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A STATE-OF-THE-ART SURVEY
OF LOW-LEVEL MULTIPLEXERS

R. E. Mahan

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OF LOW-LEVEL MULTIPLEXERS

By

R. E. Mahan

Computers and Control Section
Applied Physics and Electronics Department

September 1968

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BATTELLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORY
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A-STATE-OF-THE-ART-SURVEY OF LOW-LEVEL MULTIPLEXERS

R. E. Mahan

INTRODUCTION

Multiplexing has gained widespread acceptance in data acquisition applications where large numbers of thermocouple or other low-level inputs must be periodically sampled. A low-level input, as used herein, is defined as a signal with a full scale range between 5 and 100 mV.

Historically, low-level multiplexing has been performed, most often, using electromechanical devices such as stepping switches, reed relays, or crossbar switches. While these devices are limited to relatively slow scanning rates (50 to 500 channels per second), they do offer good switching performance at low cost. Furthermore, the time constants associated with many industrial processes are long enough that higher sampling rates are not required. In systems requiring high sample rates, as may be the case with the data acquisition system for the Fast Flux Test Facility, there are several alternative approaches to multiplexing.

Data amplifiers can be used on individual data channels, and the resulting high-level output multiplexed using solid-state switches. This method provides high-speed operation, but the cost of an amplifier for each transducer is at least an order of magnitude greater than the cost of an electromechanical multiplexer (MUX) for the same number of channels.

Another technique used to increase speed involves block switching (also called "interleaving" or "commutation") several slow MUX's to provide an increase in the overall switching speed. Block switching is simply a method of multiplexing a MUX. That

is, a high-speed solid-state MUX time-shares the amplified output of several slower-speed MUX's. The problem with this approach is that the data cannot be switched at random, but must follow a semifixed pattern.

Finally, the most recent advances in multiplexing have occurred in the area of solid-state switching, notably, with bipolar and field-effect transistors. Devices have been developed that permit millivolt switching at speeds comparable to the amplifier per channel MUX's.

The purpose of this survey is to evaluate these recent developments and present a comprehensive survey of the state-of-the-art in low-level multiplexers. The study will be performed in two parts which include a literature search and theoretical investigation followed by laboratory testing of equipment to support the theoretical investigation. The end result is intended to provide support for the preparation of a systems design description for the FFTF Central Control and Data Handling System.

SUMMARY AND CONCLUSIONS

The state-of-the-art in low-level MUX's as reported in currently available literature reveals that electromechanical commutators offer superior performance in most electrical performance categories. It should be stressed, however, that the degree of superiority is extremely small with regard to most parameters. Cost is the one parameter where electromechanical MUX's have a significant advantage. The primary defects in electromechanical MUX's are in sampling speed and long term reliability. Block switching offers an alternative to the speed limitation, but only if quasirandom access addressing can be tolerated.

The closest competitor to electromechanical MUX's are the new FET MUX's which offer an order of magnitude higher speed

and greater reliability, but currently cost about twice as much as comparable electromechanical systems. Electrical performance differences are modest with the one exception of common mode voltage protection. However, protection schemes have been devised and will be tested in the laboratory to determine feasibility, as required by Task IC-50. In addition, bench tests will be conducted on a production FET MUX to determine whether the overall performance agrees with the figures cited in the literature.

Bipolar transistor MUX's are available from a few manufacturers, but these devices are typically three times as expensive as conventional electromechanical devices. Bipolar transistor MUX's fall into the category of interim devices which were developed before the advent of the FET to overcome some of the limitations of electromechanical MUX's. They do not appear to offer any significant features that are not available on FET MUX's, with the single exception of high common mode voltage limits. That these MUX's are being phased out is indicated by the manufacturer's admission of current in-house programs designed to develop an FET MUX.

Amplifier per channel MUX's still offer a fill-in capability, being utilized where neither electromechanical or solid-state MUX's can perform satisfactorily. This market is shrinking due to the rapid acceptance of the FET MUX, and unless amplifier manufacturers reduce their prices the market is likely to get much smaller. Performance remains a strong feature of amplifier per channel systems, but cost is still an order of magnitude greater than comparable electromechanical systems.

One of the best indicators of device performance is the activity of the various manufacturers in developing new MUX products. In this area, the trend is overwhelmingly toward

FET devices. Even some of the long-time electromechanical houses such as CIMRON and General Devices are either working on, or have just announced, low-level FET MUX's. With the rapidly changing price structure for FET devices it is only a matter of time until they will be the most satisfactory devices available for use in low-level applications.

DISCUSSION

GENERAL

MUX's (also called "scanners", "commutators", and "distributors") are defined as instruments that permit a number of signal sources to share common conversion equipment in a data collection system. The only restriction placed on the MUX is that the multiplexed signals cannot occupy the same portion of the frequency spectrum at the same time. That is, data separation may be accomplished in either the frequency or time domain.

