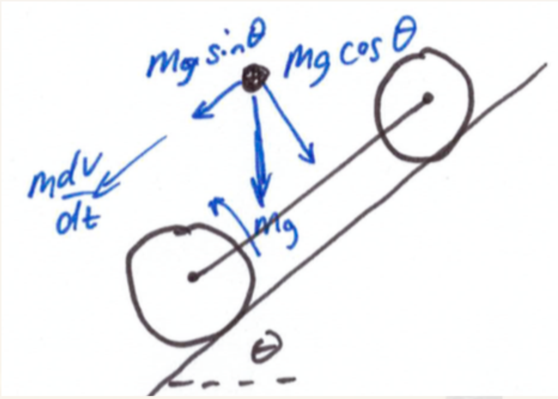
Robotic Sensors

- Slopes, revisited
- Proprioceptive
- Interoceptive
- Exteroceptive

Acceleration Limits Up Slopes



$$\frac{\ell - a}{h + r} = \frac{mg\sin\theta + m\left.\frac{dv}{dt}\right|_{\lim}}{mg\cos\theta}$$

$$\left(\frac{\ell - a}{h + r}\right) g\cos\theta = g\sin\theta + \left.\frac{dv}{dt}\right|_{\lim}$$

$$\left.\frac{dv}{dt}\right|_{\lim} = g\left[\left(\frac{\ell - a}{h + r}\right)\cos\theta - \sin\theta\right]$$

LRV: $\frac{\ell - a}{h + r} = 1.251$

Slope	$\left.\frac{dv}{dt}\right\|_{\lim} \left(\frac{m}{sec^2}\right)$
0°	1.932
10°	1.635
20°	1.288
30°	0.901

Limiting slope for acceleration = 51.4°

Longitudinal Dynamic Solutions

$$N_1 = mg\left[\left(1 - \frac{a}{\ell}\right)\cos\theta - \left(\frac{h}{\ell} + \frac{r}{\ell}\right)\sin\theta - \frac{a_x}{g}\right]$$

$$N_2 = mg\left[\frac{a}{\ell}\cos\theta + \left(\frac{h}{\ell} + \frac{r}{\ell}\right)\sin\theta + \frac{a_x}{g}\right]$$

$$T_2 = \frac{N_2}{N_1 + N_2}\left(mg\sin\theta + ma_x\right)$$

$$T_1 = \frac{N_1}{N_1 + N_2}\left(mg\sin\theta + ma_x\right)$$

Longitudinal Dynamic Solutions

$$N_1 = mg\left[\left(1-\frac{a}{\ell}\right)\cos\theta - \left(\frac{h}{\ell}+\frac{r}{\ell}\right)\sin\theta - \frac{1}{g}\frac{dv}{dt}\right]$$

$$N_2 = mg\left[\frac{a}{\ell}\cos\theta + \left(\frac{h}{\ell}+\frac{r}{\ell}\right)\sin\theta + \frac{1}{g}\frac{dv}{dt}\right]$$

