when operating on normal stone and tie rail grades. However, the accuracy is poorer on concrete, asphalt, and smooth railroad crossings. Improvements are still under development. It is expected that an accuracy of at least two percent will be achieved for these surfaces. Mr. Lenihan estimated the purchase cost to be about $2000.

2.4. Angular Rate Sensors: Non-Gyro

Appendix A-4 contains data sheets on two non-gyro angular rate transducers. One is manufactured by Humphrey Inc. and the other is manufactured by Watson Industries Inc. Ruggedness, low power consumption, and long service life are their main advantage over gyro-type angular rate sensors. Both are DC in and DC out, "solid state devices." Each is rated at over 10,000 hours mean time between failure, and will withstand over 100 g's shock. Three of the Humphrey rate sensors, with a full scale range of ±60 degrees, have been used at UMTRI for several years. Calibration checks on these units have shown a gain change of up to 4% of full scale over a period of several months. Also the zero offset is temperature-sensitive, exhibiting a drift of up to 3% of full scale during warm up (30 minutes after applying power) and up to 1% drift during a 10-minute period thereafter in a constant-temperature environment.

The Humphrey device has a bandwidth of 15 hz, a full scale output of ±2.5 VDC, operates on ±15 VDC power at 200 ma, weighs 12 ounces, and costs about $1400. By comparison, the Watson angular rate sensor has a bandwidth of 55 Hz, a full scale output of ±10 VDC, operates on ±15 VDC at 20 ma, and costs about $550. The gain stability of the Watson device is not specified in the data sheet. However, the specification on offset drift is 0.5% of full scale per degree centigrade.

For these two non-gyro rate sensors, the available data indicate that the accuracy of the Watson device is equal to or better than that of the Humphrey unit. Furthermore, it is smaller, requires less power, and is less costly. In fact, it is probably the lowest cost rate sensor available. However, more than an order of magnitude greater accuracy is obtained with gyro-type rate sensors. For example, Appendix A-5 contains data on a gyro-type rate sensor, manufactured by the Astronautics Corporation of America, which costs about $650. This device is specified to have less than ±2% change in gain and less than 1% change in offset over a temperature range of 90 degrees centigrade. It employs a brushless DC motor and photoelectric pickoffs yielding a mean time between failure of greater than 3000 hours. Input power is 28 VDC at 500 ma and ±15 VDC at 15 ma. The output is ±4.8 VDC. It weighs 1.25 pounds. Its shock tolerance is not specified, but typical gyro devices will tolerate shock on the order of only 20 g's. Specifications for several gyro-type angular rate transducers, some even more accurate (and more costly) than this one, are given in Appendix A-5.

2.5. Gyroscopic Sensors

The literature in Appendix A-5 was received from manufacturers in response to a request for data on rate gyros and data on sensors for the measurement of vehicle attitude (pitch and roll) during vehicle handling maneuvers. A nominal range of ±50 degrees per second was specified for angular rate measurements. For pitch and roll, a range of ±10 degrees was specified, with a measurement accuracy of about 0.1 degree for data acquisition over a time period of five to 30 seconds. DC input (preferably 12 volts) and DC output was indicated to be desirable but not necessary. Literature was received on rate gyros, rate integrating gyros, free gyros, vertical gyros, directional gyros, and vertical referenced stable platforms.

A rate gyro is a single-degree-of-freedom gyro, with a linear constraint proportional to force on displacement of its gimbal. Thus, gimbal displacement is proportional to the angular rate input. A pickoff on the gimbal provides an output signal proportional to angular rate.

The rate integrating gyro also provides an output signal proportional to angular rate (although to the uninitiated its name may imply that it produces an output equal to the integral of rate, i.e., displacement). The rate integrating gyro is the highest precision type rate gyro, and the most expensive. It is a single-degree-of-freedom device. Operation of the rate integrating gyro is similar to the operation of a force balance servo accelerometer. A rate signal is generated by electronically servoing the gyro in a capture loop. A torque motor holds the gyro gimbal at its null position. The torquing current is proportional to the input rate and is used to produce a proportional output voltage. The rate integrating gyro is used in navigation systems and stabilization systems in the most demanding of aerospace applications (satellites, space probes, planetary reentry probes, ballistic missiles, aircraft, etc.). Angular displacement is obtained by digital integration of the rate signal. The best rate integrating gyros have a bias stability as low as 0.01 degree per hour.

The free gyro is typically a two-degree-of-freedom device with pickoffs on the inner and outer gimbals. A gaging mechanism locks the gyro spin axis in a fixed position with respect to the case during gryo motor spin up.

Ideally, the gyro spin axis remains fixed in space in the orientation established at the moment the gyro is uncaged, and the two output signals are proportional to the angle between each gimbal and the case. A number of unwanted torques cause precession of the spin axis from its ideal position (drift), resulting in a measurement error. These derive from internal forces such as friction in the gimbal bearings, radial mass unbalance in the rotor, unbalance within the gimbal assembly, drag from the pickoff devices, etc. Also a small shift in the axis alignment may occur at the moment the gyro is uncaged. Depending on the quality of the gyro, drift rates range from about 0.1 degree per minute up to several degrees per minute. Thus in vehicle handling test applications, depending on the gyro quality and the test duration, it may be necessary to measure pre-test and post-test offset values in order to establish error limits on the data.

A vertical gyro is a special version of the free gyro with a two-axis erection system to maintain the spin axis in a vertical position. The erection system senses the total acceleration vector; thus, during turns and vehicle acceleration it will erect the gyro toward a false vertical. Depending on the erection system time response and the test duration, it may be necessary to turn off the erection system during the test to minimize pitch and roll measurement errors. Of course, during the time the erection system is off, drift errors occur, as with a free gyro.

A directional gyro is simply a vertical gyro oriented such that its outer gimbal senses yaw angle. (In a two-degree-of-freedom gyro the outer gimbal is free to rotate 360 degrees with respect to the case, but the inner gimbal is generally restrained to less than 90 degrees travel to prevent gimbal lock, which occurs when the gimbals are aligned.) A flux gate may be included in the vertical gyro package to slave the gyro to magnetic north.

Free gyros and vertical gyros are also called displacement gyros, because their outputs are proportional to angular displacement.

A vertically referenced, or vertically stabilized, platform, as implemented in the devices described in the literature in Appendix A-5 from Humphrey Inc., consists of a platform which is held horizontal relative to gravity by a mechanical linkage to a vertical gyro. Accelerometers mounted on this platform sense horizontal and vertical acceleration. Pitch, roll, and yaw are derived from pickoffs on the vertical gyro gimbals, and pitch, roll, and yaw rates are derived from case-mounted rate sensors. The number of sensors implemented in a system is optional.

2.5.1. Rate Gyros. Three of the rate gyros included in Appendix A-5 are DC to DC systems and thus they are particularly attractive for use in automotive test systems. The Northrop P/N 68215 GIG5 rate gyro may be obtained with an input power option of 12 VDC (+5, -1), 7 watts input (standard input is 28 VDC). An internal inverter powers the AC spin motor and a differential transformer pickoff. The pickoff output is demodulated to produce ±5 VDC output. It is a medium-accuracy device with a rated service life of 1000 hours minimum. The package size is 2 x 2 x 3.5 inches, and it costs $3250.

The Astronautics Corporation of America (ACA) rate gyro, model P/N 303780, has about the same accuracy as the above Northrop gyro, but at $650 it is about one fifth the price. Its rated mean time between failure is greater than 3000 hours. However, it requires 28 VDC at 0.5 amp input to power the brushless DC hall effect motor, and ±15 VDC at 15 ma input to power the optical pickoff electronics and to produce an output of ±4.8 VDC. The package size is 2.6 x 2.8 x 4 inches.

Northrop produces a high-accuracy angular rate sensor, P/N50303, using its GIG6 rate integrating gyro in a DC to DC package. Greater precision is obtained with this system than with standard rate gyros. Of course, the price is also higher. A single-axis package costs about $11,000. A 12 VDC, 8 watt input option is also available with this device, and the output is ±5 VDC. The package size is 2.5 x 4 x 4.3 inches.

The Northrop rate gyros are also available in two- and three-axis packages in only slightly larger case sizes. The approximate cost (obtained by phone) for a two-axis standard rate gyro package is $3400, and for a two-axis rate integrating gyro system is $15,000. Three-axis units cost $4200 for the standard gyros and $20,000 for the rate-integrating gyros.

In the letter of proposal sent with the gyro specifications (see Appendix

A-5), Northrop provided a proposal for a two-axis angle measuring system based on the GIG6 rate integrating gyro at an approximate cost of $17,850. Details included in the letter were minimal. However, in a telephone communication, Mr. H. Hyde indicated that the angle outputs would be derived by analog integration of the rate outputs from a two-axis rate-integrating gyro system. The package would be 5.3 x 4.2 x 3 inches and it would operate on 12VDC, 30 watts power. The output would be ±5 VDC scaled to 5 degrees per volt. A TTL input signal would be required to initialize the integrators. Mr. Hyde estimated that an accuracy of 0.1 degree could be realized over a 30-second integration period. Of course, this package could be provided with both rate and angle outputs if desired.

2.5.2. Free Gyros and Vertical Gyros. Several configurations of free gyros and vertical gyros, with two degrees of freedom and a pickoff on each gimbal, are available as standard design packages from Humphrey Inc. Mr. Jim Kaylor, at Humphrey, recommended model FG23-3602-1 free gyro or model VG24-0601-1 vertical gyro for vehicle pitch and roll angle measurements. Free drift in these units is about one degree per minute. Special modifications of standard designs are readily accommodated by Humphrey.

The Humphrey FG23-3602-1 free gyro has a 28 VDC spin motor (400 ma running) and potentiometric pickoffs. For improved service life (1000 hours) an optional 115 VAC, 400 Hz motor can be used. A plastic element pickoff potentiometer with full-scale electrical travel as small as ±10 degrees can be provided as an option for an additional cost of $500. The basic unit cost is $5290. It weighs about 1.8 pounds in a case about 2.5 inches in diameter and 4.8 inches long. Its shock rating, non-operating, is about 20 g's, 11 ms.

The Humphrey VG24-0601-1 vertical gyro employs a 115 VAC (190 ma running) spin motor and potentiometric pickoffs. It weighs 2.3 pounds and is about 3.3 inches in diameter and 5.5 inches long. Its price is $3700. Its shock rating, non-operation, is 40 g's, 20 ms.

Humphrey also manufactures gyro-stabilized platform systems which operate from 12 VDC power and are designed for automotive testing. These systems provide up to three axis measurements of angle and acceleration, referenced to the vertical, and angular rate referenced to the instrument case. Prices range from about $25,000 to $45,000, depending on the number of sensors and other options. For example, the Model SA07-0301-1 provides outputs of pitch and roll, longitudinal and lateral acceleration, and yaw rate. Including a remote control box, it costs $25,800. Specifications on the Humphrey stabilized platform systems are in Appendix A-5.

Courter, Inc., a subsidiary of Bendix Guidance Systems Division, manufactures free gyros and vertical gyros. These are nominally the same quality, size, weight, and cost of the Humphrey devices. Mr. Moody at Courter stated that Humphrey is their main competitor. The motor in the Courter designs may be "re-designed to specific customer requirements," for example, 115 V-400 Hz single phase, or DC. Pickoffs may be film potentiometers, optical encoders, synchros, or resolvers. Courter and Humphrey were the only manufacturers found that manufacture free gyros.