In frequency division multiplexing (FM), signal voltages modulate separate carrier frequencies, producing several distinct frequency bands. The bands are widely spaced so a common transmission medium can be used without interaction. Due to the requirements for band separation, FM is best suited for multiplexing a small number of wideband signals and is widely used in aerospace applications where radio frequency links are required. In applications such as reactor temperature monitoring, where the data is narrowband, consists of many points, and may be hard-wired, FM is not economical and is rarely advocated. Systems such as reactor temperature monitoring almost universally use time division multiplexing techniques where the data sources all use the same portion of the frequency spectrum, but share the time domain. Multiple inputs are selectively switched, one at a time, to a common output line. The output

of the MUX is a series train of amplitude-modulated pulses. The time position of each pulse identifies the data source, or channel, and the amplitude represents the analog quantity being measured. For inputs from digital transducers, the output is simply a single amplitude pulse train where the time position again represents the channel, or source.

MUX ORGANIZATION

The electrical organization of a low-level MUX is similar for both electromechanical and solid-state devices and is divided into four basic sections as follows:

- 1) Signal Input Lines
- 2) Amplifier
- 3) Address Logic
- 4) Sampling Switches

Signal Input Lines are configured according to the characteristics of the input signal and may be single-ended, differential, or differential-guarded as shown in Figure 1. The single-ended input of Figure 1(a) is the simplest, using a single MUX switch with a ground return common to the instrument system. The simplicity and low cost of the single-ended input makes it popular for high-level MUX's, but its performance in low-level applications is limited by the common ground. Since the grounds are separated, they seldom exist at the same potential and tend to introduce unwanted error signals into the system. At millivolt levels, these error signals are often large enough to swamp the true input signal. Single-ended MUX's are also susceptible to induced voltages from stray fields due to the unbalanced configuration of the amplifier input.

Figure 1(b) shows the preferred differential input where two lines are used to couple the signal to the MUX. This configuration provides a balanced transmission path from the transducer that is isolated from the system ground. Isolation reduces ground effects, and the lines are usually twisted to reduce

external coupling. This configuration is widely used for narrowband signals operating at low sampling rates. For wide-band signals or high sampling rates, leakage capacity becomes significant, resulting in system inaccuracies, and the differential-guarded input of Figure 1(c) must be used. The guard acts to reduce the leakage capacity of the line and reduces field coupling to the line. Most commercially available low-level MUX's utilize the three-pole, guarded input, although a few offer only the differential configuration. None of the low-level MUX's surveyed were single-ended.

Input Amplifiers for all low-level MUX's are high quality operational amplifiers with large gain bandwidth products to supply the required slew rates for high speed throughput. The amplifiers are further characterized by high input impedances which reduce loading effects and have rapid overload recovery to prevent adjacent channel interference during faults. Automatic or programmed gain control is also provided by a few manufacturers. Programmed gain configurations permit mixing low- and high-level inputs within a single MUX facilitating the addition or change of an input level at any desired time. In addition, programmed gain selection offers the capability of disabling the amplifier through the automatic control during faults on input lines. Thermocouples often fail, creating an open or grounded circuit at the input which can cause the amplifier output to drift or overload. The automatic system is designed to sense these faults and automatically limit amplifier saturation so adjacent channels are not adversely affected.

Address Logic performs the timing and channel address processing in the MUX. Three basic modes are possible which include random access, sequential access, and manual access. Random and sequential access are operating modes, while manual is primarily a maintenance mode. Random access implies that

(a) Single-ended Input-MUX Switch and Amplifier

(b) Differential Input-MUX Switch and Amplifier

(c) Differential-Guarded Input-MUX Switch and Amplifier

FIGURE 1. Multiplexer Input Configurations

there are no sampling pattern restrictions. Because any channel can be selected at any time, the system has a wide range of flexibility. Random access is useful in computer based systems since the computer can address any channel on a priority interrupt basis. However, the computer may not always be available to supervise the MUX, so most systems include a sequential mode that permits the MUX to cycle through a fixed pattern of addresses without the need for external control. Manual operation is a maintenance aid used for calibration and troubleshooting with an external switch wired for channel selection.

MUX Switches are generally organized in several levels, or tiers, as shown in Figure 2. The rationale behind using several levels of commutation (called subcommutation) lies in reducing the leakage resistance and input capacity presented by a large number of parallel switches. For a few channels, leakage is negligible, but as switches are added in parallel the leakage impedance begins to decrease to the point where common mode coupling and crosstalk begin to create detectable errors. By inserting a second level of commutation, the leakage can be isolated in blocks that contribute negligible errors. For the special case of a solid-state MUX, subcommutation is used to reduce errors caused by the leakage currents of "off" switches. The number of levels of subcommutation required for a data system varies with the MUX type and the number of channels being multiplexed, but it rarely exceeds three levels.

HARDWARE TRADEOFFS FOR DESIGN

MUX's can be systematically evaluated by a set of hardware performance criteria that describes the overall performance of the MUX. These criteria are listed as follows:

- 1) Electrical Performance
  - a) Sampling Rate
  - b) Series Path Resistance
  - c) Contact or Junction Potential
  - d) Crosstalk

FIGURE 2. Two-Level MUX Configuration

- e) Noise
- f) Common Mode Effects
- g) Scatter
- 2) Environmental Capabilities
- 3) Reliability
- 4) Cost

Table I presents a condensed comparison matrix of available MUX types and their performance characteristics.

