

# Application Note 42003

## Data Conversion Design Techniques for Process Control Applications

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### INTRODUCTION

Process control technology has developed and adapted from its earliest form of single channel, analog control loops, to enormously complex, multiple parameter control systems. High performance microprocessors are the heart of such systems, and it is assumed that sheer processor speed alone will determine the overall control loop bandwidth and response time of the system. However, the "number crunching" power of such processors cannot effectively be optimized until the process control parameters are accurately digitized using proper conversion techniques within the requirements of the control loop response. To further complicate the design process, restrictions such as single supply operation and low power consumption may be imposed.

This application note will address the five common types of measured analog parameters that are associated with virtually all process control situations, and the transducers utilized to convert these parameters into usable signals. Specific characteristics such as range, output type, accuracy, bandwidth, response time, etc., will be discussed, as well as their effects on the requirements of the data conversion design. Application specific design "cases" will be reviewed for each parameter type, with recommended data converters and appropriate schematics.

### PROCESS CONTROL PARAMETERS

The most common process control parameters used in the industry are:

- Temperature
- Pressure
- Flow (Linear & Volumetric)
- Position
- Photometry/Radiometry

#### TEMPERATURE

Temperature is perhaps the most widely used physical measurement, for most processes are temperature dependent, or is the final controlled parameter as in building HVAC. Common devices used for temperature measurement are:

- 1) Thermistors
- 2) Resistance Temperature Detectors (RTD's)
- 3) Thermocouples
- 4) Semiconductor Sensors

The comparative characteristics of these devices are as follows:

#### THERMISTORS:

- a) Composition: Negative Resistance Material
- b) Temperature Range: -30°C to +100°C
- c) Accuracy: ±0.5°C (limited range); ±1.5°C (max.)
- d) Response Time: 0.5 sec
- e) Relative Cost: ~ \$18 for element
- f) Converter Resolution: 8-bits

Thermistors are high resistance (>10kΩ) sensors that are used for fast response measurement (gas temperature, for instance) over a limited range. Although they suffer from extreme non-linearity, it is offset by the relative cost. Typical output voltages when derived from bridge or direct excitation circuits are around 2 volts full scale. However, due to their inaccuracy at the extreme temperature range, and interchangeability of devices, a resolution of 8-bits for a converter is adequate; in limited ranges where accuracy is improved 10-12-bits may be needed.

The general form of a thermistor response is given by:

$$\frac{1}{T} = A + B(\text{Log}_e R) + C(\text{Log}_e R)^3$$

where:

- A, B, C, are constants
- T = Degrees Kelvin
- R = Resistance at a known temperature

#### RESISTANCE TEMPERATURE DETECTORS (RTD'S):

- a) Composition: Copper, Nickel or Platinum
- b) Temperature Range: -200°C to +600°C
- c) Accuracy: ±3°C
- d) Response Time: 2 sec
- e) Relative Cost: ~ \$70 for element
- f) Converter Resolution: 10 or 12-bits

RTD's are relatively low resistance sensors (10Ω for Cu, 50Ω for Ni and 100Ω for Pt) that are used for high accuracy temperature measurements. Accuracy can be less than ±0.2°C, with ±3°C only at the extremes of usable range. Direct excitation circuits can deliver up to 500mV of usable, single ended signal voltage, usually with very good linearity. The range and accuracy requirements usually will dictate that at least a good 10-bit, or standard 12-bit data converter be used.