The Singer Corporation, Kearfott Division, recommended the use of their C 70 4101 030 vertical gyro (3.3 x 3.3 x 3.8 inches) and C 70 3184 erection amplifier/control unit (5.7 x 5.7 x 4 inches). This is a precision system designed for shipboard applications. Its rated service life is 2500 hours. It costs approximately $25,000. Power required is 115 VAC, 400 Hz. The pitch and roll pickoffs are three-phase synchro control transformers. Thus synchro-to-digital or synchro-to-analog converters must be added to convert the outputs to computer-input-compatible signals. Although these requirements are not attractive for automotive use, this system is indicative of the performance that can be obtained with the vertical gyro technology (see the specifications in Appendix A-5). When the erection loop is open, the gyro drifts at less than 0.125 degree per minute. Repeatability to the established vertical is five arc minutes maximum. Typical verticality and synchro transform errors are three arc minutes. Singer also manufactures rate integrating gyros (for example, the K130A081 in Appendix A-5). However, they do not have a standard package including loop closure electronics like the Northrop units.

Data was received from Lear Siegler on their model 9010 series of directional gyros and model 9000 series of vertical gyros. These are high-quality devices with free drift rates of about 0.25 degree per minute. The motor power is 115 VAC, 400 Hz. Pickoffs are synchro transmitter, resolver transmitter, or potentiometric. These gyros have been used on such vehicles as helicopters, drones, torpedoes, the Lunar Rover, and ships. Some modifications may be required for automotive applications, provisions for erection system cut-out, for example. The data books are not clear on this point. The data books did not fit into the appendix binder and thus they are separate from the binder. Prices for these devices are in the area of $8000, depending on model, options, etc. Shock ratings are 15 to 40 g's, 11 ms, depending on the model. Despite the disadvantage of the AC input and AC output, these units appear worthy of serious consideration for the direct measurement of pitch and roll.

Honeywell manufactures rate-integrating gyros, but data requested from Honeywell have not yet arrived. When data are received they will be forwarded to be added to Appendix A-5.

Companies serving the navigation requirements of the private aircraft and light aircraft community were not adequately surveyed in this study, but may be worth looking at for low-cost vertical gyro systems. King Radio, serving the high end of this market, that is light to medium executive aircraft, is sending data on the King KVG 350 vertical gyro. This gyro provides electrical outputs to drive instrument panel displays. Mr. Dan Walker, of King Radio, provided minimal information on the phone. The device operates on 28 VDC and costs about $4000. It is a direct replacement for the Collins model 332D11 and the Sperry VG14A. Mr. Walker pointed out that vacuum-driven gyros are also available. These may be worth consideration for automobile test applications. Also, he expressed reservations with respect to whether these instruments, designed for aircraft use, were sufficiently rugged to tolerate frequent moving from one vehicle to another. Once installed they are quite reliable, but they must be handled carefully during installation and removal. When the data are received from King Radio, they will be forwarded to be added to Appendix A-5.

From our discussions with various engineers in the aerospace industry during this hardware search program, we have gained the impression that it should be practical to derive accurate vehicle pitch, roll, and even yaw data by integration of the outputs from good angular rate sensors in the vehicle-handling test environment. In fact, generally the opinion was expressed that the high-accuracy rate-integrating gyro was an overkill for the task. Further evaluation of this technique seems worthwhile. Also, given that this approach is viable, the standard GRG5 rate gyro DC to DC packages from Northrop are particularly attractive. A three-axis package weighs only two pounds in a case approximately 2 x 4 x 4 inches. It can be powered directly from the automobile 12 VDC buss drawing less than 1.5 amps. Two- or one-axis packages are even smaller.

Possible sources of gyroscopic sensors were selected from a list under "Gyroscopes" in the Thomas Registry and in the Electronic Engineers Master. Others were suggested by the companies contacted. The following is a list of all the companies contacted with comments on their response.

American Design Components
39A Lispenard St.
New York, N.Y. 10013
(212) 966-5650

Sells surplus equipment including various types of gyros. Over 3000 in stock. Call with requirements. A catalog was requested, but it has not arrived.

Astronautics Corp. of America
P.O. Box 523
Milwaukee, WI. 53201
(414) 447-8200
Mr. Herbert J. Sandberg

Sent data on rate gyros. Company does not manufacture free gyros or vertical gyros.

Bell Aerospace
Textron Division
Buffalo, N.Y.

(716) 297-1000
Mr. Hugh Neson

Primarily does aerospace contract work. Company does not manufacture a standard line of gyroscope devices.

Bendix Corp.
The Guidance Systems Division
Teterboro, N.J.
(201) 393-2789
Mr. Torn

Builds systems on contract and special order only. Possibly would enter contract to design and build a system to GM specification. Pitch and roll measurement package would cost over $20,000 dollars each for quantity of three or four. Referred us to Courter, inc., a Bendix subsidiary in Boyne Mountain, Michigan, Mr. Steven Moody.

Conrac Corp.
Stanford Conn. 06901
(203) 348-2100

Company no longer manufactures gyros.

Courter, Inc.
Subsidiary of Bendix Guidance Systems Division
Boyne City, Michigan 40712
(616) 582-6527
Mr. Steven M. Moody

Received data packet including data on free gyros and vertical gyros.

GM Delco
Avionics Division
Milwaukee, WI.
(414) 768-2283
Mr. John Kaufman

Manufactures rate-integrating gyros for use in in-house navigation systems. Would design special package for automotive measurements, using rate-integrating gyros, but cost would be in the $50,000 range. Considered such a package to be an overkill.

Honeywell
Aerospace and Defense Systems
Minneapolis, Minn.
(612) 378-4384
Mr. Jack Eike

Honeywell manufactures rate-integrating gyros that may be applicable. Data sheets have not been received yet.

Lear Siegler Inc.
Grand Rapids, MI.
(616) 241-7000
Mr. Bob Parsons

Received data on directional and vertical gyros.

Jet Electronics
Grand Rapids, MI.
(616) 949-6600
Mr. Richard Otzman

Manufactures a precision-rate gyro exclusively for Gates Lear Jet. Data was to be sent to us on the assumption that it could be purchased from Lear Jet, but the information was not received. Jet Electronics would be happy to enter a development program with GM to build a vehicle attitude measurement system.

Northrop Corp.
Precision Products Div.
El Monte, CA.
(818) 579-2240
Mr. Howard Hyde (technical)
Mr. Chuck Gonsalves (sales)

Received data on the line of precision-rate gyros manufactured by Northrop, and an approximate cost proposal for a pitch and roll angle measurement system based on analog integration of precision-rate gyro outputs. Company sold a special three-axis rate gyro and accelerometer package to GM for use in crash barrier testing. Company does not manufacture free gyros or vertical gyros.

Precision Electronics & Instrumentation Co.
Delray Beach, FL. 33444
(305) 276-031

Company manufactures synchros and resolvers. No gyros.

Sanders Associates Inc.
Nashua, NH. 03060

Company no longer makes gyros.

Sperry Gyroscope Division
Great Neck N.Y.
(516) 574-0111
Mr. John Hobgood

Company does not make a standard line of free gyros or vertical gyros. Primarily does aerospace contract work. Suggested we contact GM Delco Avionics Division, Milwaukee, WI.

3.0 DIGITAL DATA ACQUISITION

The following sections present our views on digital data acquisition applicable to vehicle motion measurement. Section 3.1 is a discussion of the UMTRI Data Acquisition System. This is included to indicate the qualities we feel are important in a data acquisition system and how such qualities are realized in a specific hardware and software configuration. Section 3.2 considers the characteristics of an "ideal" system and explores the possibility of developing a near-ideal system with available hardware modules. Section 3.3 evaluates three packaged, commercially available systems in light of the discussion of the ideal system in the previous section.

3.1 UMTRI Digital Data Acquisition

UMTRI has been using digital data acquisition in the laboratory and in vehicles since 1979. Over the last five years, the system has evolved from a distributed collection of computer, tape recorder, analog conditioning box, and power supplies to a well-packaged, all in one, acquisition unit. Since the system is used in both research and testing activities, it caters to a wide variety of transducers, sampling rates, acquisition modes, control capabilities, and operator feedbacks. Table 2 gives a summary of the design considerations that were incorporated into the system. This design represents a departure from the normally configured data acquisition system. From our experience with field testing and laboratory test machines, we found most errors were due to improper signal conditioning calibration, confusion over log sheets, and breakdowns in communication between the test engineer and the system operator. The potentiometer adjustments and signal switching involved in calibration were both tedious and error prone. To eliminate these problems, computer-controlled signal conditioning cards were developed. The test engineer configures these cards (via hardware and software) for a given set of transducers and test parameters and the calibration is done automatically by the computer. The operator need only enter simple commands to calibrate and acquire data. The computer records all scaling and log information on tape with the data to properly document each test. Thus, calibration and communication errors are significantly reduced. The following sections give a brief discussion of the major system elements and an overview

Table 2. Summary of UMTRI-DAS Features and Design Considerations

Packaging

1. Major components are in one enclosure which minimizes cabling and facilitates installation
2. All components are accessible for troubleshooting and repair
3. Analog outputs are monitored from the front panel
4. All transducers use the same type of connector

Analog Signal Conditioning

1. Provisions for a wide variety of transducers
2. Accurate and reliable signal conditioning
3. Minimal potentiometer adjustments
4. Automatic calibration
5. Flexible filtering
6. Field replaceable modules

Data Acquisition and Storage

1. Sampling rates to 1 K Hz/channel
2. Tests up to 4 megabytes in length
3. Reliable mass storage for data and programs
4. Setup information recorded on tape

Operator Interface

1. Real-time feedback of data in engineering units
2. Printout of data in engineering units (post test)
3. Averaging and smoothing of data
4. Diagnostic control of analog system from keyboard
5. Flexible control of start and termination of tests
6. Operator selection of test parameters from keyboard

Test Documentation

1. Date and time stamping of tests
2. Test identification and operator comments are recorded with test data
3. All scaling information is recorded with the data
4. Permits logging of other test parameters

of how the system operates.

The UMTRI Data Acquisition System (UMTRI-DAS) is shown in the photographs in Figures 1-4 and diagrammed in Figure 5. The system consists of three main subassemblies: computer, tape recorder, and analog signal conditioning unit. These units, along with the appropriate power supplies, are mounted in an enclosure that is approximately 16 inches wide by 12 inches high by 21 inches deep. A removable top panel (via four screws) provides easy access to all of the system components. The cables are conveniently routed and the backplanes are aptly situated so that any board can be plugged into an extender for troubleshooting and repair. Each analog channel has its own transducer connector mounted at the back panel and output monitor jacks on the front panel. Tapes are inserted through the front panel and are securely latched in place. Only a keyboard and CRT display are external to the system enclosure.

Computer

The main control element of UMTRI-DAS is a Texas Instruments microcomputer that is based on the TM990 series microcomputer modules. The modules and software are specifically designed for the industrial real-time I/O environment. The system consists of a CPU and memory module, combination memory and I/O module, and an analog I/O module. The CPU is a true 16-bit processor (1 megabyte addressing) with a unique memory-to-memory architecture that allows fast response to and processing of interrupts. The combination of memory-mapped I/O and serially driven I/O simplifies interface designs. The combination board supplies RAM and EPROM, and opto-isolated inputs and outputs. The analog I/O module is comprised of a protected input multiplexer (16 channels -- expandable to 256), a software programmable gain instrumentation amplifier (gains of 1, 2, 4, and 8), a sample and hold, a 12-bit A/D converter, and two 12-bit D/A converters. An UMTRI-designed tape controller board provides the interface to the tape recorder and also five programmable 16-bit counters which control data collection rates, filter clocks, debouncing clock, and any digital serial inputs.