The three MUX types evaluated with regard to the established criteria are electromechanical switches, amplifier per channel MUX's, and solid-state devices. These types include the following subgroups:

- 1) Electromechanical MUX's
  - a) Stepping Switches
  - b) Crossbar Switches
  - c) Dry Reed Relays
  - d) Mercury Wetted Relays
- 2) Amplifier per Channel MUX's
- 3) Solid-State MUX's
  - a) Bipolar Transistors
  - b) Field-effect Transistors

ELECTRICAL PERFORMANCE

Sampling Rate defines the speed of operation of the MUX and is obtained by dividing the total number of channels by the time required to scan all channels. The specific sampling or throughput rate must be selected to be compatible with the basic data frequency and the computer processor. It has been shown by Nyquist that all of the information contained in data of bandwidth A, where A represents the upper cutoff frequency, can be uniquely defined by sampling the data at a rate of $2A$ samples per second.⁽¹⁾ Due to uncertainties in specifying bandwidth, most systems are sampled at rates of 5 to 10 times the basic data frequency. Thus, a lower sampling rate limit is placed on the MUX. The upper limit is imposed by limitations of the MUX switches.

TABLE I. Comparison Matrix of MUX Characteristics

Characteristic	MUX Type					
	Reed Relay	Stepping Switch	Crossbar Switch	Amplifier Per Channel	Transistor Switch	FET Switch
Offset Voltage	5 to 10 μ V	5 to 10 μ V	<5 μ V	<5 μ V	<20 μ V	<5 μ V
Noise	1 to 5 μ V			<1 MV in output of 10 V	<5 μ V	<5 μ V
Nonlinearity	$\approx 0.01\%$	$\approx 0.01\%$	$\pm 0.01\%$	$\pm 0.1\%$	$\pm 0.1\%$ removable by calibration	$\pm 0.01\%$
Off Resistance	>1000 M Ω	>1 M Ω	>10,000 M Ω	>100 M Ω	>1 M Ω	>10 M Ω
Max. Common Mode Voltage	200 V dc	1000 V ac ^(a)	1000 V ac ^(a)	>200 V dc or ac	115 to 1500 V ac	± 5 to ± 20 V dc
Common Mode Rejection Ratio	120 dB @ 60 Hz	120 dB @ 60 Hz	120 dB @ 60 Hz	130 dB @ 60 Hz	120 dB @ 60 Hz	120 Db @ 60 Hz
Input Signal Range (f.s.)	± 10 MV to ± 10 V	± 10 MV to ± 10 V	± 10 MV to ± 10 V	± 10 MV to ± 10 V	± 5 MV to ± 10 V	± 5 MV to ± 10 V
Sampling Rate (Max.)	100 to 500 ch/sec	50 to 100 ch/sec	50 to 300 ch/sec	5 to 20 kch/sec	to 20 kch/sec	1 to 50 kch/sec
Crosstalk				<0.005% f.s.	<0.02% f.s.	$\pm 0.004\%$ to $\pm 0.1\%$ f.s.
Cost Per Channel (Based on 100 ch)	\$30 to \$50/ch	$\sim$ \$20/ch	\$15 to \$30/ch	\$300 to \$500/ch	\$180/ch ^(b)	\$50 to \$100/ch
Reliability	1 x 10 ⁸ to 1 x 10 ⁹ oper.	20 x 10 ⁶ to 20 x 10 ⁷ oper.	20 x 10 ⁶ oper.		MTBF of 15,000 hr	MTBF of 5000 hr

(a) Does not include an amplifier.

(b) As low as \$60/ch for ± 6 V dc common mode voltage range.

Electromechanical switches are inertia-limited, operating at maximum rates from 100 to 500 channels per second depending on the switch type. Stepping switches, with their relatively massive rotating wiper, are the slowest at rates up to 100 channels per second. Crossbar switches are also inertia limited, but can operate at speeds up to 300 channels per second. The fastest electromechanical switch is the reed relay which can be driven at rates up to 500 channels per second. This speed is attained by reducing the mass of the reed until contact bounce becomes the limiting factor. At rates near 500 channels per second another factor, that of reed vibration, also limits the sampling speed. As the inertia of the reed is decreased, so is the mechanical damping, and the reed tends to oscillate at its fundamental mechanical frequency. Since the reed is immersed in a strong magnetic field, the oscillation induces currents which flow in the external circuit and cause measuring errors. The magnitude and duration of the oscillatory wave is highly variable and depends on such diverse factors as construction, coil design, and recent sampling rate history. This effect is not generally specified by manufacturers of relays or MUX's and can cause speed limitations below those rates specified by the manufacturer. Several sources estimate the magnitude and duration of reed relay oscillations at 5 to 10 mV for durations up to 10 msec or more. (2,3)

Solid-state switches are speed-limited by the inter-element capacities and storage characteristics common to semiconductors. An added limitation is imposed by the capacity of the input cabling which is in the drive signal path for most solid-state switches and becomes the limiting factor when long input cables are used. Free standing (no input cabling) solid-state and amplifier per channel MUX's are capable of switching at maximum rates between 20,000 and 50,000 channels per second. In large systems, with long input lines rates of 5000 to 10,000 channels per second are more realistic.