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RTD's will generally adhere to the following response:

$$R(T) = R_0[1 + \alpha\Delta T]$$

where:

$R_0$  = Nominal (25°C) Resistance

$\alpha$  = Temperature Coefficient

$\Delta T$  = Change In Temperature (°C)

## THERMOCOUPLES:

### a) Composition:

J type (Iron — Constantan)

K type (Chromel — Alumel)

E type (Chromel — Constantan)

T type (Copper — Constantan)

R & S type (Pt/Rh — Platinum)

b) Temperature Range: -250°C to +1400°C

c) Accuracy:  $\pm 1\%$

d) Response time: 10 sec

e) Relative cost: ~\$25 for assembly

f) Converter Resolution: 12-bits

Thermocouples generate their own voltage output, typically tens of millivolts, by the Seebeck effect where dissimilar metals will develop a voltage potential based on the difference of two temperature junctions. However, the reference junction is usually at ambient temperature, which varies in most systems, and must therefore be compensated with additional circuitry that also conditions the output signal to a usable single ended voltage. Thermocouples can be used in a variety of ranges and environments, and are relatively inexpensive. However, they do suffer from extreme non-linearity. Depending on the required range, 12-bit data converters are usually employed.

Thermocouples are very non-linear, and are usually represented by 3rd or 4th order equations.

## SEMICONDUCTOR SENSORS

a) Composition: Silicon PN Junction

b) Temperature Range: -55°C to +150°C

c) Accuracy:  $\pm 1.5\%$

d) Response Time: 100msec

e) Relative Cost: ~\$6

f) Converter Resolution: 8- to 10-bits

There are semiconductor sensors on the market today that use a compensated PN junction and related circuitry to generate a  $1\mu A/^\circ K$  linear output. Additional circuitry must be used to generate a usable signal. Although limited in range and accuracy, the small cost offsets these deficiencies. The limited range allows the use of 8- or 10-bit data converters.

## PRESSURE

Pressure measurements have been used to determine a variety of process parameters such as weight, gas pressure and mechanical strain. Chemical synthesis batch reactors need to sense the amount of a material prior to being added to a reaction vessel, or HVAC controllers being required to sense air pressure controlling a valve actuator unit. The most common pressure transducers are:

- 1) Piezoelectric Elements (Strain Gauge)
- 2) Integrated Piezoresistive Bridges

## PIEZOELECTRIC ELEMENTS

- a) Composition: Barium Titanate, etc.
- b) Pressure Range: >100psi
- c) Accuracy:  $\pm 0.5\%$  F.S.
- d) Response Time: 100–200msec
- e) Relative Cost: Inexpensive
- f) Converter Resolution: 8- to 10-bits

Materials such as barium titanate generate a voltage proportional to the strain induced on the crystal lattice by an external pressure. This voltage, however, is in the millivolt range, and requires conditioning, usually to a single ended output. The accuracy limitations dictate that 8- to 10-bits are required.

## INTEGRATED PIEZORESISTIVE BRIDGES

- a) Composition: Piezoresistive Silicon
- b) Pressure Range: 1 to 10,000psi
- c) Accuracy:  $\pm 1\%$
- d) Response Time: 100–200msec
- e) Relative Cost: Inexpensive
- f) Converter Resolution: 12-bits

Integrated strain gauge bridges employ semiconductor manufacturing techniques to fabricate full pressure sensors with a small signal, differential output voltage. These are usually highly accurate, but need some signal conditioning to generate a useful single ended output. Others provide a resistive bridge to which a reference voltage is applied. Due to the large range and accuracy inherent with these devices, 12-bit systems are usually required.

In general, strain gauges follow:

$$\Delta R \approx 2 \times R_0 \left( \frac{\Delta \ell}{\Lambda} \right)$$

where:

$\Delta R$  = Resistance Change

$R_0$  = Initial Resistance

$\left( \frac{\Delta \ell}{\Lambda} \right)$  = Strain/Stress of Material

## FLOW (LINEAR &amp; VOLUMETRIC)

Flow (linear or volumetric) is a process control parameter that is used to determine a rate of mass movement, or volume flow. We see this as a critical process parameter in HVAC and the petroleum industries, where air and petroleum products volumetric data must be obtained. This can be accomplished with the use of pressure sensors placed in a pipe or duct.