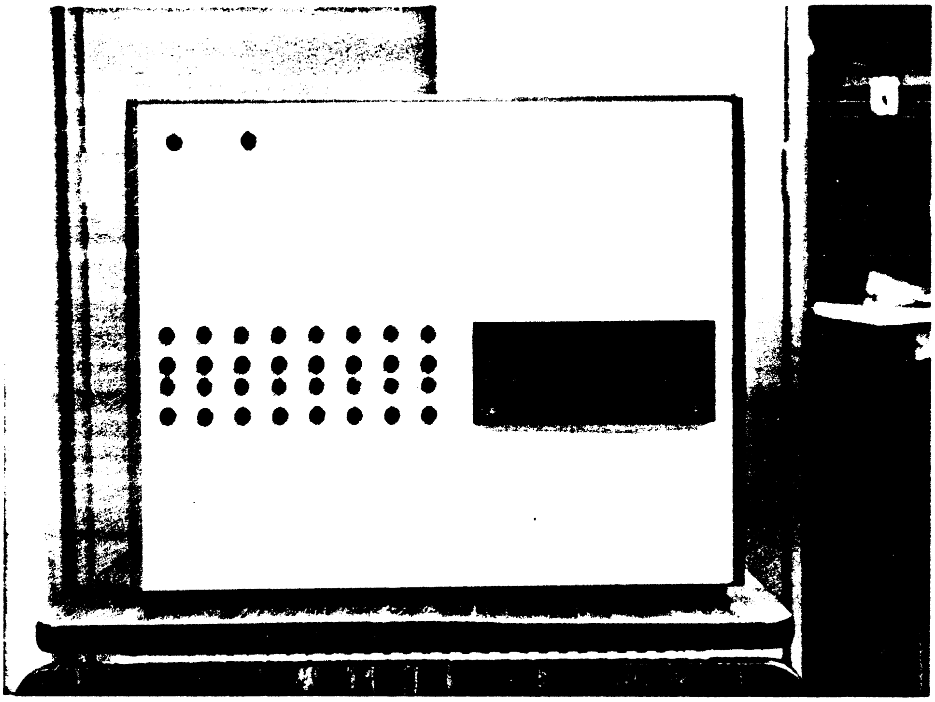

Figure 1. UMTRI-DAS Front View.

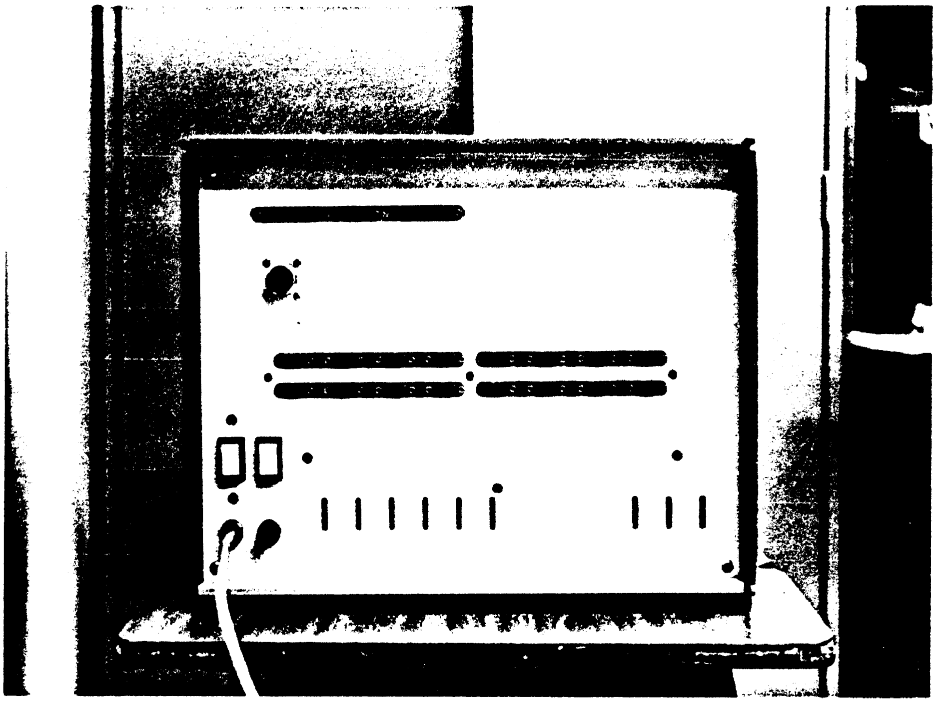

Figure 2. UMTRI-DAS Rear View.

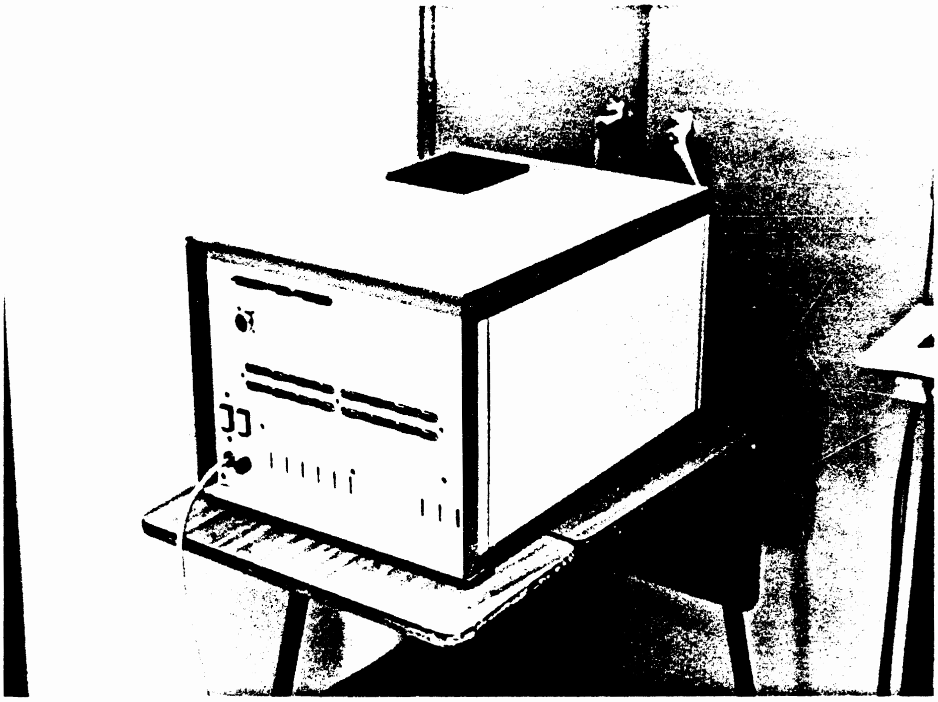

Figure 3. UMTRI-DAS Rear Quarter View.

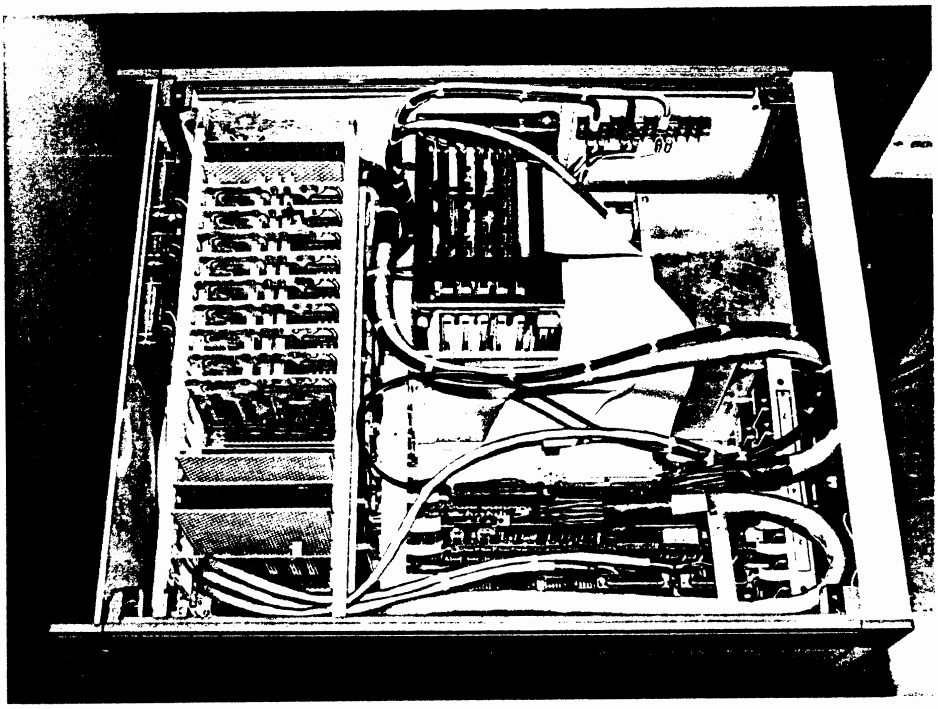

Figure 4. UMTRI-DAS Top View.

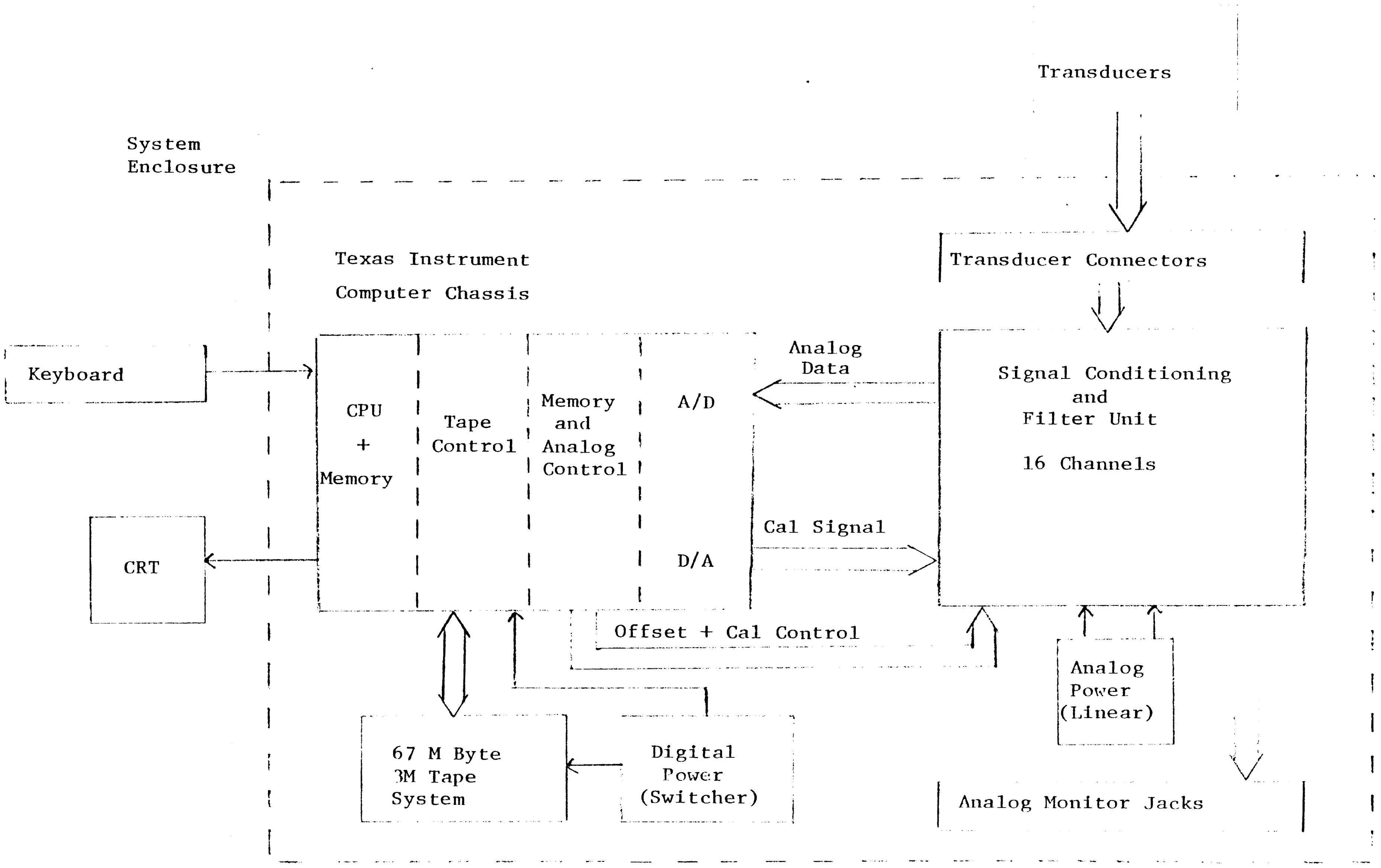

Figure 5. UMTRI Data Acquisition System (UMTRI-DAS).