$$T_2 = \frac{N_2}{N_1+N_2}\left(mg\sin\theta + m\frac{dv}{dt}\right)$$

$$T_1 = \frac{N_1}{N_1+N_2}\left(mg\sin\theta + m\frac{dv}{dt}\right)$$

Longitudinal Dynamic Solutions

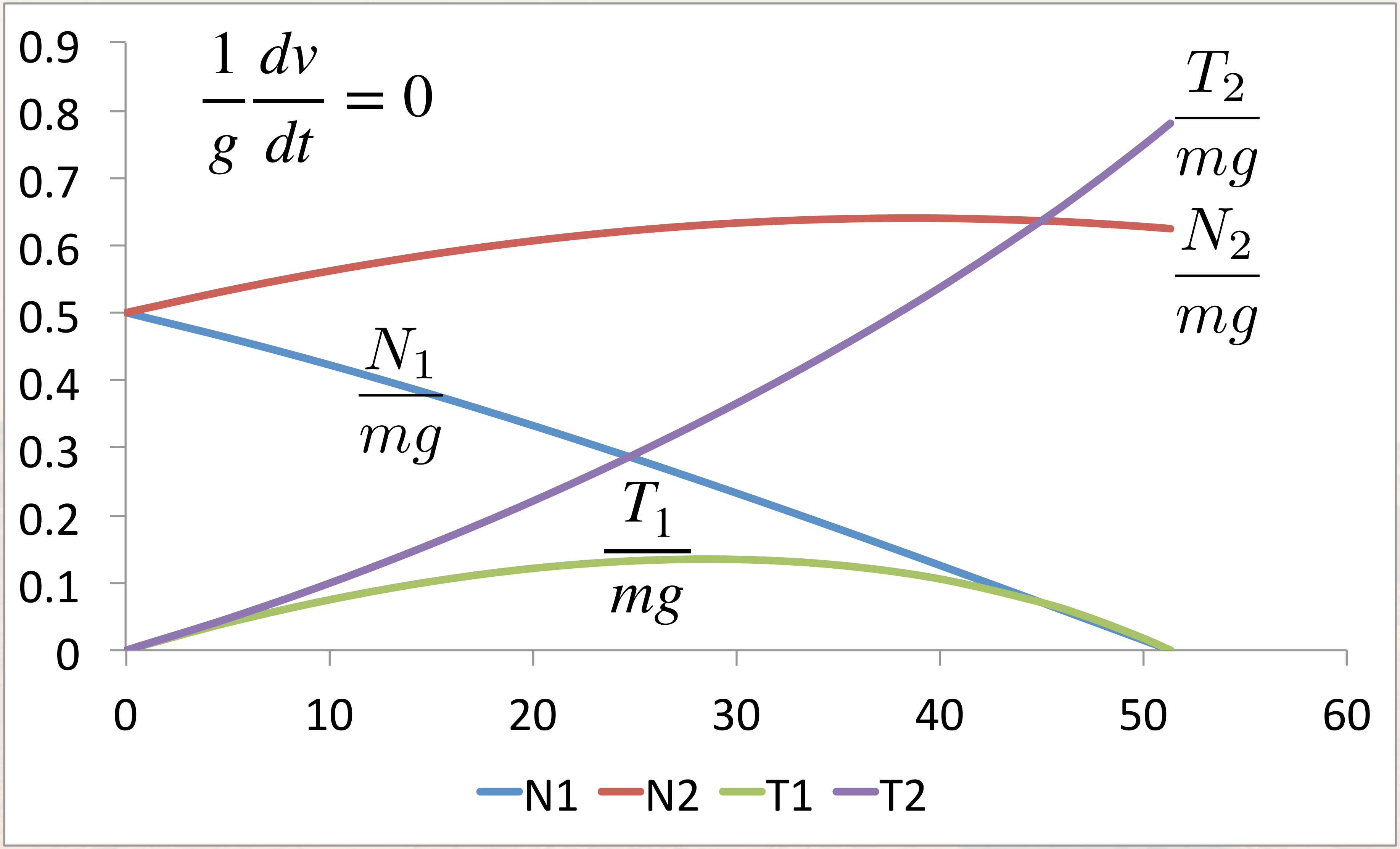
$$\frac{N_1}{mg} = \left(1 - \frac{a}{\ell}\right)\cos\theta - \left(\frac{h}{\ell} + \frac{r}{\ell}\right)\sin\theta - \frac{1}{g}\frac{dv}{dt}$$

$$\frac{N_2}{mg} = \frac{a}{\ell}\cos\theta + \left(\frac{h}{\ell} + \frac{r}{\ell}\right)\sin\theta + \frac{1}{g}\frac{dv}{dt}$$

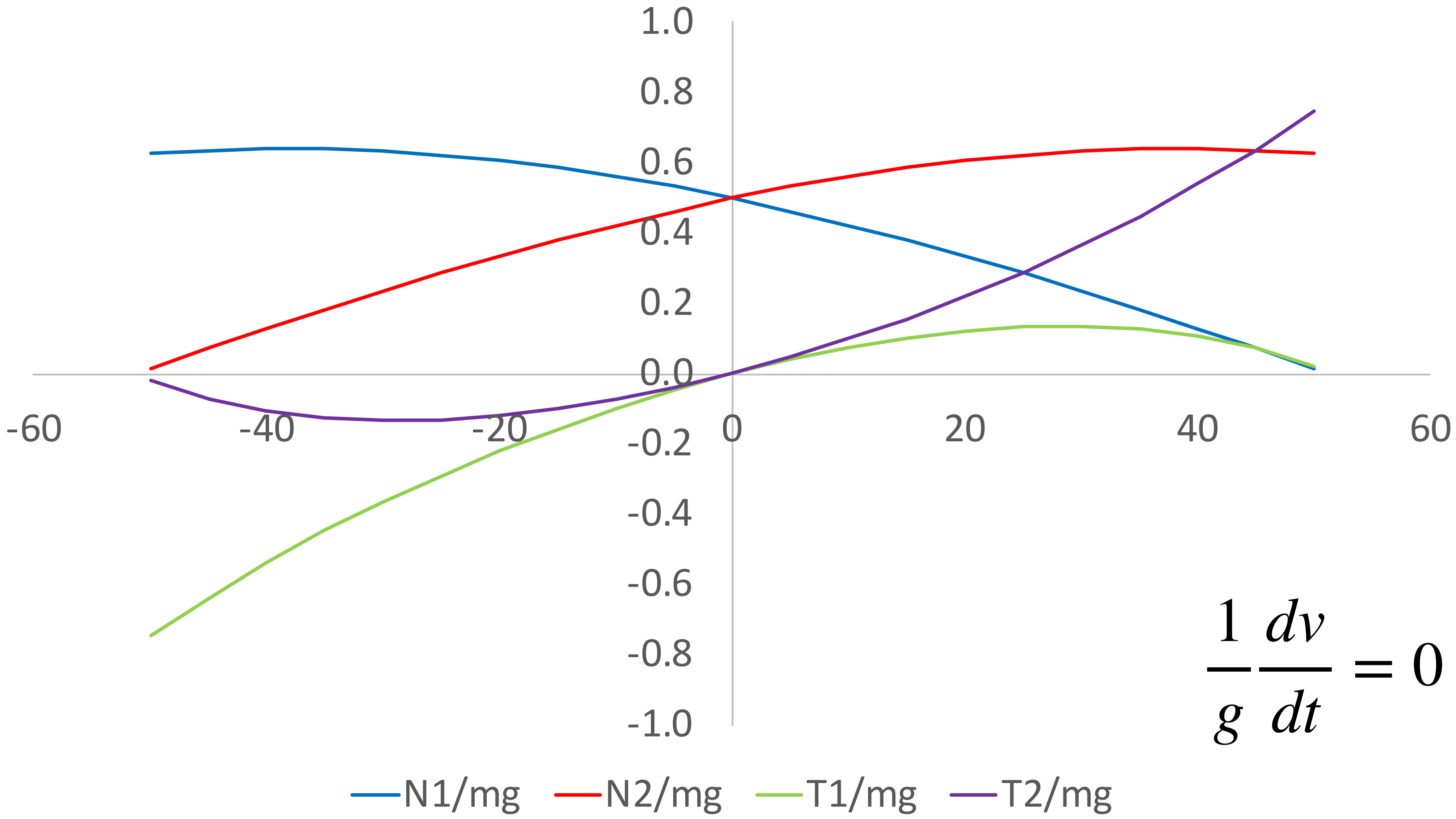
$$\frac{T_2}{mg} = \frac{N_2}{N_1 + N_2}\left(\sin\theta + \frac{1}{g}\frac{dv}{dt}\right)$$