We can determine the flow of a material by the following relationship:

$$F = \sqrt{2g} \times \sqrt{\Delta p} \quad \text{ft/sec}$$

where :

$g = 32 \text{ ft/sec}^2$  (gravitational constant)

$\Delta p =$  differential pressure along pipe

Mass flow can be determined by the relationship:

$$Q = \sqrt{2g} \times L \times H \times \sqrt{\Delta p} \quad \text{ft}^3/\text{sec}$$

where:

$L \times H =$  cross sectional area of flow

Accuracy and converter resolutions are identical to those of the integrated piezoresistive pressure sensors.

## LINEAR DISPLACEMENT

In many situations, the process controller needs to be able to determine linear position along an axis, or shaft angle. Actuator and valve positioning are two of many applications. The device of choice for measuring linear position is the Linear Variable Displacement Transformer. Its characteristics are as follows:

- Composition: Transformer w/movable core
- Range: Variable
- Accuracy:  $\pm 0.5\%$
- Response Time: 200–600 msec
- Relative Cost: Expensive
- Converter Resolution: 10-bits

With this sensor, an AC signal inserted through a variable reluctance coupling is induced in an output circuit through the movable core which determines the amount of displacement. The LVDT is insensitive to temperature variations, but is much more massive than the strain gauge type sensors. Sensitivity increases with frequency, but a minimum ratio of 10:1 between excitation and signal frequencies can be considered a practical limit. Depending on the type of LVDT, the converter requirements are usually 10-bits.

## PHOTOMETRY/RADIOMETRY

The measurement of light and light intensity is a critical parameter used in the medical electronics and photographic industries. Diagnostic instruments utilized emitted light from sensitized chemicals combining with antibodies to determine the level of an infectious disease a patient has, as in an HIV or Hepatitis immune-assay. The photographic industry uses combined light intensity to correct for exposure errors in the development of photographic or theatrical film. The devices used for these measurements are:

- Photomultiplier Tubes (PMT's)
- Photodiodes

## PHOTOMULTIPLIER TUBES (PMT'S)

- Composition: Multiple Coated Anode Tubes
- Sensitivity: 1 Photon of Energy
- Range: Up to 1 Lumen
- Response Time:  $< 1 \text{ nsec}$  in photon counting mode
- Relative Cost: Very Expensive
- Converter Requirements: 12-bits or more

PMT's are tube-like devices that have a series of sensitized dynodes that when a photon strikes the cathode, electrons are released. These electrons then strike into the first dynode, releasing more electrons, then to the second anode, etc., etc. This generates a very large multiplying effect, or gain, that results in an output current proportional to the intensity of photons striking the cathode. The output is logarithmic, is temperature sensitive, and requires specialized signal conditioning due to the high output impedance of the PMT. They do, however, offer phenomenal sensitivity, down to the level of photon counting. The transfer function of a PMT is described by:

$$I_0 = (1.6 \times 10^{-19}) \delta^n$$

where

$\delta^n =$  Ratio of primary to secondary electrons

$n =$  Number of Dynodes in PMT

## PHOTODIODES

- Composition: Silicon PN Junction
- Sensitivity:  $< 1 \text{ m ft-cdl}$
- Range: Up To 2000 ft — candelas
- Response Time:  $> 10 \text{ MHz}$
- Relative Cost: Inexpensive
- Convert Resolution: 10-bits

Photodiodes are PN devices specifically doped to enhance light sensitivity. They are more linear than PMT's, but at reduced sensitivity. They are also the most widely used light sensors in process control. A typical example is that of a light sensor in a Nikonos V underwater camera, which measures the average light striking the film for TTL flash control. 10-bits is usually the most resolution required, but it is application specific.

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## APPLICATION STUDIES

### CASE #1 : HVAC CONTROL SITUATION

A measurement application exists in an HVAC control environment where outside ambient air must be measured, the bearing temperature on AHU's (Air Handling Units) must be monitored, and pneumatic pressure controlling the damper actuators must be monitored and used for control feedback.