Series Path Resistance is present in every MUX switch and creates a voltage division between the switch and the load which degrades the accuracy of the input signal. The magnitude of path resistance varies widely between electromechanical switches and solid-state switches, but the overall effect on accuracy is negligible for both types.

The total series path resistance of all electromechanical switches is typically less than 1 Ω and remains relatively constant throughout the life of the switch, rarely exceeding 5 Ω . The resistance of solid-state switches is much greater, varying from 5 to 20 Ω for bipolar transistors and from 5 to 1000 Ω for field effect transistors.

No significant errors will result from the effect of these resistances as long as the MUX load impedance (typically an amplifier input) at the sampling frequency is several orders of magnitude greater than the series resistance of the MUX switch.

Contact or Junction Potential in electromechanical MUX's is due to thermal electromotive forces generated by thermocouple action of dissimilar metals. While this phenomena can cause very large errors in low-level systems, most MUX's are designed to minimize dissimilar contacts and thermal gradients. Commercially available devices have typical offsets in the 5 to 10 μV range. The same general effect is present in solid-state MUX's and, in addition, bipolar transistors exhibit an offset due to the behavior of P-N junctions. This offset is more difficult to minimize than thermal offsets since it is a function of multiple parameters including temperature, junction material, base current, and collector current. It can be controlled to about 20 μV in high quality systems. Field effect transistors do not exhibit this offset since there are no P-N junctions in the signal path when the switch is on.

Furthermore, the low drive currents required by FET's result in only small temperature rises so thermal offsets tend to be comparable with the best electromechanical switches. Both cross-bars and FET's exhibit offsets of less than 5 μ V at room temperature. Reed relay and stepping switches exhibit nominal offsets of 5 to 10 μ V due to self-heating of the energizing coil which is located close to the contacts. Amplifier per channel MUX's present the input of an operational amplifier to the transducer and are limited to the voltage and current offset of the amplifier which can be held to less than 5 μ V in high quality amplifiers. It is also possible to trim this offset to zero, so the problem becomes the short-term drift of the amplifier which is also less than 5 μ V.

Crosstalk in all MUX's is a function of the leakage impedance of open switches and the isolation provided by several levels of commutation. Crosstalk in electromechanical and bipolar transistor MUX's is seldom a problem if at least two levels of commutation are used to isolate the inputs. The problem is somewhat more acute in FET commutators since the gate drive voltage causes leakage currents to flow in the drain circuit. As mentioned earlier, this effect is reduced by adding a second level of commutation which isolates the leakage. The difference in implementation between FET's and other switches lies in the number of switches that can be cross-strapped before subcommutation must be employed. FET's must be subcommutated at levels of 20 switches, or less, while other MUX's can use up to 50 switches at the first level and still maintain the same crosstalk performance.

Noise is inherent in any system, and MUX's are no exception. Two distinct types of noise occur during a typical sampling interval in a low-level MUX. The first, called edge noise, occurs just after switch closure and is associated with switching transients. The mechanization of edge noise in electromechanical

MUX's is due to contact bounce, magnetostriction, and induced currents, while solid-state switches suffer from drive signal feedthrough. Both types of noise may be avoided as long as the transients occupy a small portion of the sampling interval and can be damped out before data measurements take place. The second type of noise, which cannot be avoided, is that which is present during the center of the channel dwell time. This type of noise is the result of many varied noise sources including noise from building power, variations in contact resistance during channel "on" times, wideband amplifier noise, and digital noise from the peripheral circuits. In any case, this noise can only be minimized through filtering techniques, and is considered in the design of the total system.

Common Mode Effects are classified in two categories and define the ability of the MUX to (1) reject common mode voltages without error, and (2) sustain common mode voltages without damage to the MUX. Common mode rejection depends on the degree of balance between both sides of the input configuration and differential input MUX's of all types typically exhibit rejection ratios of 120 dB. Unfortunately, this similarity in performance does not hold with respect to maximum allowable common mode voltages. Electromechanical, amplifier per channel, and bipolar transistor MUX's are available with common mode protection up to 200 V ac or dc, but FET MUX's are all limited to common mode voltages below 20 V. In FET MUX's the maximum voltage is limited by the gate-to-source and gate-to-drain breakdown voltage (BV_{gsd} and BV_{gds}) of the FET. For example, a typical value of BV_{gsd} of 30 V is common. If +10 V is used to hold the FET switch off, then the maximum voltage that can be applied to the source without reaching the breakdown limit is -20 V. There appear to be some alternative schemes that may be applied to protect FET's, but they are not available in commercial, off-the-shelf MUX's

and must be investigated to determine their feasibility. The most obvious solution would be to place a matched pair of signal diodes across each input line as shown in Figure 3.