Tape Recorder

The tape recorder is a 3M HCD-75 High Capacity Data Cartridge System. Each cartridge contains 600 feet of 1/4" tape with a capacity of 67.1 megabytes (65,536 1024-byte blocks that are randomly accessible). The two principal components of the system, a drive module and controller module, have their own microprocessors. The drive module has a stable baseplate that allows repeated, accurate positioning of the cartridge, a microprocessor controlled digital speed servo, read/write electronics with digital gain control, and stepper motor head positioning. The digital design eliminates all potentiometer adjustments. The controller module includes a fully buffered (dual 1024-byte I/O buffers), asynchronous parallel interface. The controller issues motion commands to the drive module, positions the tape to the correct record, formats the data block, adds CRC and error correction frames on write, performs error detection and correction on read, and keeps track of and skips over bad blocks on the tape. The system does several self-tests and adjustment procedures automatically on power-up and cartridge insertion. It has proven to be a convenient and reliable mass storage device.

Analog Signal Conditioning Unit

The analog conditioning unit is made up of a backplane, a control card, and from 1 to 16 signal conditioning cards. The control card provides address decoding and generates the control signals that are supplied through the backplane to the individual amplifier cards. All transducer inputs/outputs and amplifier outputs are also routed through the backplane (see Figure 6).

A signal conditioning card is shown in the photographs in Figures 7 and 8, and diagrammed in Figure 9. The primary component is an Analog Devices 2B31 Signal Conditioning Module (all components within the dashed lines in Figure 9). This module contains a high-performance instrumentation amplifier with input protection to 130 volts RMS, a buffer amplifier, a three-pole filter, and a precision excitation regulator. The other components on the card provide automatic calibration capabilities and flexible gain and transducer configurations.

The transducer is linked to the card via a nine-pin connector and an I/O

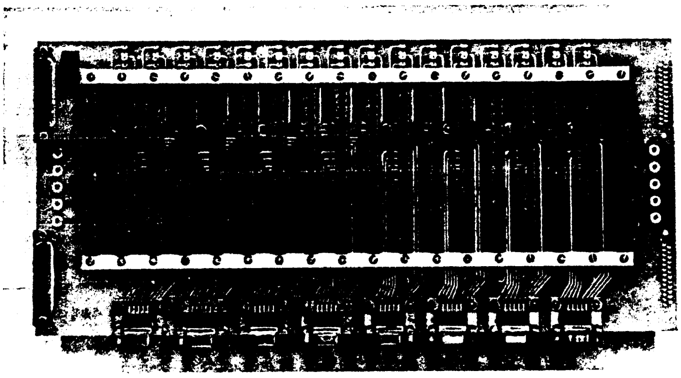

Figure 6. Analog Backplane

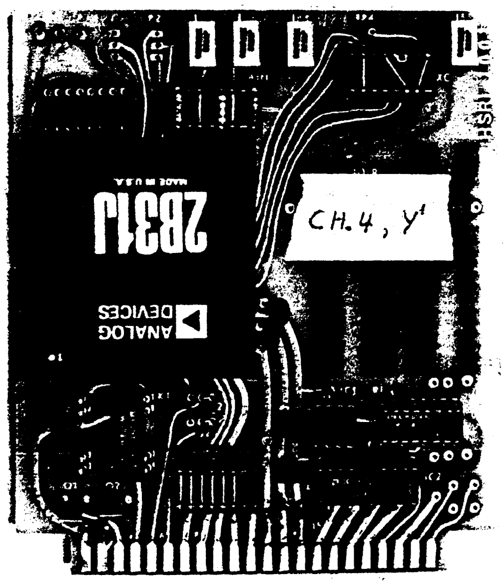

Figure 7. Signal Conditioning Card

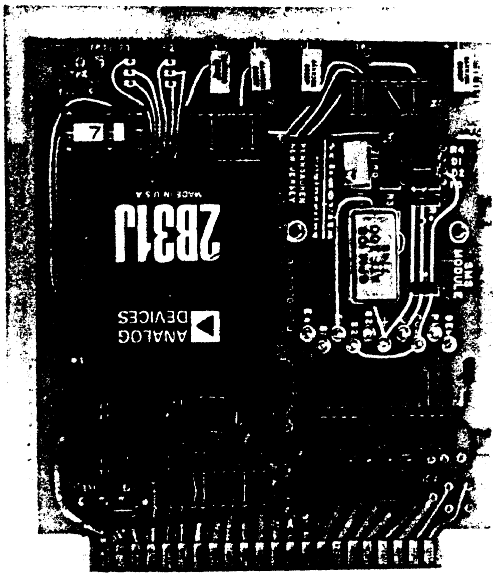

Figure 8. Signal Conditioning Card with LVDT Module.

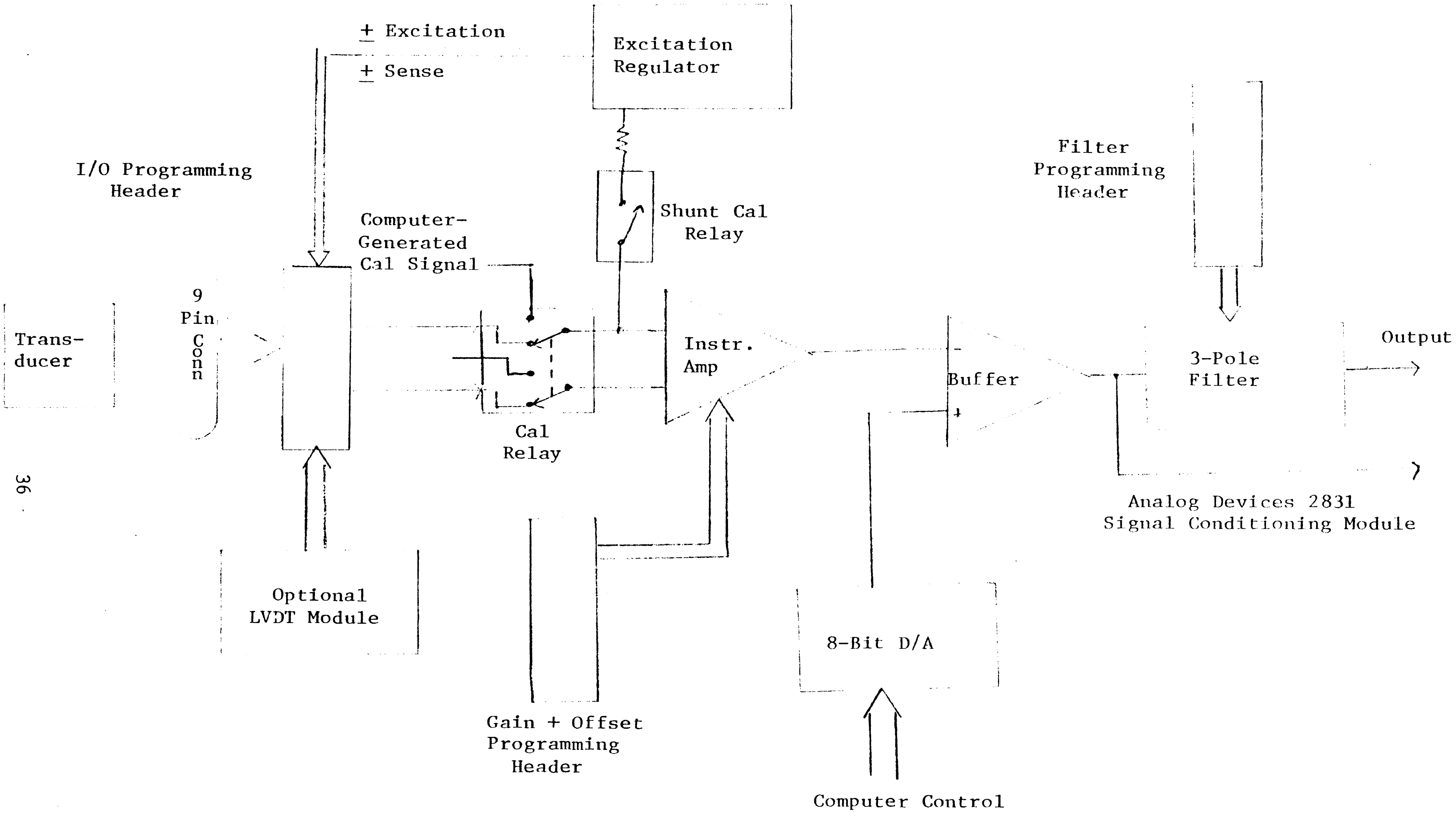

Figure 9. UMTRI Signal Conditioning Card.

programming dip header. Jumpers on this header provide the transducer's excitation (± 15 for servo accelerometers and yaw rate gyros and 0-10 volt with remote sense for strain gauges and potentiometers) and routes the transducer output(s) through the cal relay to the instrumentation amplifier. The photograph in Figure 8 shows an optional LVDT module mounted on the card that can provide AC excitation and signal conditioning for LVDTs. By switching the calibration relay, the computer can disconnect the transducer from the amplifier and apply a D/A-generated calibration signal to the amplifier input. This process permits the computer to measure the offset, gain, and linearity of each signal conditioning card. In addition, an 8-bit D/A on the card provides a computer-generated signal to cancel any offsets via the transducer output or single conditioning circuitry. The remaining dip headers provide convenient and flexible ways to set gains, gain ranges of the amplifiers, and the cutoff frequency of the filter.

Operation

Given a specific set of transducers, the test engineer first configures the analog signal conditioning cards. The proper dip headers for gain range and filter cutoff are inserted in the cards and nominal offset and gain adjustments are made. These adjustments are facilitated by the diagnostic commands incorporated in the system software. Next, the test setup information is entered and recorded on tape. The configuration of the analog cards and the typing of the setup information is usually done only once per set of transducers. Henceforth, the operator need only enter "RDSET" (read setup) and a file name to initialize the system. An example channel list is given in Table 3. Names, units, scaling information, transducer type, and output format are usually entered only once. Sampling rate, start and stop modes, and monitor channels are also selected at this time. Once the above information is entered via keyboard or tape, the system is ready for calibration and data collection.