#### PARAMETER RANGES:

Ambient Temperature:  $-50^{\circ}\text{C}$  to  $50^{\circ}\text{C}$   
 Bearing Temperature:  $50^{\circ}\text{C}$  to  $200^{\circ}\text{C}$   
 Pneumatic Pressure: 1 to 15psi

#### Accuracy Required:

Ambient Temperature:  $\pm 0.5^{\circ}\text{C}$   
 Bearing Temperature:  $\pm 0.5^{\circ}\text{C}$   
 Pneumatic Pressure:  $\pm 0.2\text{psi}$

Selected Sensors Are:

Ambient Temperature: Thermistor  
 Bearing Temperature: Platinum RTD  
 Pneumatic Pressure: Piezoresistive Bridge IC

This scenario indicates that our ambient temperature accuracy needs to be one part in 200, or 8-bits, minimum. The bearing temperature requirements dictate that we must be accurate to one part in 400, or 9-bits, minimum, while our pneumatic requirement calls for one part in 70, or 6-bits minimum. Thus, a 10-bit system is required.

DEVICE OF CHOICE: ML2375

The ML2375 is a 10-bit, analog I/O peripheral that is capable of multiplexing 4 channels of analog signals. (It is assumed that an appropriate signal conditioning circuit has been added.) It also has the capability of using an internal 8- or 10-bit D/A for control functions. The bipolar input capability is ideal for the ambient temperature input requirements, while the 8-bit D/A can be utilized to perform pneumatic control functions. A schematic of the proposed system is shown in Figure 1.