FIGURE 3. Input Diode Protection Scheme

The resistor-diode combination forms a voltage divider that limits the input voltage drop to the forward drop of the diode pair, or about ± 0.5 V. Of course, any mismatch of diode characteristics results in conversion of the common mode signal to a differential signal. However, diodes are available in matched quadruples with typical values of ΔV_f of less than 10 mV for a change of I_f over the range of 0.1 to 10 mA and over the temperature range

of -55 °C to +125 °C. Other schemes involve using additional FET's or bipolar transistors for protection, but are considerably more expensive with no appreciable performance advantage. (4,5)

Scatter defines a change in the MUX output from channel-to-channel with the same input applied to all channels. Ideally, the MUX user wants to apply a single calibration signal to one channel and thereby calibrate all channels. The calibration will be valid only if channel scatter is zero which is never the case. Variations in contact potential, contact resistance, crosstalk, etc. cause each channel to exhibit its own peculiar transfer curve. By employing rigid selection rules for switches, most MUX manufacturers hold scatter to within a few microvolts. Where scatter is not specifically defined, it can be roughly calculated as two times the maximum offset error. This is a worst case situation, but gives a general approximation of the overall effect of nonuniformity.

ENVIRONMENTAL CAPABILITIES

There are a number of environmental effects that can be used as a basis for comparison between electromechanical and solid-state MUX's. The most important of these effects are temperature, storage life, and susceptibility to operation in severe environments.

Electromechanical MUX's tend to be the most affected at extreme temperatures where they may exhibit starting and running defects. Low temperatures tend to stiffen lubricants and cause intermittent operation, while high temperatures affect duty cycle limitations for power dissipation. Accuracy is slightly degraded by changes in offset due to contact potential variations which are temperature driven. Commercial devices are typified by offset temperature coefficients of 0.01 to 0.1 $\mu\text{V}/^\circ\text{C}$.

Solid-state commutators are not prone to starting or running problems at temperature extremes, but suffer greater accuracy degradation because of temperature-induced changes in offset voltage and leakage current. Overall coefficients of 0.5 to 3 $\mu\text{V}/^\circ\text{C}$ are typical of commercial solid-state devices.

The shelf life of solid-state commutators is generally much longer than for electromechanical devices. Electromechanical devices can be stored for periods not exceeding the long-term stability of the lubricants contained in their moving parts. Greases tend to separate into their liquid and solid components in periods of about two years. Solid-state devices do not tend to be degraded by long-term storage as long as the storage is within established temperature limits. Of course, the problem in electromechanical devices can be circumvented by careful inspection, cleaning, and relubrication, and therefore it is not important unless the application of the device will require extended storage intervals.

Other severe environments such as shock, vibration, and corrosive atmospheres tend to affect electromechanical MUX's to a greater degree than solid-state devices. Solid-state commutators are typically designed to meet rigid military specifications with respect to mechanical performance and are easily packaged to meet the requirements of corrosive atmospheres.

For the same stress levels, electromechanical MUX's undergo larger changes in noise performance and operating instability than solid-state MUX's. Performance in corrosive atmospheres is comparable to solid-state devices for stepping switches and reed relays, but crossbars require special packaging techniques, at higher cost, to achieve the same degree of protection.

Reliability

There is general agreement in industry that the inherent reliability of solid-state MUX's is much greater than electromechanical MUX's. There is, however, general disagreement on the

actual reliability attained in operating systems. Proponents of electromechanical devices point to figures for Mean-Time-Between-Failures (MTBR) of 1000 to 2000 hr as being typical.^(6,7) They are also quick to point out that these failure rates are at high confidence levels. That is, electromechanical devices seldom fail catastrophically but simply die of old age at a predictable rate. Experience at Hanford indicates that this is true for stepping switches, crossbars, and dry reed relays, but that mercury-wetted relays tend to suffer from high failure rates when they are new. However, once these early failures are repaired, the rate drops to the predicted low level of the other types. In fact, mercury-wetted relays tend to be more reliable than other electromechanical switches once the early failures are culled out of the system.

Unlike electromechanical switches, solid-state switches do not wear out, but fail in a random manner that is attributed to uncertainties in the control of the manufacturing process. They do, however, suffer from early, or freak, failure like the mercury-wetted switches. These early failures are generally screened by the MUX manufacturer by using established burn-in techniques.⁽⁸⁾ Bipolar transistor MUX's are available with reliability figures in excess of 15,000 hr MTBF. Field-effect transistors (FET's) are not as reliable yet. However, Astrodata claims a rate of 5000 hr MTBF which is still several times better than published figures for electromechanical devices. It should be pointed out that the field-effect transistor is a relatively new device and that it has attained a fair degree of reliability only in the past year or two. While failure rates on the older devices tended to be excessive, the rates on devices in use today are much improved as evidenced by the Astrodata figures. While FET's are not yet as reliable as bipolar transistors, they possess some inherent processing advantages that should eventually improve their reliability beyond that of conventional transistors.

In addition, the drive circuits in an FET MUX use about half the components, and thus the reliability is further enhanced.

COST

While the cost of FET devices has dropped significantly (e.g., the MEM 2009 6-channel MUX switch went from \$45.00 to \$25.00) in the past year, FET MUX's have not yet reached the low cost per channel levels of electromechanical MUX's. Electromechanical MUX's nominally cost from \$15.00 to \$50.00 per channel on a 100 channel basis. FET's start at \$50.00 and run to \$100.00 per channel depending on the manufacturer. Bipolar transistor MUX's are even more expensive at \$180.00 per channel, and amplifier per channel systems are the most expensive at \$300.00 to \$500.00 per channel. The prices quoted are generally the lowest stable for all devices except FET's and should not change significantly with time. The high quality FET's used in low-level MUX's are not likely to reach their price bottom for another 3 to 5 years at which time FET MUX's should be able to compete with electromechanical devices with respect to price.