$$\frac{T_1}{mg} = \frac{N_1}{N_1 + N_2}\left(\sin\theta + \frac{1}{g}\frac{dv}{dt}\right)$$

Normal and Shear Wheel Force w/Slope

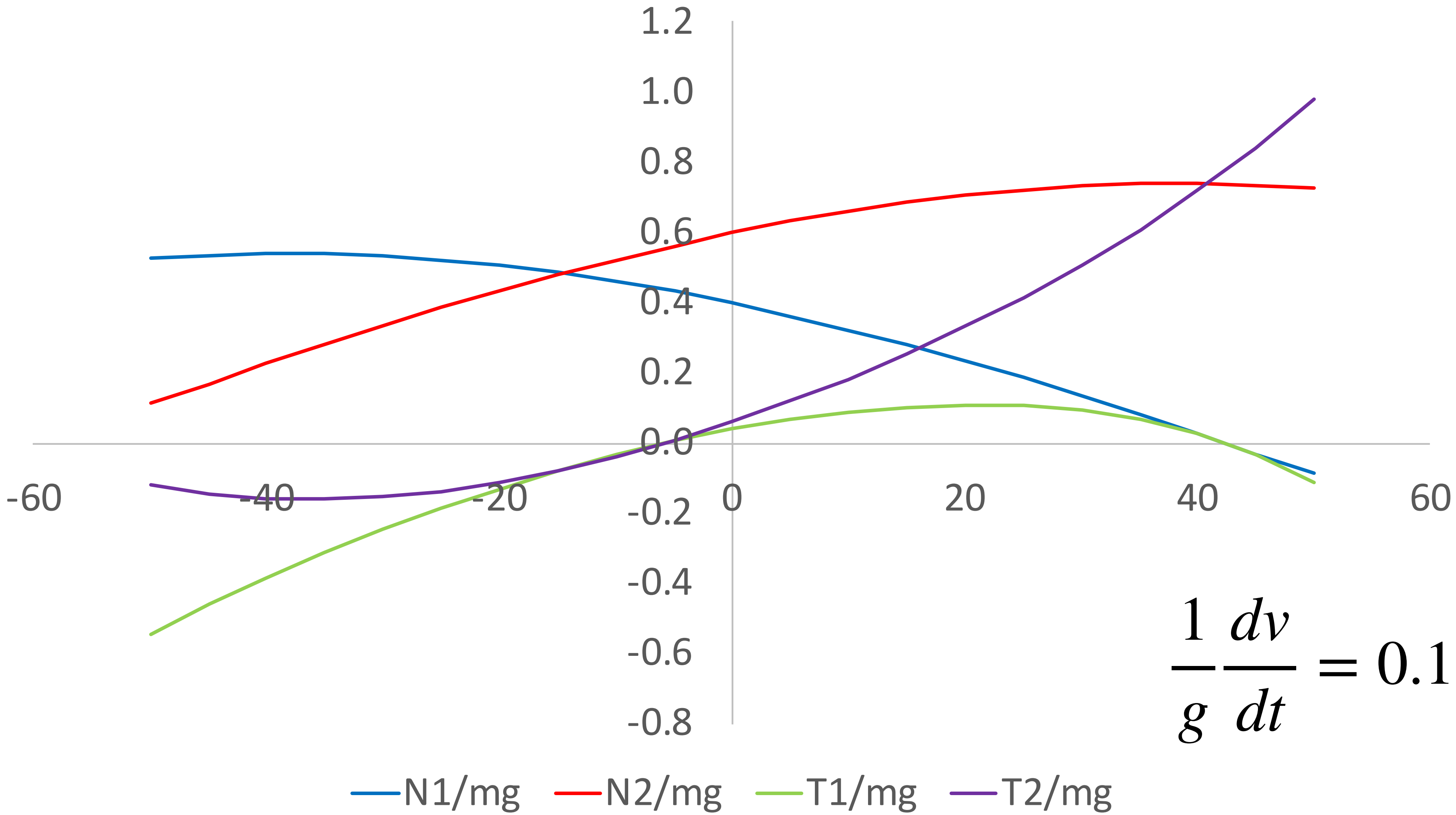


Normal and Shear Wheel Force w/Slope



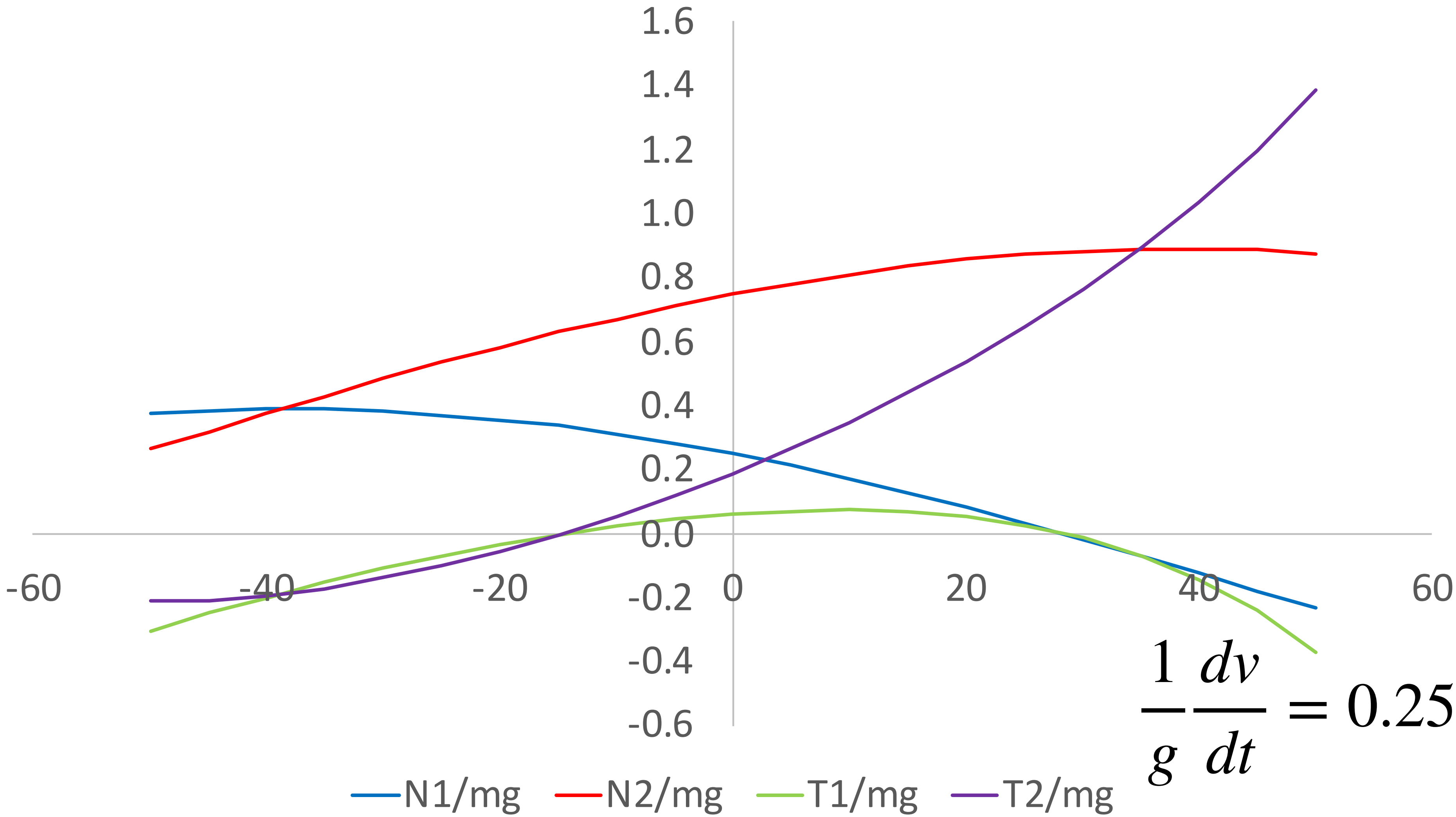