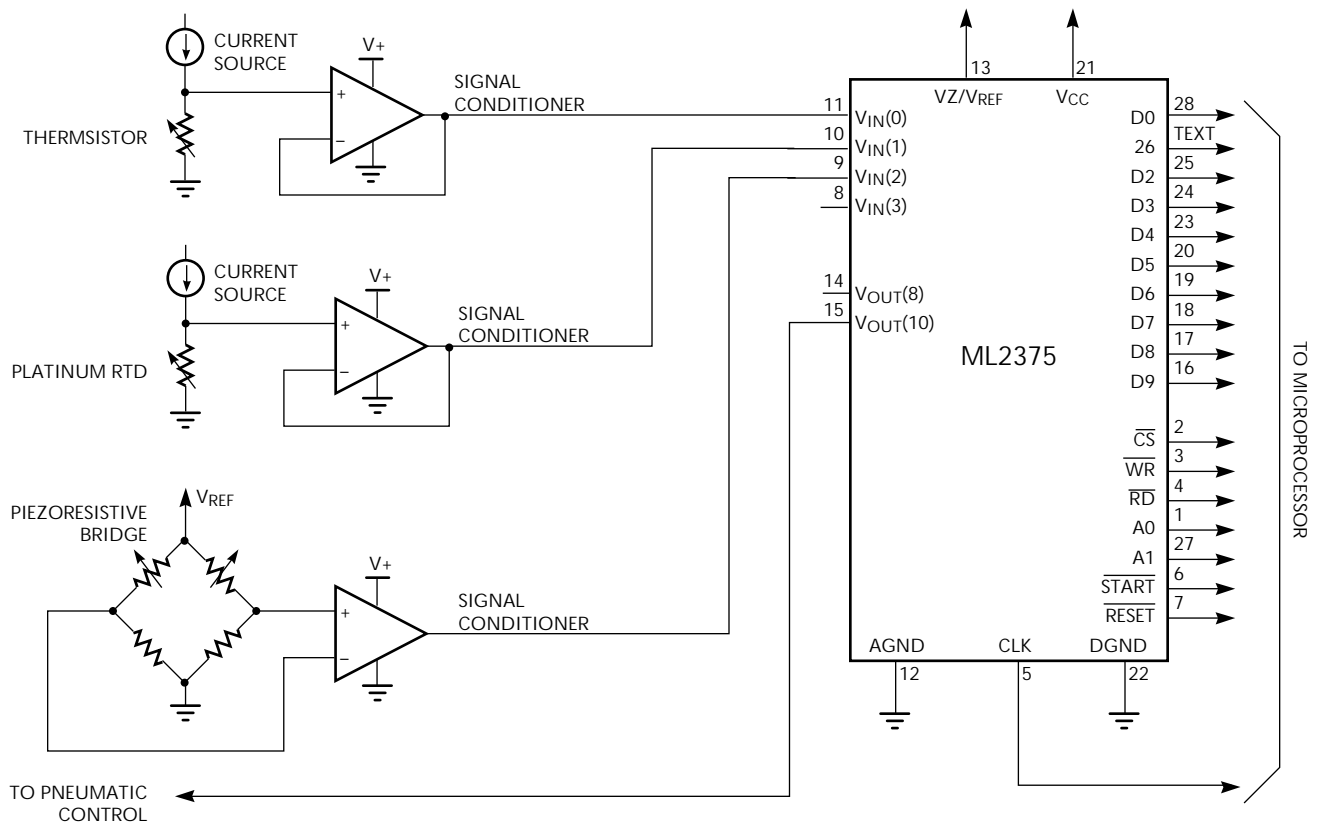


Figure 1.

## CASE #2: STEEL SMELTING PLANT CONTROL

A control scenario exists where the high temperature of the batch reactor must be monitored. In addition, the metering of reactants into the reactor is extremely critical, where LVDT's are used to sense valve positions.

### Parameter Ranges

Smelting Temperature: 600°C to 1200°C  
 Positioning Range: 0 to 6 inches

### Accuracy Required

Smelting Temperature:  $\pm 3.5^\circ\text{C}$  at 600°C-850°C range  
 $\pm 5.0^\circ\text{C}$  at 850°C-1200°C range

Positioning:  $\pm 0.0125$  in. at 0-3.0 in. range  
 $\pm 0.0250$  in. at 3.0-6.0 in. range

### Selected Sensors:

Smelting Temperature: R-Type Thermocouple  
 Positioning: LVDT

The requirements for this system indicate that we need to resolve 1 part in 240, or 8-bits, minimum. Our position sensor requirements show that we need to have a minimum resolution of 1 part in 240, or 8-bits, minimum. In addition, an additional input may be needed for reference junction compensation of the thermocouple.

### DEVICE OF CHOICE: ML2264

The ML2264 is ideally suited for this application. It operates from a single supply, has 8 bits of resolution. With 4 channel inputs, the device can monitor both process control parameters, and a silicon temperature sensor for thermocouple compensation. A sample and hold is provided, has a serial output for simple interfacing and it operates from a single 5 volt supply. A schematic of the proposed system is shown in Figure 2.