SYSTEM CONSIDERATIONS

Input Filtering is often desired to reduce the effects of unwanted higher frequencies, especially those at the power line frequency. The three basic filtering techniques available to the system designer include conventional hardware filtering, digital (software) filtering in the computer, and integrating filtering in the analog-to-digital converter.

Conventional filtering has been widely used in the past, but tends to be difficult from a technical standpoint, especially in differential input MUX's. To provide effective rejection of high frequencies, the filter must be placed in the input sample lines, have a known time delay, and have very high single-ended

impedance.⁽⁹⁾ These requirements are difficult to meet and still retain high common mode rejection at direct current and high sampling speed. Sampling speed usually suffers the greatest limitation when input filtering is required and speed may have to be reduced by an order of magnitude or more below comparable nonfiltered systems.

A more desirable approach to filtering is the digital method where the higher frequencies are permitted to modulate the input and the computer performs long-term averaging to remove the unwanted frequencies. This method is extremely effective, but requires computer time and memory that may not be readily available.

The third method, that of using an integrating A/D converter, is essentially the same process as used with the computer, but the function is performed in peripheral equipment. The problem with this method is that sampling rate restrictions are required to assure a sampling time long enough to detect and remove all of the noise. The computer process does not operate under the same limitation since it has memory and can perform the autocorrelation over several input cycles.

Block Switching is a suitable method of permitting an electromechanical MUX to operate at high speed, but the system cannot operate in a purely random address mode at the high speed. Block switching techniques take advantage of a priori information, such that a specified channel address is known several channel times before it is required. For example, consider a relay MUX that is capable of operating at 300 channels per second and is divided in groups of 30 switches and amplifiers. Then a solid-state MUX is operated across the amplifiers at a rate of 3000 thousand channels per second. If 10 relays are switched on at a time, the availability of relays is 10 times 300 channels per second or 3000 channels per second, which is the

switching rate of the solid-state portion of the system. Therefore, 10 channels are always preselected, and if the user desires access to some random channel then the channel must be selected in the next block of 10 switches. At any one time the system is 1/300 sec away from access to a random channel. Since a great deal of multiplexing is done on a priori basis, block switching may be desirable. On the other hand, if random access at the highest transfer rate is required, then block switching is inadequate.

Hardware requirements for block switching are similar to requirements for other methods. The second level switches are usually employed for a standard MUX to reduce common mode and crosstalk voltages so the only basic change would be the addition of an amplifier for each block. If a 1000 channel configuration and block switching in groups of 50 are assumed, the requirement would entail 20 additional amplifiers at about \$100.00 per amplifier or \$2000.00, which is a modest increase of \$2.00 per channel.

Remote Multiplexing is one of the two basic system configurations in use today. Most installed data acquisition systems rely on hard-wire connections between the transducer and the central data collection site, or control room, where the signals are multiplexed and processed. This approach is widely used, but suffers from severe noise problems especially power line generated pickup. In addition, the cost of installing several thousand lines for signal paths is expensive in terms of building space and wire. Remote multiplexing is now being used to eliminate long wire runs and their associated problems, by performing multiplexing and analog-to-digital conversion near the transducer. The digital signals can then time share (TDM) a single coaxial cable for data transmission. FET's are used almost exclusively in these remote systems with several manufacturers, including General

Electric and Motorola, offering prototypic systems. The consideration of this approach must be based on the overall design criteria of the data collection system. If hard-wire runs are required as a part of the basic design criteria, then this approach cannot be considered.

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APPENDIX

CHARACTERISTICS OF COMMERCIAL MULTIPLEXERS

APPENDIX

CHARACTERISTICS OF COMMERCIAL MULTIPLEXERS

Control Equipment Corp. (CEC)
Type 3010

MUX Type	Electromechanical - Relay Switches - Solid-State Logic
No. of Channels	5 channels standard (expandable to 100 channels)
Sampling Rate	200 channels/sec
Signal, full scale	± 100 MV to ± 10 V
Input Impedance	10,000 M Ω minimum
Offset Voltage	5 μ V maximum thermal offset at 25 °C
Max. Common Mode Voltage	200 V dc
C. M. Rejection Ratio	--
Noise	Less than 3 μ V electromagnetic pick-up from drive source
Crosstalk	--
Temp. Effects	--
Gain Accuracy	--
Cost	\$1720 (5 channel); \$4750 (100 channel); \$344/channel and 47.50/channel respectively
Comments	Addressable in Single, Sequential and Random Access Modes; 10^9 operations minimum life; Logic drive, 0 to 6 V dc