$$\frac{1}{g}\frac{dv}{dt} = 0$$

Normal and Shear Wheel Force w/Slope



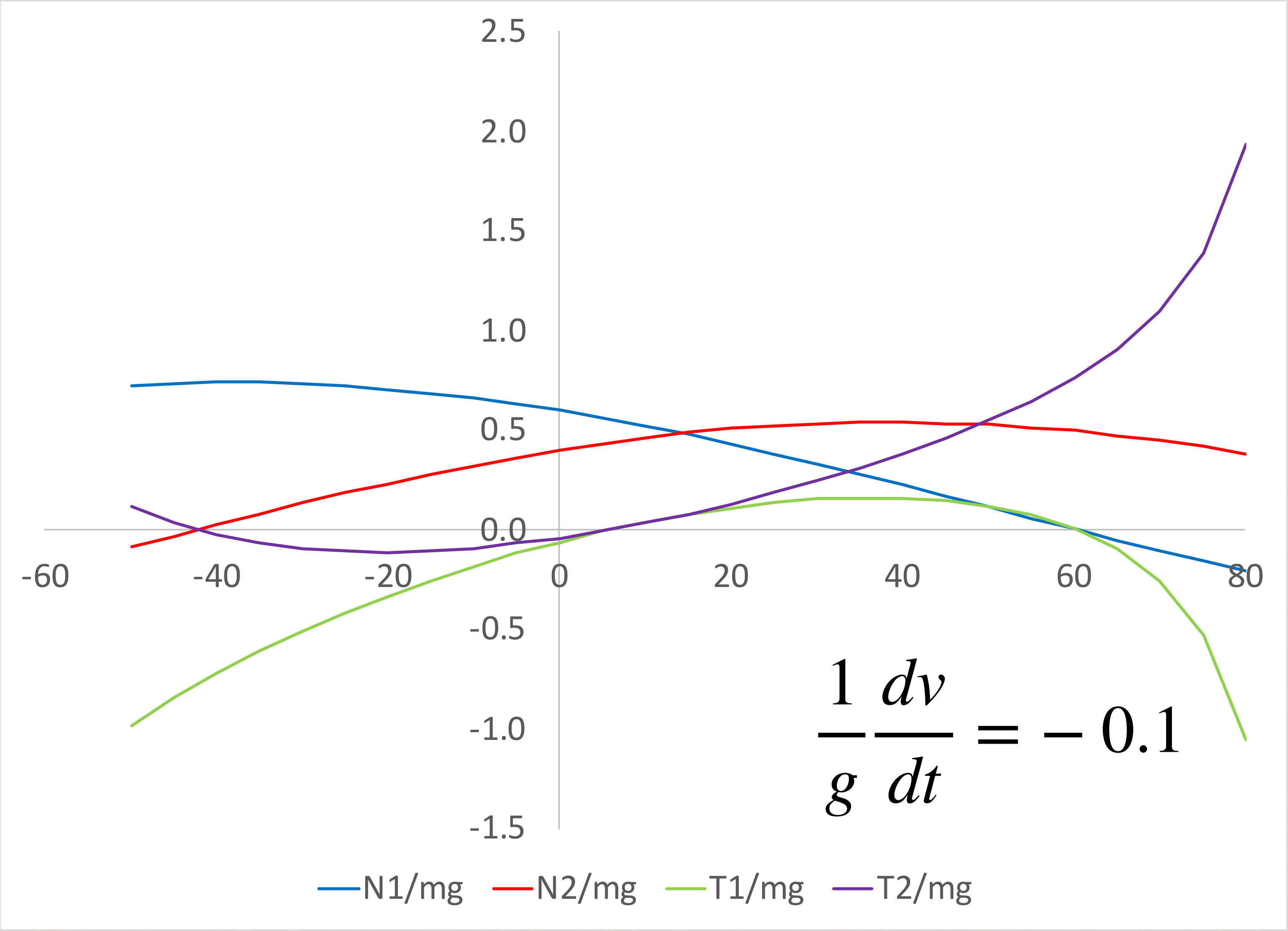
$$\frac{1}{g}\frac{dv}{dt} = 0.1$$

Normal and Shear Wheel Force w/Slope



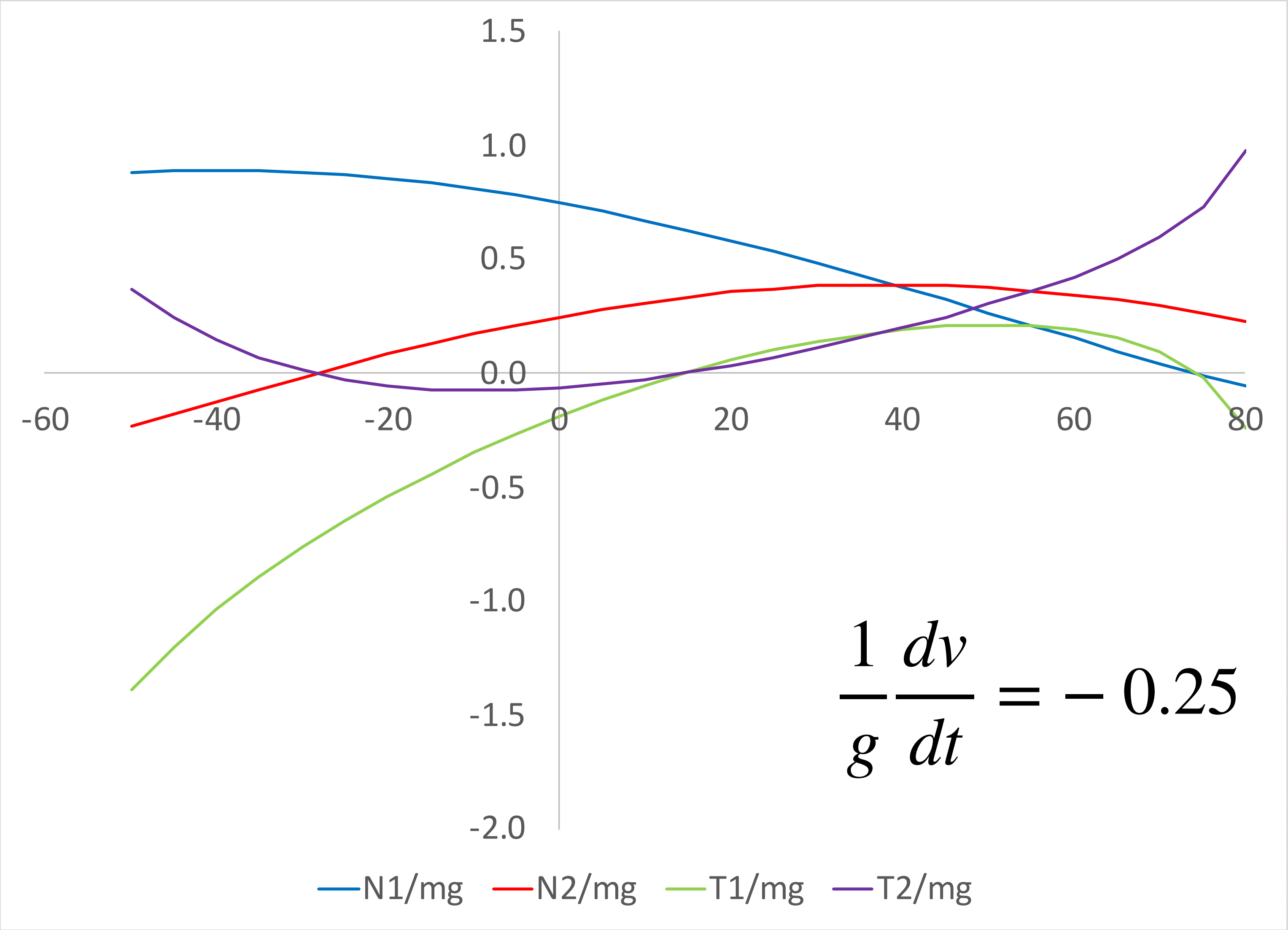