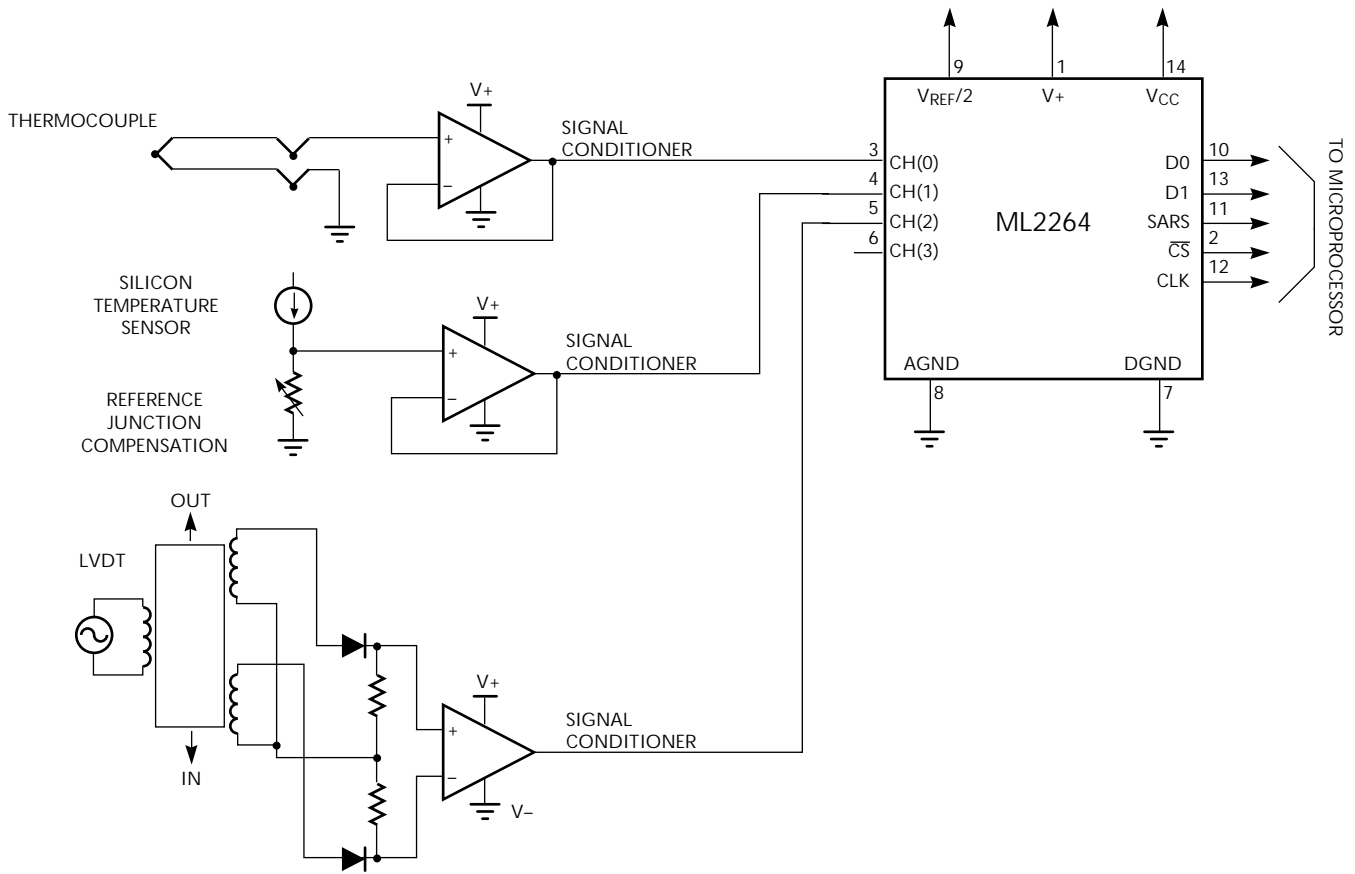


Figure 2.

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## CASE #3: DIAGNOSTIC INSTRUMENT

There is a requirement to measure the time delayed fluorescence of a metal chelated, ligand bonded antibody. In a delayed fluorescence, like in an RC time constant, 37% of the signal decays in the first time constant. The system is required to capture as much signal as possible given a 200nsec,  $3\tau$  time interval.

### Selected Sensors

Light Sensor: PMT

Such a system requirement requires the use of an accurate flash A/D converter, capable of at least 50nsec conversion time. It is assumed that an appropriate current to voltage converter has been in place to convert the current output from the PMT to the input of the A/D converter.

### DEVICE OF CHOICE: ML6401

The ML6401 is a 8-bit, 20 MSPS (min.) flash A/D capable of converting the PMT output to usable data. An integral sample and hold is provided. It has integral accuracy of +1 LSB, differential accuracy of + 0.5 LSB, operates from a single 5 volt supply and consumes 250mW. The schematic of such a system can be found in Figure 3.

## SUMMARY

The design of data conversion systems for process control applications requires a comprehensive knowledge of not only the type of parameters that must be measured and monitored, but also of sensor and transducers that are currently available. The ultimate accuracy of the system is a combination of sensor accuracy, signal conditioning and data conversion. With the introduction of fast, accurate gain blocks, the errors attributed to signal conditioning are minimized. Optimization of data conversion systems can occur only with proper analysis of the true system accuracy and utilization of converters that exhibit required accuracy without compensation or adjustment.