The calibration sequence is started by typing "CAL." All or selected channels are then calibrated (Figure 10 gives a sample calibration output). The current zero data and peak-to-peak noise values are printed. If the zero is greater than .040 volts, then the offset is automatically nulled (to ± .040 volts). This zero value is stored and subsequently subtracted from all

Table 3. Example Channel List

```
CHANNEL=  1
ID=FX
UNITS=LBS
XDUCER TYPE= 2
SHUNT CAL= 6992
A/D GAIN(0=1 1=2 2=4 3=8) 1
FORMAT=8888
MONITOR START= -500
INCREMENT= 25
POINTER= 0

CHANNEL=  2
ID=FY
UNITS=LBS
XDUCER TYPE= 2
SHUNT CAL= 7080
A/D GAIN(0=1 1=2 2=4 3=8) 1
FORMAT=8888
MONITOR START= -5000
INCREMENT= 250
POINTER= 0

CHANNEL=  3
ID=FZ
UNITS=LBS
XDUCER TYPE= 2
SHUNT CAL= 7200
A/D GAIN(0=1 1=2 2=4 3=8) 1
FORMAT=8888
MONITOR START= 0
INCREMENT= 250
POINTER= 4000

CHANNEL=  4
ID=FXP
UNITS=LBS
XDUCER TYPE= 2
SHUNT CAL= 320.6
A/D GAIN(0=1 1=2 2=4 3=8) 1
FORMAT=888.9
MONITOR START= -500
INCREMENT= 25
POINTER= 0

CHANNEL=  5
ID=FYP
UNITS=LBS
XDUCER TYPE= 2
SHUNT CAL= 684
A/D GAIN(0=1 1=2 2=4 3=8) 1
FORMAT=888.9
MONITOR START= -1000
INCREMENT= 50
POINTER= 0

CHANNEL=  6
ID=FXPP
UNITS=LBS
XDUCER TYPE= 2
SHUNT CAL= 308.5
A/D GAIN(0=1 1=2 2=4 3=8) 1
FORMAT=888.9
MONITOR START= -500
INCREMENT= 25
POINTER= 0

CHANNEL=  7
ID=WP
UNITS=IN
XDUCER TYPE= 1
XDUCER GAIN IN   /VOLT= 5.945
AMP GAIN= 1
A/D GAIN(0=1 1=2 2=4 3=8) 2
FORMAT=8.999
MONITOR START= 0
INCREMENT= 0.5
POINTER= 0

CHANNEL=  9
ID=TS
UNITS=IN/S
XDUCER TYPE= 0
XDUCER GAIN IN/S /VOLT= 1.06
AMP GAIN= 1
A/D GAIN(0=1 1=2 2=4 3=8) 2
FORMAT=8.999
MONITOR START= -5
INCREMENT= 0.25
POINTER= 0
```

```
?CAL
GAIN CHECK (Y/N) ?Y
ALL CHANNELS (Y/N) ?Y
CH# 1  FX
CUR ZD=-0.014 VOLTS  NSE=0.0048 VOLTS
NEW ZD=-0.017 VOLTS  NSE=0 VOLTS
SH CAL=3.4887 VOLTS
FSC=10020.LBS
CH# 2  FY
CUR ZD=-0.014 VOLTS  NSE=0 VOLTS
NEW ZD=-0.014 VOLTS  NSE=0 VOLTS
SH CAL=3.5375 VOLTS
FSC=10006.LBS
CH# 3  FZ
CUR ZD=0 VOLTS  NSE=0 VOLTS
NEW ZD=0 VOLTS  NSE=0 VOLTS
SH CAL=3.5937 VOLTS
FSC=10017.LBS
CH# 4  FXP
CUR ZD=-0.009 VOLTS  NSE=0 VOLTS
NEW ZD=-0.008 VOLTS  NSE=0.0024 VOLTS
SH CAL=3.2190 VOLTS
FSC=497.97LBS
CH# 5  FYP
CUR ZD=0.0341 VOLTS  NSE=0 VOLTS
NEW ZD=0.0341 VOLTS  NSE=0 VOLTS
SH CAL=3.4276 VOLTS
FSC=997.78LBS
CH# 6  FXPP
CUR ZD=0 VOLTS  NSE=0 VOLTS
NEW ZD=0.0000 VOLTS  NSE=0.0024 VOLTS
SH CAL=3.0736 VOLTS
FSC=501.83LBS
CH# 7  WP
CUR ZD=-0.009 VOLTS  NSE=0 VOLTS
NEW ZD=-0.008 VOLTS  NSE=0.0012 VOLTS
OFFSET? 0
GAIN=1.0364 NOM GAIN= 1
FSC=13.680IN
CH# 9  TS
CUR ZD=-0.004 VOLTS  NSE=0 VOLTS
NEW ZD=-0.004 VOLTS  NSE=0.0012 VOLTS
GAIN=1.0482 NOM GAIN= 1
FSC=2.5280IN/S
```

Figure 10. Sample Calibration Output.

data readings. Next, the gain of the channel is measured by either engaging a shunt cal relay for bridges or by putting in an 11-point staircase waveform, measuring the channel output, and performing a linear regression to calculate the gain. The resultant full scale in engineering units is then reported. After the calibration, data collection can begin. Tests can then be stored on tape, printed on the screen, or analyzed. A summary of the system commands is given in Table 4.

3.2 Ideal System

This section describes what we feel is an ideal system for large-scale vehicle test programs. Although such a system may be unattainable (as of 1984), it can be used to judge the merits of available commercial systems and suggests a design approach that is subsequently discussed.

As can be seen in Figure 11, the vehicle computer is only a part of the total acquisition and processing system. Ideally, it should be strongly coupled to the analog signal conditioning. It should provide offset, gain and filtering control, and thorough calibration and diagnostic functions. In turn, the analog conditioning channels should be as universal as possible, providing excitation, amplification, and filtering for any of the transducers. By allowing software to configure a flexible system, operator intervention and errors can be minimized. The vehicle system should be small, light, durable (few moving parts and external cables), and able to operate from 12 volts.

The laboratory and vehicle computers should be based on the same microprocessor, and if possible, the same operating system. In addition, the on-vehicle data storage medium should appear as a standard system device. By matching the two systems, software development, maintenance, and data handling could be simplified. Programs could be written or changed on the laboratory computer and then transferred to the vehicle computer. Data could be transferred by using a single system command (e.g., copy files from device A to device B). The laboratory computer should be one that is readily available, easily maintained, and fully supported (hardware and software). It should have the processing power and the file capabilities to process the raw data from the vehicle and to store and display the results to the test engineer. Commercial communications software should be available to permit

Table 4. UMTRI-DAS Command Summary

Experimental Setup

SETUP - Input setup information (channel number, ID, transducer type, and gain information)

ACHAN - Add a channel

DCHAN - Delete a channel

CHCH - Change the setup for a specific channel

ESET - Edit setup information

MODE - Select sampling frequency and start and stop modes

SDATA - Select data channels

RCSET - Record setup information to tape

RDSET - Read setup information from tape

TSTID - Indicate overall test type, e.g., "Step Steer"

Pre-Test Activity

SMON - Select data channels to monitor on the screen during data taking (two groups of up to 4 channels)

MONO - Select monitor group 0

MON1 - Select monitor group 1

CAL - Calibrate the signal conditioning cards

Data Taking and Display

DATA - Collect data as specified by SDATA and MODE commands

SAVE - Record data, setup, and comments to tape

MONIT - Display data channels on the CRT but do not collect

IRPLY - Instant replay of last run

Post-Test

PDATA - Print data to screen

ANLZ - Calculate averages and maximums and minimums

FVAL - Find the first occurrence of a specified value on a specified channel

LIST - List the tests on the tape

Diagnostics

RELAY - Turn a cal relay on or off

CALOA - Put out a calibration signal of a specified voltage

OFF - Offset a specified channel by a specified voltage

SHUNT - Turn a shunt cal relay on or off

RESTO - Restore the analog unit to a previous configuration

TERR - Indicate cause of tape error

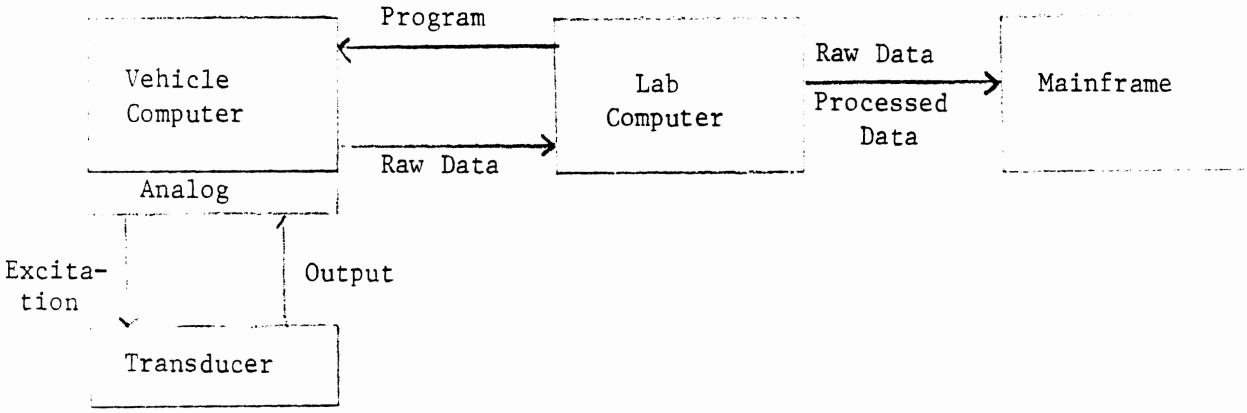

Figure 11. Ideal Acquisition and Processing System

the transfer of raw or processed data to a mainframe computer or another laboratory computer at a different site. Finally, both the vehicle and laboratory systems should be inexpensive and readily available.

A Possible Approach

Because of the availability of the IBM-PC, and its wide use in the GM vehicle-handling group, a PC-based system is attractive. The major difficulty is in finding a PC-compatible computer that meets the requirements of the in-vehicle system. A "PC-like" portable might be used, but it might be difficult to integrate into a system package. We would recommend the approach used in the UMTRI-DAS of packaging off-the-shelf components into a single enclosure.

An IBM-PC compatible system can be built from an I-BUS Systems Model R188 single-board computer and an I-BUS six- or nine-slot chassis (see Appendix B-1 for data sheets). This system is compatible with all PC expansion cards and when equipped with the ROM BIOS can execute PC-DOS. Instead of a floppy disk drive, a bubble memory board or a bubble "floppy" is used as the primary mass storage device (see data sheets). The remaining boards (memory with clock, CRT adapter, and A/D) can be purchased from any of several vendors.

Four possible "PC" systems are diagrammed in Figures 12-15. Each system includes the base system as summarized in Table 5, a different mass storage configuration, a signal conditioning and filter unit, CRT, and keyboard. It is possible that the CRTs and keyboards in the current GM system could be used. An analog control card (wired on a prototype card) is also required.

System 1 is equipped with a Hicomp or Helix 512 K bubble memory board (see Appendix B-1). Either board comes with software that enables floppy emulation. Both programs and data are stored in the memory. When the memory is full (after approximately 13 minutes of data of 8 channels at 40 Hz), the vehicle is returned to the laboratory and the data transferred to the laboratory computer via a RS-232 link (taking approximately 12-13 minutes at 9600 baud). This is the least expensive system.