A. D. Date Systems, Inc.
Model 103

MUX Type	Electromechanical - Reed Relay - No Logic
No. of Channels	100
Sampling Rate	up to 300 channels/sec
Signal, full scale	--
Input Impedance	300,000 M Ω
Offset Voltage	--
Max. Common Mode Voltage	--
C.M. Rejection Ratio	--
Noise	2 μ V
Crosstalk	--
Temp. Effects	--
Gain Accuracy	--
Cost	\$1150 + \$1350 = \$2500.00; \$25.00/channel
Comments	Logic Cost = \$1350.00

Cunningham

MUX Type	Electromechanical - Crossbar Switches
No. of Channels	50 differential inputs
Sampling Rate	50 to 100 channels/sec
Signal, full scale	--
Input Impedance	10,000 M Ω
Offset Voltage	--
Max. Common Mode Voltage	1000 V ac
C.M. Rejection Ratio	--
Noise	--
Crosstalk	50 dB at 100 MHz
Temp. Effects	0.01 μ V/ $^{\circ}$ C thermal offset
Gain Accuracy	Amplifier not included
Cost	Not available
Comments	Random Access Mode, except by changing a mechanical switch; 400 μ sec bounce. Life rated at 20 million operations

Control Equipment Corp. (CEC)
Type 3080

MUX Type	Electromechanical - Crossbar Switches - Solid-State Logic
No. of Channels	100 channel differential (expandable to 1000 channels)
Sampling Rate	50 channels/sec
Signal, full scale	± 10 mV to ± 10 V
Input Impedance	1 M Ω minimum
Offset Voltage	--
Max. Common Mode Voltage	1500 V ac dielectric strength
C.M. Rejection Ratio	--
Noise	--
Crosstalk	--
Temp. Effects	--
Gain Accuracy	Amplifier not included
Cost	\$3450 (100 channel); \$5450 (400 channel); 34.50 and 13.60 per channel for power supply add \$300/MUX
Comments	2 million operations (minimum life); 200 μ sec bounce; Requires ± 12 V dc and -6 V dc power supply. Addressable in Single, Sequential, or Random Access Modes Logic drive 0 to +6 V

Teledyne
Type 365

MUX Type	Solid-State - J-FET - IC Logic
No. of Channels	Any number up to 256 differential, guarded
Sampling Rate	1 to 25 kHz
Signal, full scale	± 5 mV to ± 10 V
Input Impedance	50 M Ω shunted by 50 pF
Offset Voltage	$< \pm 20$ μ V over range of 0 to 60 $^{\circ}$ C
Max. Common Mode Voltage	± 5 V standard, ± 10 V optionally available
C.M. Rejection Ratio	100 dB at 60 Hz
Noise	< 5 μ V rms RTI
Crosstalk	$< 0.1\%$ for all low-level; for inter-mixed low-high level inputs crosstalk in the first low-level channel $< \pm 0.4\%$
Temp. Effects	--
Gain Accuracy	$\pm 0.2\%$ for inputs of 10 mV and lower ($\pm 0.1\%$, above 10 mV)
Cost	\$6220.00 (90 channel) = 69.00/channel
Comments	--

Teledyne
Type 366

MUX Type	Solid-State - MOSFET - IC Logic
No. of Channels	90 standard
Sampling Rate	1 to 25 kHz
Signal full scale	± 5 mV to ± 5 V
Input Impedance	100 M Ω typical
Offset Voltage	$< \pm 25$ μ V -25 $^{\circ}$ C to +85 $^{\circ}$ C
Max. Common Mode Voltage	± 5 V
C.M. Rejection Ratio	100 dB dc to 60 Hz
Noise	< 5 μ V RTI
Crosstalk	$< 0.1\%$
Gain Accuracy	$\pm 0.1\%$
Cost	\$5320 (90 channel) = 59.00/channel
Comments	--

Dynamic Systems Electronics (DSE)
851 Series

MUX Type	Solid-State - MOS-FET Switches - IC Logic
No. of Channels	128 single ended or differential is standard
Sampling Rate	30 kHz
Signal, full scale	± 10 mV to ± 10 V
Input Impedance	100 M Ω
Offset Voltage	--
Max. Common Mode Voltage	5 V
C.M. Rejection Ratio	60 dB at 60 Hz balanced input
Noise	--
Crosstalk	$\pm 0.05\%$ maximum
Temp. Effects	3 μ V/ $^{\circ}$ C referred to input
Gain	--
Gain Accuracy	$\pm 0.01\%$
Cost	7700.00 single ended; 12,700 double ended. 60.00/channel and 100.00/channel respectively
Comments	--