$$\frac{1}{g}\frac{dv}{dt} = 0.25$$

Normal and Shear Wheel Force w/Slope



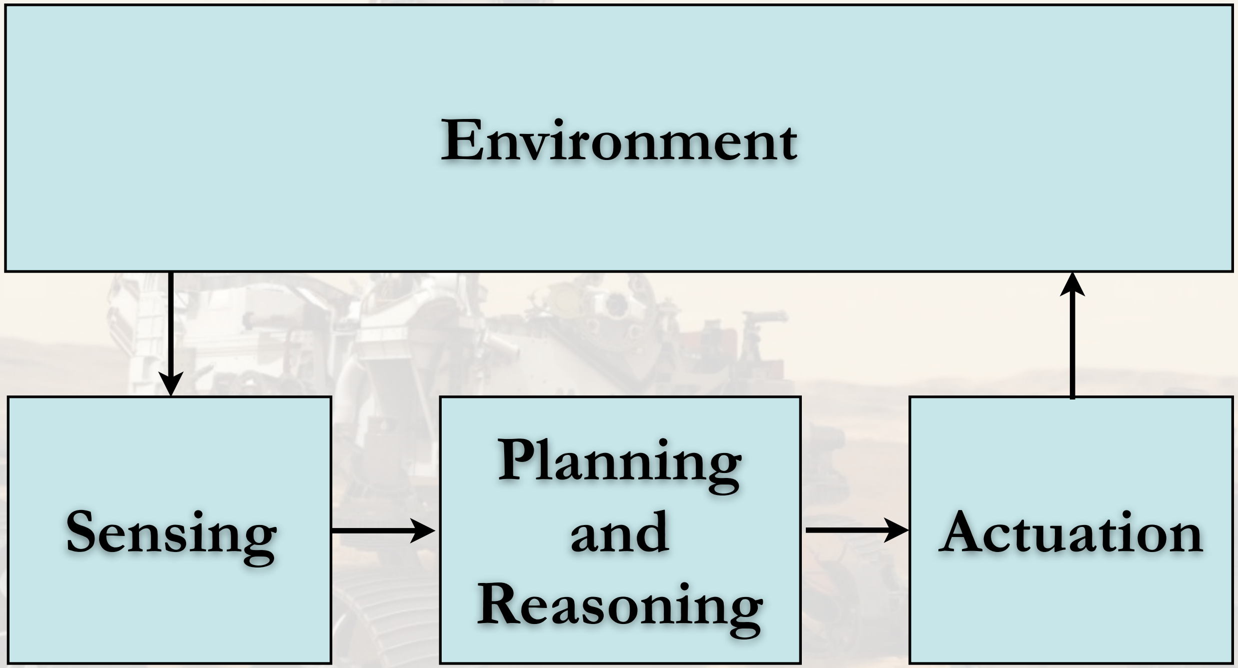
$$\frac{1}{g}\frac{dv}{dt} = -0.1$$

Normal and Shear Wheel Force w/Slope



$$\frac{1}{g}\frac{dv}{dt} = -0.25$$