Figure 12. "PC" System 1

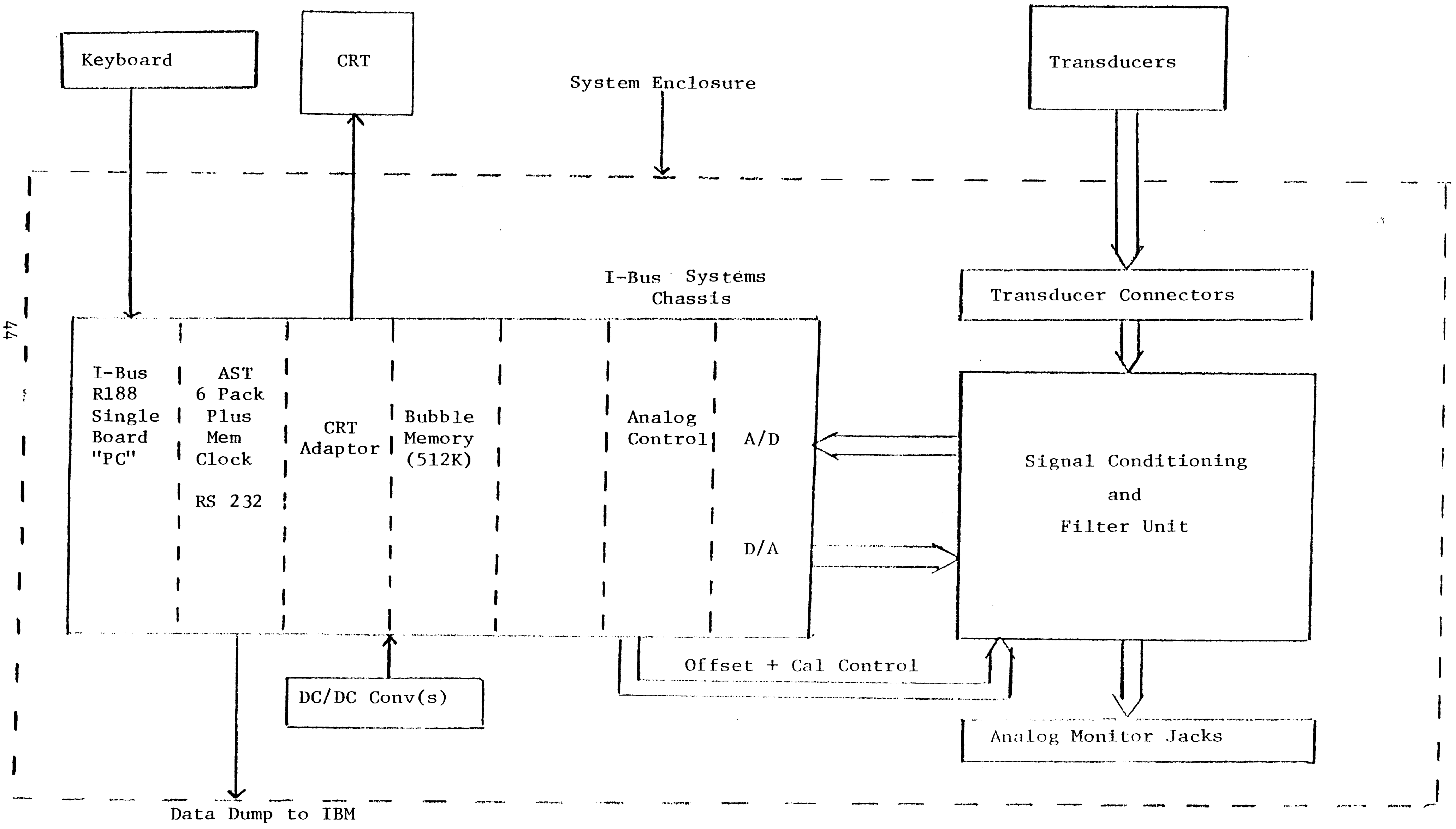

Figure 13. "PC" System 2

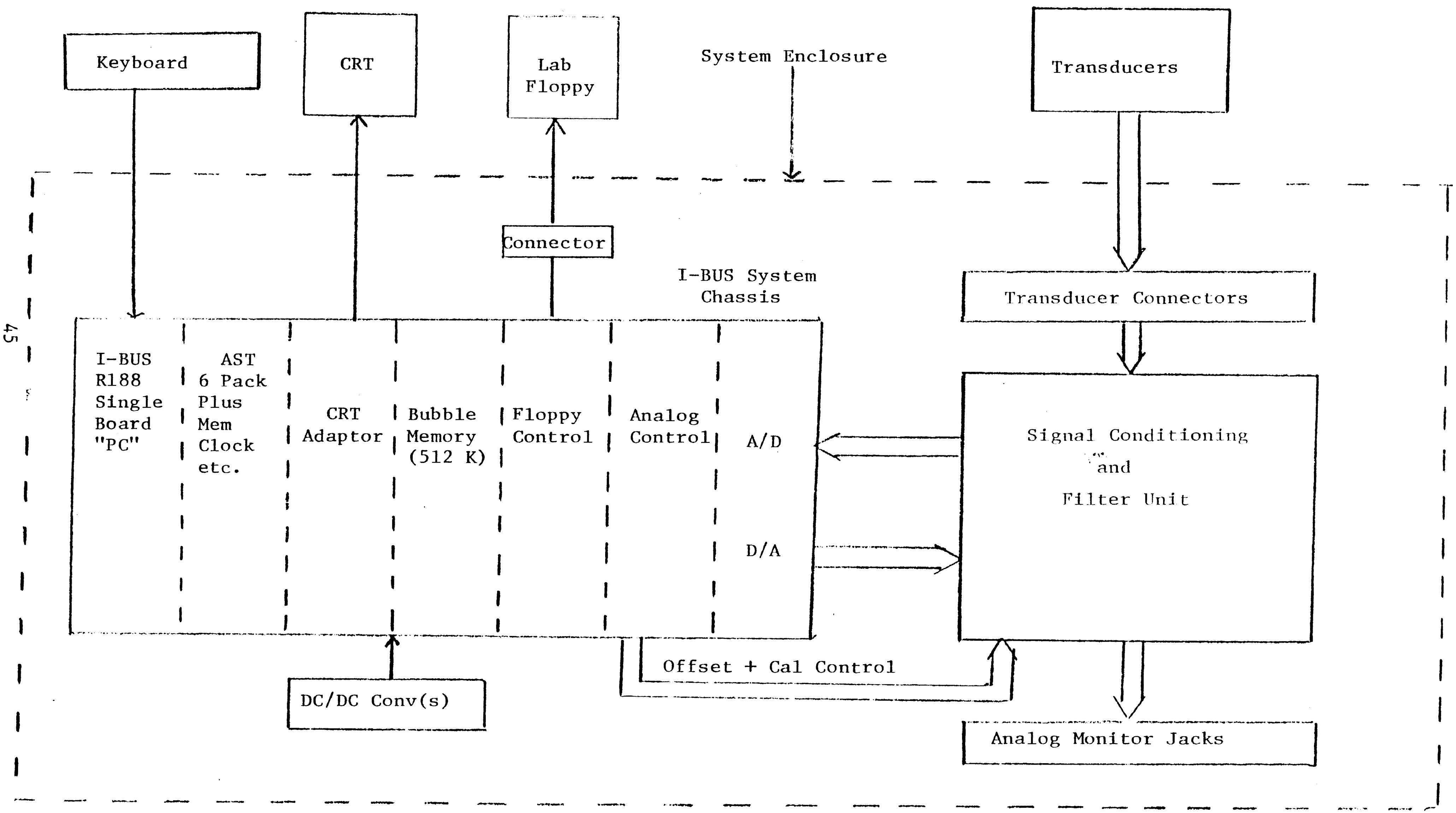

Figure 14. "PC" System 3

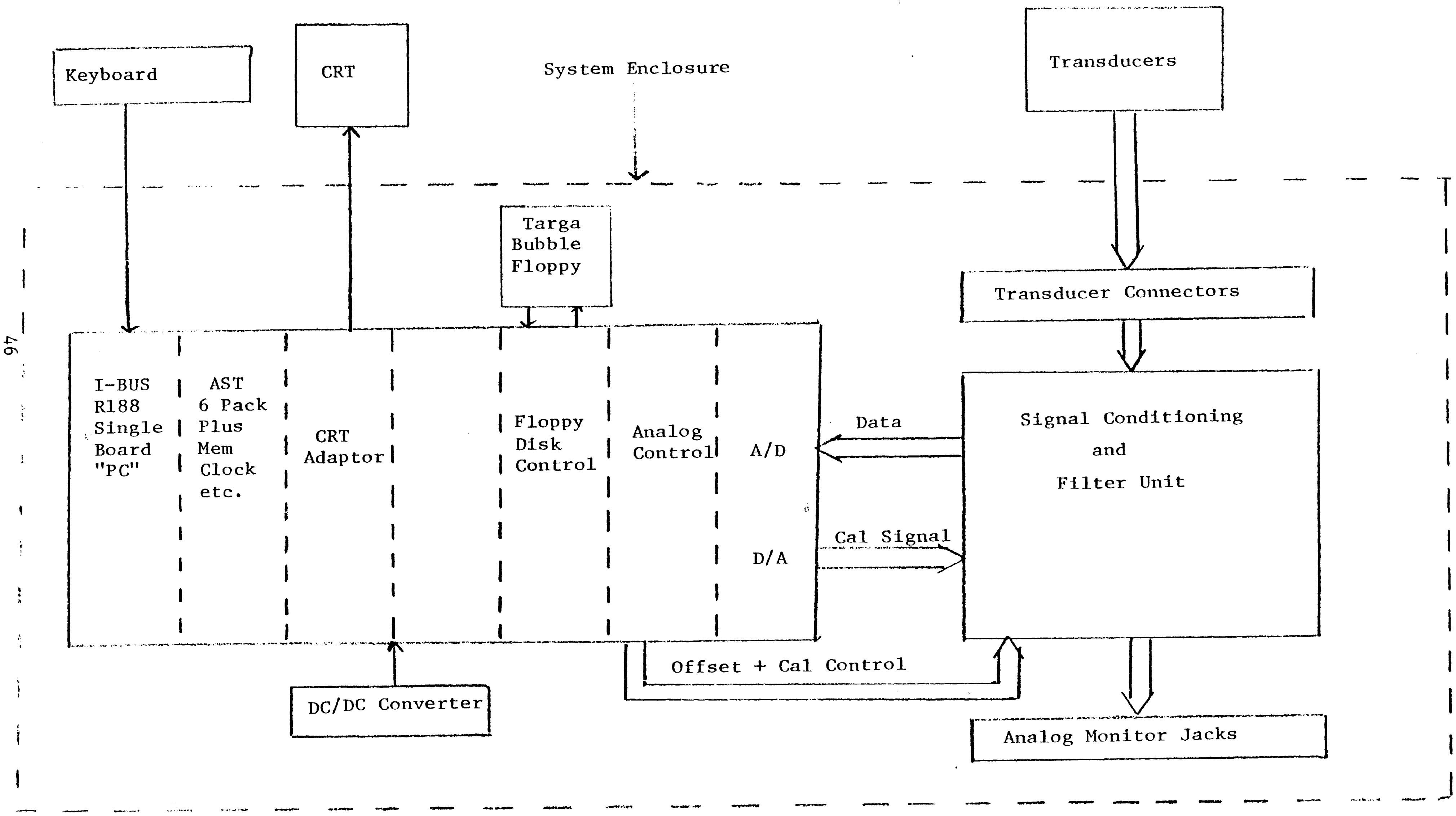

Figure 15. "PC" System 4

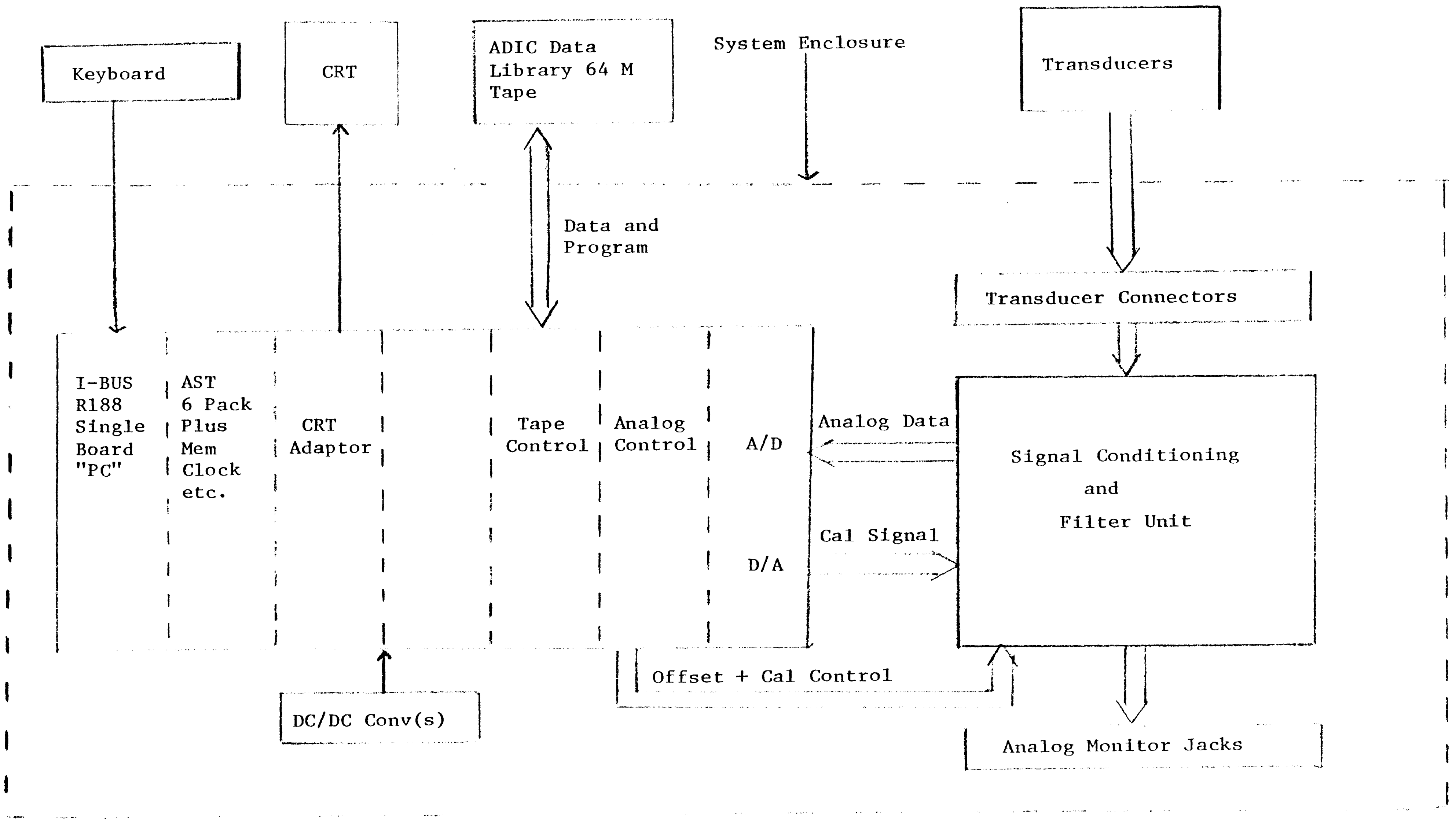

Table 5. "PC" Base System

Part	Estimated Cost
1. I-BUS R188 CPU board with BIOS	$ 870
2. I-BUS nine-slot chassis	360
3. AST memory expansion, clock, and serial port	265
4. Data translation A/D	1344
5. CRT adaptor	350
6. DC/DC converter	400
7. System enclosure and fan	250
Base System Total	$3839

System 2 is the same as System 1, except for an added floppy disk controller and drive. The controller is resident in the system, but the drive is external. When the bubble memory is full, the drive is plugged in and the data transferred via a copy command (3-4 minutes). The drive would be kept at some convenient stationary location.

The third system uses the Targa Solidrive and a floppy disk controller. The Solidrive is a solid-state floppy disk emulation system that employs removable bubble cartridges (see Appendix B-1). The drive requires no special software to operate as a 5-1/4 disk emulator. It even has the same power and data connectors as a normal 5-1/4 floppy. When the bubble cartridge is full, it is simply replaced by a different cartridge. A second drive would be purchased for the laboratory system to allow transfer to real floppies. This configuration, however, is much more expensive than Systems 1 or 2 because the cartridges cost about $1,500 each and a minimum of two or three cartridges would be needed.

The fourth system uses the Advanced Digital Information Corporation's Data Library Storage System (see Appendix B-1) as the on-vehicle mass storage system. This tape system employs the same 3M tape recorder that is used in UMTRI-DAS, along with an IBM-compatible controller and software. The 64 megabytes of storage appears to the IBM as six separate 10-megabyte disks. The Data Library operates from 110 volts and would therefore require an inverter. Although larger than the devices discussed above, it would make the system more suitable for high-frequency, extended-length tests. The Data Library should also be considered as an archival storage device for the laboratory system.

All of the above systems require an analog signal conditioning and filter unit. This unit would have a backplane holding 8 to 10 amplifier cards. A computer-controlled signal conditioning card is depicted in Figure 16. This card is very similar to the UMTRI-DAS card with two major exceptions. The instrumentation amplifier in the UMTRI-DAS card is replaced with a programmable gain amplifier which provides gains of 1, 2, 4, 8, 16, 32, 64, 128, 256, 512, and 1024 and, if necessary, an 8-bit multiplying D/A converter to allow more specific scaling (i.e., total gain ($G_T = G_{PCA} \times G_{D/A}$, with $G_{D/A} = x/256$ where $x = 1,2,3....256$)). The filter is also replaced by a

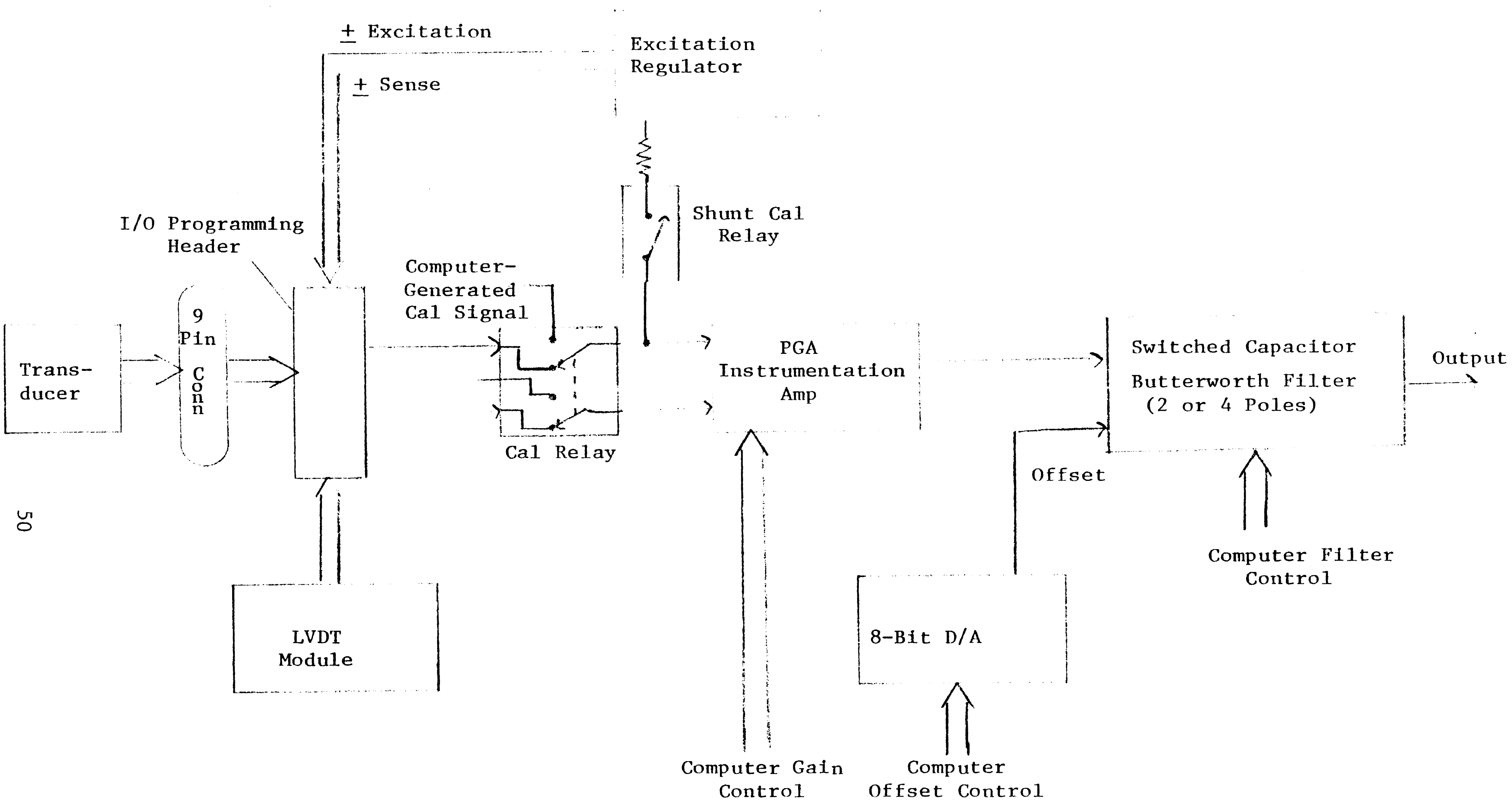

Figure 16. Computer-Controlled Signal Conditioning.

switched-capacitor filter whose cutoff frequency is proportional to a clock provided by the computer. The computer (and therefore software) can control the gain, offset, and filter cutoff. The calibration relay would allow the computer to ensure proper operation. An 8-card system would probably cost around $2,000, assuming a printed circuit board implementation.