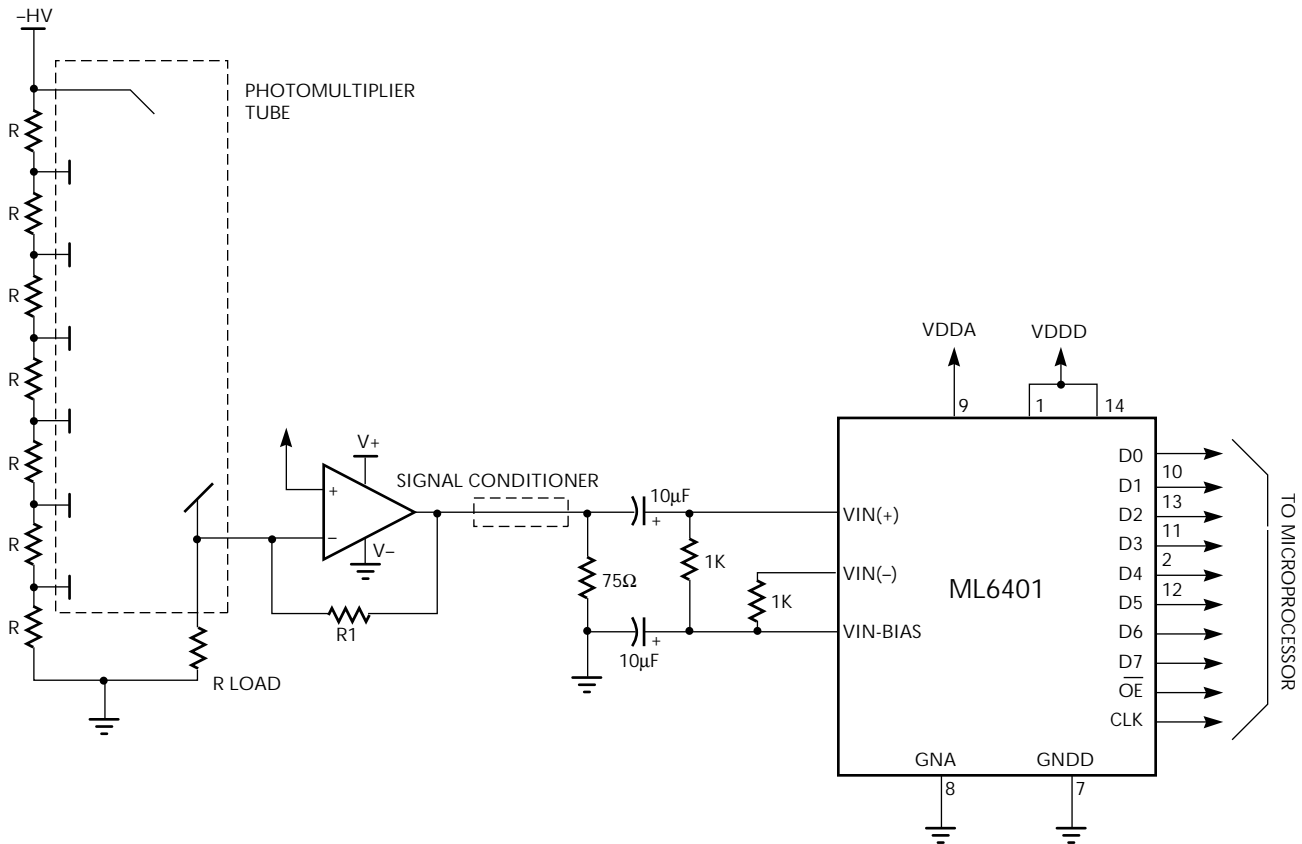


Figure 3.

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