Fundamental Elements of Robotics

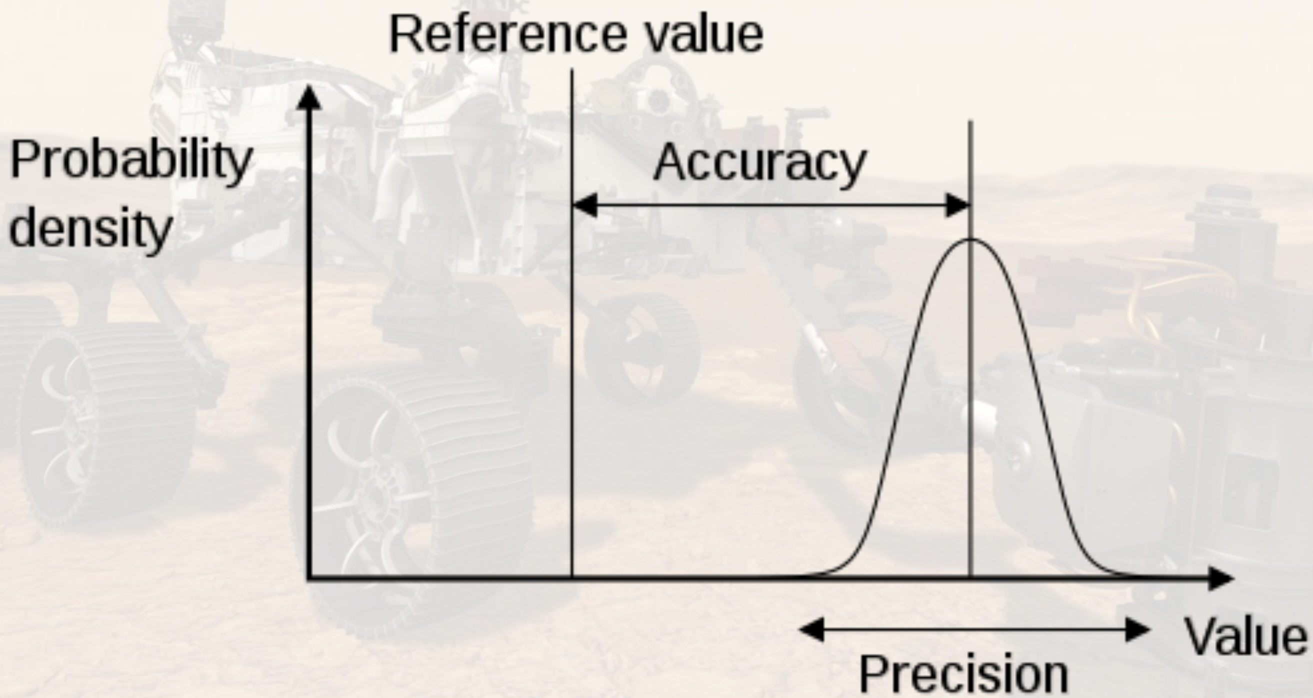


Sensor Components

- An overview of robotic operations
- Generic discussion of sensor issues
- Sensor types
  - Proprioceptive (measures robotic interaction with environment)