Astrodata
Series 960

MUX Type	Solid-State - J-FET - Transistor Logic
No. of Channels	up to 100 channels in groups of 10, guarded differential
Sampling Rate	0 to 10 kHz
Signal, full scale	± 10 mV, ± 20 mV, ± 40 mV, ± 80 mV, ± 160 mV (others available)
Input Impedance	> 10 M Ω
Offset Voltage	$\pm 3 + 15 R \times 10^{-4}$ μ V RTI; 0.5μ V RTI + 0.005% of full scale/8 hr ^(a)
Max. Common Mode Voltage	± 10 V
C.M. Rejection Ratio	120 dB at 60 Hz (1000 Ω source unbalance)
Leakage Current	1.5 nA
Noise	$4 + 6\sqrt{R \times 10^{-4}}$ μ V RTI or 0.02% of full scale, whichever is greater
Crosstalk	$\pm 2 \mu$ m RTI or $\pm 0.025 R \times 10^{-4}$ % of previous channel amplitude whichever is greater
Temp. Effects	Offset, $\pm 1 \mu$ V and ± 1 nA RTI/ $^{\circ}$ C between 0 and 50 $^{\circ}$ C
Gain Accuracy	± 0.1 %; ± 0.01 % gain stability/8 hr
Cost	\$6000 + 35.00/channel = 95.00/channel (100 channel); no break for 1000 channels
Comments	Output = +5 V dc full scale, full short circuit protected addressable in Random Access Mode; Sequential operation requires external control

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(a) RT 1 = Referred to Input
 R = Scanning rate in channels/sec

Interstate Electronics Corp. (IEC)
MX 500 Series

MUX Type	Solid-State - J-FET Switches - IC Logic
No. of Channels	up to 1000 differential-guarded (basic unit = 120 channel)
Sampling Rate	50 kHz
Signal, full scale	± 5 mV to ± 500 mV
Input Impedance	>10 M Ω
Offset Voltage	$<\pm 4$ V referred to input; ± 50 μ V referred to output per day
Max. Common Mode Voltage	± 10 V maximum
C.M. Rejection Ratio	120 dB at 60 Hz balance source; 85 dB at 60 Hz 1 k Ω
Noise	3.5 μ V rms referred to input ± 500 μ V rms referred to output
Crosstalk	0.004% of full scale for 100% overload on adjacent channel
Temp. Effects	leakage variation 3 nA/ $^{\circ}$ C from 0 to 50 $^{\circ}$ C
Gain Accuracy	0.1%
Cost	\$110.00/channel (100 channel); drops to \$55.00/channel for 1000 channel
Comments	Output may be short circuited indefinitely without damage

Systems Engineering Lab. (SEL)
Series 501

MUX Type	Solid-State - Transistor Switches - Transistor Logic
No. of Channels	up to 100 channels guarded differential
Sampling Rate	up to 20 kHz channels/sec
Signal, full scale	± 5 mV, ± 10 mV, ± 20 mV, ± 50 mV, ± 100 mV (can be intermixed)
Input Impedance	1 M Ω minimum
Offset Voltage	20 μ V peak-to-peak
Max. Common Mode Voltage	115 V ac standard; 1500 V available as an option
C.M. Rejection Ratio	120 dB at 60 Hz (120 Ω source unbalance)
Noise	<5 μ V peak referred to input and 0.01% peak referred to output
Crosstalk	<0.02% for on-scale inputs; <0.2% for overloaded channels
Temp. Effects	Gain, <0.01%/°F; Offset, <2 μ V/°F; Leakage, <1 nA/°F
Gain Accuracy	$\pm 0.1\%$ of scale (can be removed by calibration)
Cost	\$18,000/100 channel \$180/channel
Comments	New FET system is estimated at 1/2 price, 6 months away. Addressable in Single, Sequential, and Random Access Modes no significant price break for 1000 channels

Preston Scientific, Inc.
Model 8300-S

MUX Type	Solid-State - Amplifier per Channel
No. of Channels	10 amplifiers, MUX per 19 in. relay rack differential, guarded
Sampling Rate	up to 5 kHz
Signal, full scale	± 10 Mv to ± 10 V
Input Impedance	100 M Ω minimum
Offset Voltage	± 1 μ V RTI; ± 0.5 mV RTO for 40 hr
Max. Common Mode Voltage	250 V peak ac or dc
C.M. Rejection Ratio	130 dB at 60 Hz
Noise	Output < 1 mV peak-to-peak for 3000 kc bandwidth
Crosstalk	0.005% maximum for 100 channels
Temp. Effects	Gain TC = 0.002%/°C; Offset TC = 1 μ V RTI/°C, ± 0.1 mV RTO/°C
Gain Accuracy	$\pm 0.1\%$; $\pm 0.01\%$ of full scale ± 3 μ V RTI for 6 month stability
Cost	--
Comments	Full scale output ± 10 V. Output fully short-circuit protected

SDS
AM-60

MUX Type	Amplifier per channel
No. of Channels	1
Sampling Rate	to 100 kHz
Signal, full scale	± 5 mV to ± 10 V
Input Impedance	$3 \times 10^{10} \Omega$ isolation, input to output
Offset Voltage	$\pm 1 \mu\text{V}$ short term (40 hr) $\pm 5 \mu\text{V}$ for 6 month (RTI)
Max. Common Mode Voltage	± 200 V without damage
C.M. Rejection Ratio	150 dB at 60 Hz
Noise	< 1 mV peak-to-peak at output
Crosstalk	$< \pm 0.005\%$ full scale
Temp. Effects	± 0.1 mV/ $^{\circ}\text{C}$ referred to output
Gain Accuracy	$\pm 0.01\%$
Cost	435.00 (1-49) 405.00 (100 or more)
Comments	Output filters at 10 Hz, 100 Hz, 1000 Hz, and 10 kHz available at extra cost

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