Estimated costs for all of the systems are given in Table 6. If a CRT and keyboard are required, $250 to $350 should be added.

3.3 Commercial Systems

Most of the commercial data acquisition systems today are either laboratory systems or slow data loggers. The laboratory systems usually rely on floppy or hard disks for mass storage and are inappropriate for a vehicle application. The data loggers are more rugged but lack the speed and storage capability for this application. Only three systems could be found that might be suitable: Cyber Systems MiniDAS, Optim Megadac System 2000, and Ithaco CompuDAS 3. The key elements of the systems are summarized in Table 7 and data sheets are located in Appendix B-2.

Cyber Systems MiniDAS

MiniDAS is a turnkey data acquisition system based on the Z8002 16-bit microprocessor that includes a keyboard for alpha numeric input, a CRT for operator feedback, and a DC-100 cartridge tape for data storage (300 K byte). It has signal conditioners for a wide variety of transducers such as strain gauges, thermocouples, LVDTs, RTDs, thermistors, DC voltage, AC voltage, and frequency to voltage. Each card accommodates up to eight channels of that specific type of transducer. This is convenient if several channels of strain gauges or LVDTs are used, but can result in added expense if a number of different transducers are used in a specific application. Also, none of the cards include active anti-aliasing filters. This could necessitate higher sampling rates and, therefore, higher volumes of data which would slow down data transfer to a laboratory computer and the subsequent processing. Some of the cards do contain a passive RC network, but they may not be adequate. Alternatively, the user could supply active filtering.

Table 6. Cost Estimates

System 1

Base system	$3,839
Hicomp bubble memory	1,495
Analog unit	2,000
	$7,334

System 2

Base system	$3,839
Hicomp bubble	1,495
Floppy disk controller	160
Floppy disk drive	290
Analog unit	2,000
	$7,784

System 3

Base system	$3,839	
Targa "disk" drive	1,500	
Two bubble cartridges @1,495	2,990	
Analog unit	2,000	
	$10,329	(not including drive for laboratory system)

System 4

Base system	$3,839
Tape system	3,900
Analog unit	2,000
Converter	200
	$9,939

Table 7. Command System Summary

	Cyber Systems MiniDAS	Megadac System 2000	Ithaco CompuDAS 3
Programmable	No	No	Yes
Control	Keyboard	Front Panel	Front Panel
Display	9" CRT	80-Character Liquid Crystal	40-Character Dot Matrix
Speed	20K Hz	20K Hz	3.3K Hz
Mass Storage	300K Byte DC-100 Cartridge	60M Byte Cartridge	60K Byte Cartridge
Engineering Units	Yes	No	Yes
Auto Calibration	Yes	No	No
Data Dump	RS232 IEEE-488	RS232 IEEE-488	RS232
Analog Support	Strain Gauges RTD Thermocouples Thermisters DC-LVDT AC-LVDT DC Voltage AC Voltage Frequency to Voltage	Strain Gauges RTD Thermocouples DC Voltage	Strain Gauges RTD Thermocouples
Active Anti-Aliasing	No	No	No
Size	10.5x17x34	12.25x19x21	10.5x16.5x22.25
Weight	75 lbs	50-60 lbs	60-75 lbs
Approx. Power	200 W	120 W	300 W
Approx. Cost	$16,500	$17,000	$14,000

Because the MininDAS package is 34 inches deep, it is unlikely that it would fit on the passenger seat in a car.