  - Exteroceptive (measures environment directly, usually remotely)
  - Interoceptive (internal data - engineering quantities)

Sensing Definitions

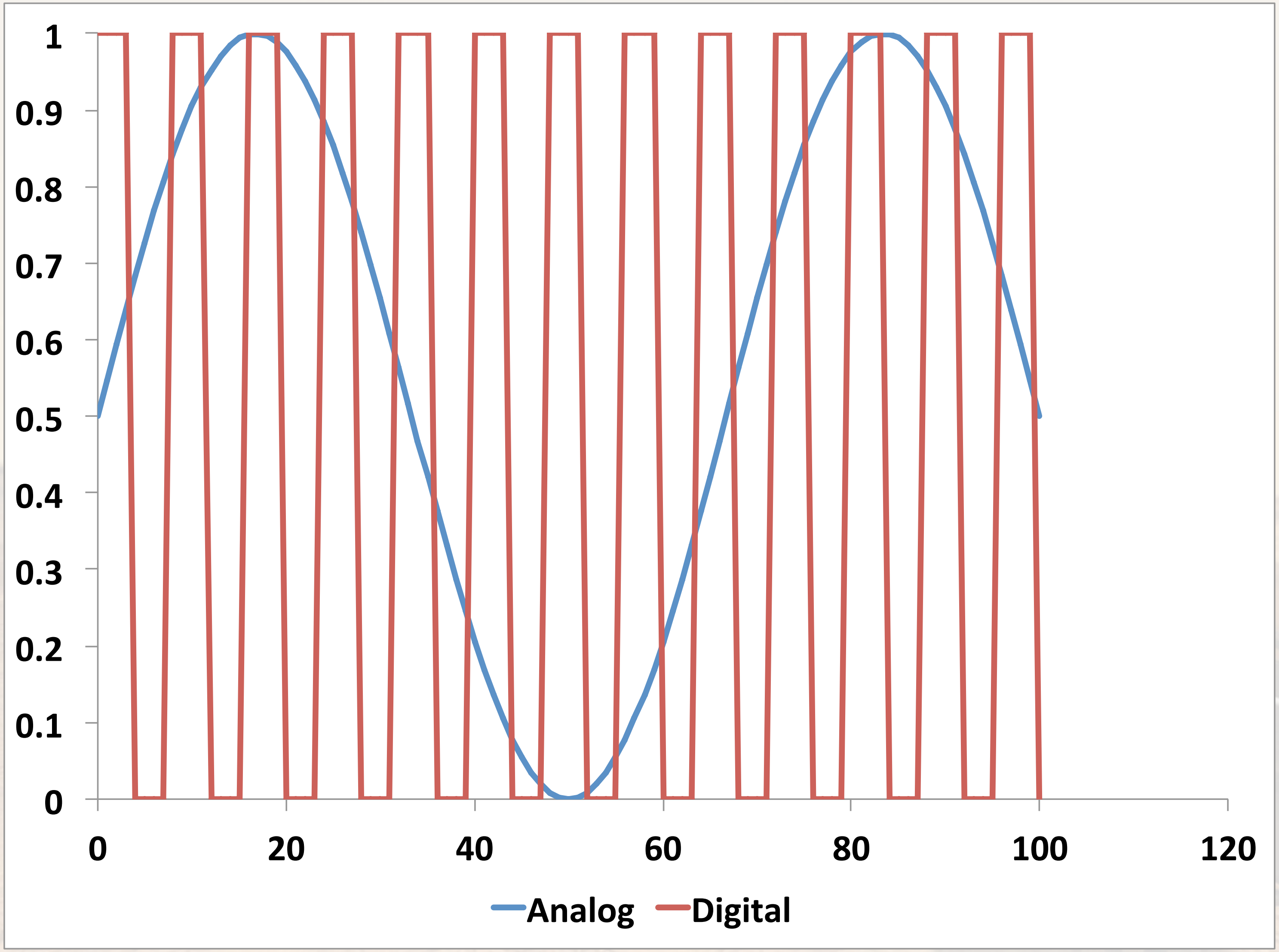
- Resolution
- Accuracy
- Precision/Repeatability