The firmware includes power-on diagnostics, setup programming including test identification and channel names, auto calibration, data acquisition, and transfer functions. The setup information can be recorded on tape and read back later to eliminate repeated entering of transducer configurations. Auto calibration is similar to UMTRI-DAS except that offsets are not nulled but simply recorded. Resistors are shunted across one arm of the bridge for strain gauge calibration and a four-level voltage staircase is applied for other amplifier channels. After a calibration, all data are represented in engineering units. Data stored on tape can be transferred to the laboratory computer via a IEEE-488 link. It appears that all commands for this process originate not from the computer, but through operator inputs. This could make data dumping a tedious endeavor.

At first look, MiniDAS appeared to be very attractive, but considering its size, lack of filters, and operational questions, it may not be adequate for this application.

Megadac System 2000

The Megadac System 2000 is a high-speed data acquisition system that can be used as a stand-alone unit or as a front end for another computer. It has a 60-megabyte tape for data storage, an 80-character LCD display for operator feedback, and a numeric keypad for inputs. It does not support as many transducers as the MiniDAS nor does it provide for auto calibration functions. Like the MiniDAS, it has no anti-aliasing filters. It does have programmable gain amplifiers, allowing full scale inputs from 25 mv to 10 volts. There are no provisions for the operator to input test identification or other useful log-type information (e.g., vehicle, test type, weather, etc.). It seems that this system was optimized for use with a host computer acting as a controller. Data channels are referred to by numbers instead of meaningful names. Recorded data can be viewed on the two-line display, but not in engineering units, and tests cannot be conveniently named. It would be desirable to have a quick look at a directory of files on tape so that the operator can verify what tests have been done. It does not appear likely that this could be done on the Megadac System. In summary, the Megadac System 2000 is a high-performance data-capture device that lacks some of the user friendliness that is appropriate for this application.

Ithaco CompuDAS 3

CompuDAS 3 is a programmable data acquisition system based on dual 8086/Z80 architecture. The base system contains 128 K bytes of error-correcting RAM, 64 K EPROM, a battery backed-up real-time clock, multi-tasking operating system, two RS232 ports, chassis, and power supplies. Several front panel options are required for a stand-alone system (front panel interface board, micro-cassette, 40 character dot matrix display, and keyboard). A 12-bit A/D converter with individual channel programmable gains of 1, 3, 30, 100, 300, or 1000 is also required. A small number of signal conditioning cards are available, but since they lack anti-aliasing filters and automatic calibration features, they may be inadequate for this application.

Unlike the other two systems, CompuDAS 3 is programmable. This feature is both an asset and a drawback. An application program must be written in DABIL (a Basic with real-time extensions). The system could be tailored for vehicle testing with the expense of learning a new language and operating system and writing and testing of the software. At a cost of approximately $14,000, this system is almost twice the price of a "PC system" and only provides the packaging of the hardware.

4.0 DATA REDUCTION - OPTIMAL STATE ESTIMATION

Vehicle "motion" sensors generally are available in three classifications, viz., position, velocity and acceleration sensors. Probably the most common "complete" instrumentation set for the measurement of sprung mass motions is the combination of (1) a vertical gyro for deriving signals proportional to pitch and roll position, (2) an angular rate sensor (generally body-fixed) yielding a signal proportional to yaw rate (as modified by the roll and pitch inclinations of the body-fixed co-ordinate system), (3) and one, two, or three rectilinear accelerometers (vertically stabilized or on the principal body axes) from producing signals proportional to the principal, linear accelerations of the sprung mass (modified by the angular motion of the body fixed coordinate system if so mounted), and (4) a "5th wheel" velocity sensor providing a signal proportional to longitudinal velocity. This group of sensors generally provides direct measurement of those sprung mass motion variables (or close approximations thereof) most meaningful to vehicle dynamics analysis, with the notable exception of body sideslip angle. Although, as noted elsewhere herein, sensors are currently available for the more-or-less direct measurement of sideslip, many experimenters have used yaw rate, lateral acceleration, and velocity to calculate the rate of change of sideslip, and integrated that result to obtain sideslip, with varying levels of success.

In addition to the calculation of sideslip, the mathematical manipulation of transduced variables to generate time histories of other motion variables is attractive in that it holds promise for redefining the basic transducer set, where such a redefined set of transducers might be chosen more on the basis of cost, compactness, ruggedness, and other practical considerations than is currently the case. The practical engineer might immediately contemplate disposing of the costly and delicate vertical gyro and its attendant vertically stabilized accelerometers, to be replaced, perhaps, by body-fixed angular rate sensors and accelerometers. The question then arises, of course, as to how accurately the motion variables of primary interest can be obtained, via the mathematical manipulation of other, more conveniently measured variables. The answer would appear to be: quite accurately.

There exists in the scientific literature, a substantial body of work dealing with the subject of "optimal state estimation." This subject, in general, deals with obtaining the "best estimate" of the state of a dynamic system (where that state is defined by a state vector composed of n state variables) given a set of m sensors where $m =< n$. The estimation problem is referred to as one of "smoothing," "filtering," or "predicting," depending on whether the time of the estimation of interest is the past, present or future, respectively. Generally, the smoothing and prediction problems can be solved in terms of the filtering problem.

The most significant "modern" work in the field would appear to be that of R.E. Kalman and R.S. Bucy [3] wherein the so-called Kalman filter was derived. To give an example of the Kalman filter, consider a homogeneous dynamic system with time variant coefficients (expressed in matrix notation) of the form:

$$dx/dt = A(t)x(t)$$

and a measurement process of the form:

$$y(t) = H(t)x(t) + v(t)$$

where x is the n dimensional state vector
A is an n x n matrix describing the dynamic system
y is the m dimensional vector of measurements
H is an m x n vector describing the relationship between the measurement
system and the dynamic system (the "observer" matrix)
v is an m dimensional vector of noise elements

The Kalman filter for such a system is:

$$dP/dt = P(t)A^T + A(t)P(t) - P(t)H^T(t)W(t)H(t)P(t)$$

$$d\hat{x}(t)/dt = A(t)\hat{x} + P(t)H^T(t)W(t)[y(t) - H(t)\hat{x}(t)]$$

where $()^T$ indicates the transposed matrix

P is the error covariance matrix when

W, the weighting matrix, is the inverse of the covariance matrix of the noise and

$\hat{x}$ is the estimate of the state vector.

Notice that the Kalman filter is actually a model of the system with a correction term proportional to the difference between the measurement, $y(t)$, and the predicted measurement, $H(t)\hat{x}(t)$.

Formulations similar to those given above have been developed for the simpler homogeneous system with constant coefficients, as well as for nonhomogeneous systems of both forms. Further, the linear Kalman filter and the Extended Kalman filter are applicable to nonlinear systems through the use of truncated Taylor series expansions.

The above subjects are well covered in the literature. In Section 5.0, we have included a list of basic references. We have chosen to start that list with "An Algebraic Approach To Optimal State Estimation," since this document is particularly useful to the engineer. The author states expressly that the work was prepared with the practicing engineer in mind. Rather than depending on high-level mathematics, he develops the subject from the simpler bases of least squares estimation and the state variable concept, and proceeds to carry the development through applications to nonlinear, continuous dynamic systems.

Many papers describing the application of optimal-state estimation techniques to real problems are also found in the literature. Appendix C contains an extensive listing of titles and abstracts of such works. Most deal with aircraft and aerospace applications; some deal with naval vessel applications. Only one reference (the last entry) dealing with ground vehicles was found.

While the potential for obtaining good quality state definition in road vehicles with "non-traditional" instrumentation systems appears to be good in light of the above, we note that there is nothing "magic" about Kalman techniques which will solve the basic dilemma of defining the D.C. signal error, and/or "initial condition" component of state variables of position, given the existence of only first (velocity) or second (acceleration) derivative instrumentation. That is to say, some position "measurement data" must be made available to account for the D.C. error in the derivative data and the otherwise unknown I.C. conditions. This general subject is particularly significant, since we assume that the fundamental goal of the instrumentation engineer is to remove the less desirable angular position instrumentation (vertical gyro) from his system, and that linear position instrumentation is generally not used.

Before addressing the problem in the Kalman filter context, we will digress briefly. At UMTRI, we have found this problem to be manageable in a less sophisticated context by using simple, closed-loop integration. Specifically, we have, in the past, integrated yaw rate to obtain heading angle, and employed a more complicated integration calculation to obtain lateral position from yaw rate, lateral acceleration, and velocity signals. In each case, it was necessary to arrange the experiment such that the initial and final value (or at least the difference thereof) of the position variable of interest was known. (For example, a lane-change maneuver may be arranged such that the initial and final paths are parallel--zero heading angle differential--and so that the net lateral displacement is known.) Then, an "outer-loop" could be added to the basic integration, which was used to iteratively obtain the "correct" D.C. value of the higher-order, transduced variables. Viewing this iterative, closed loop function as an after-the-fact "zero calibration," we note that the fidelity required of this calibration is generally greater than could reasonably be expected from normal calibration in the field. Naturally, as the time duration of the experiment increases, this accuracy requirement becomes more severe.

Returning to the Kalman filter context, we note that positional data of the "same type" considered in the preceding paragraph is easily employed. Note that in the definitive expressions given earlier, the weighting function matrix is time variant. Thus there is no requirement that data sampling rates associated with various "instruments" be consistent. Indeed, while sampling of on-board, electronic instruments may take place many times per second, auxiliary position "instruments" may be sampled as practicable (specifically, only before and after a given run for the simple procedure described above).

In processing the measured data, the appropriate (different) weighting function matrices would be applied to data derived from different sources at different times, where, presumably, weighting factors applied to the limited number, but well established, position data points would be appropriately strong as to "pin" the resulting time histories.

Any number of ground-based, auxiliary systems for position measurement are conceivable. They could include, for example, (1) the simple system described above wherein the driver is trusted to establish a known before/after position condition, discernible in the recorded data by a quasi-steady-state condition, (2) systems in which discrete positions are established in a time continuum via stationary position sensors (light beam devices, tape switches, etc.), and (3) sophisticated ground-based tracking instruments. For the large-scale, repetitive test programs described by GM, a reasonably practical and cost-effective combination of (1) and (2) seems probable.

Finally, note that the time-variant nature of the weighting function holds potential for accounting for the "phase shift" inherent in multiplexed digital data acquisition systems. In some applications, the time lag between the sampling of two different instruments may be significant relative to the frequency content of the data such that it is not valid to assume that all instruments are sampled at the same instant. This phase shift problem is handled quite naturally by the straightforward recognition that sampling of different instruments is accomplished at different times, and that different weighting functions are appropriate for those different times.

In conclusion, it appears that high-quality time histories of road vehicle state can be had using "non-traditional" instrumentation systems and Kalman filtering techniques. While obtaining high-quality time histories of sprung mass motions from simplified on-board instrumentation is clearly possible, a substantial investment in preliminary "systems engineering" will be required to assure the desired balanced between technical quality and cost effectiveness. Number and type of measurement devices vis-a-vis accuracy and complexity of the vehicle model, A(t), and the observer, H(t), will clearly effect this balance.

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