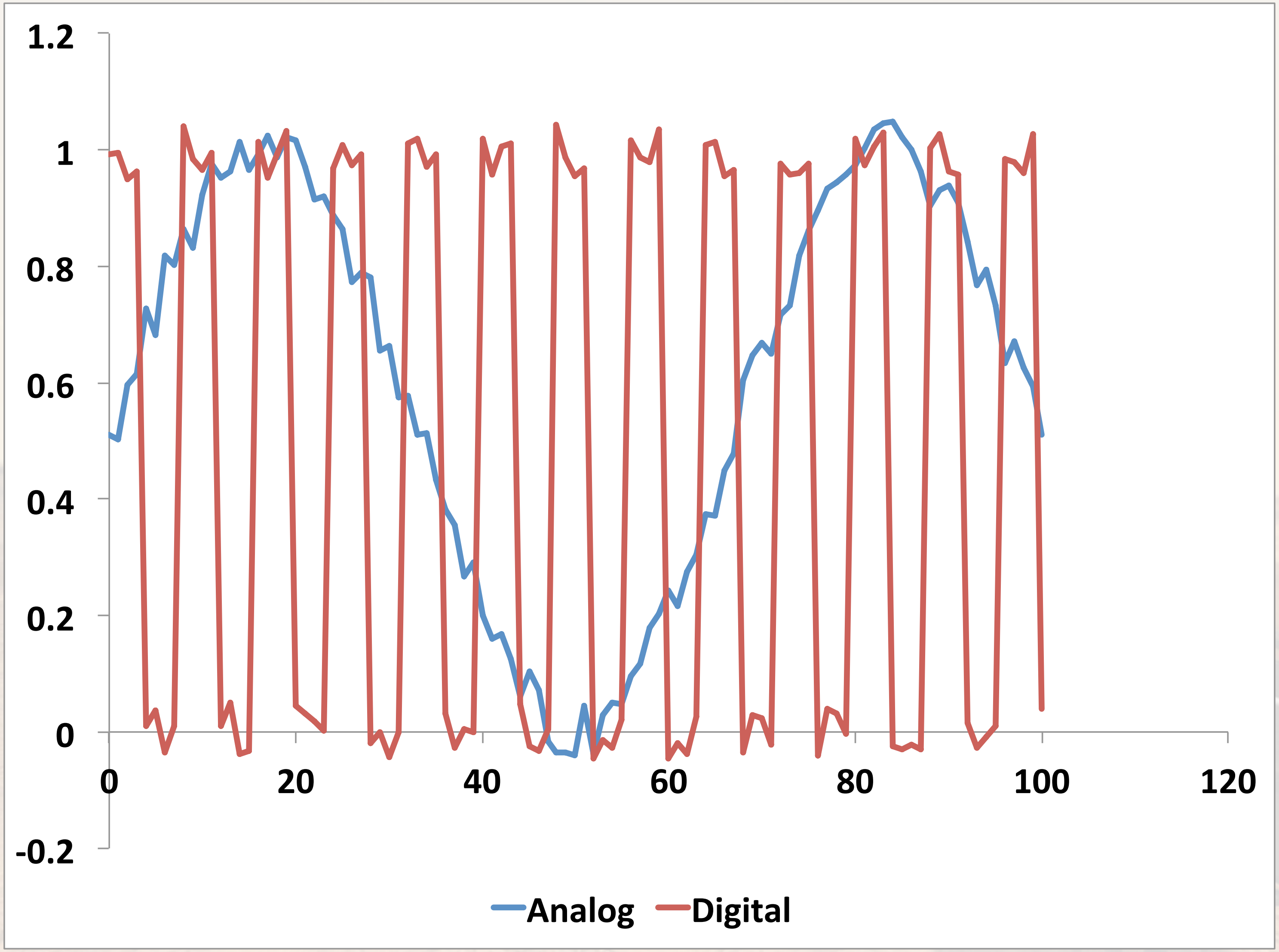
Some Notes on Data and Noise

- Noise is inherent in all data
  - Sampling errors
  - Sensor error
  - Interference and cross-talk
- For zero-mean noise,
  - Integration reduces noise
  - Differentiation increases noise
- Use the appropriate sensor for the measurement
  - Don't try to differentiate position for velocity, velocity for acceleration

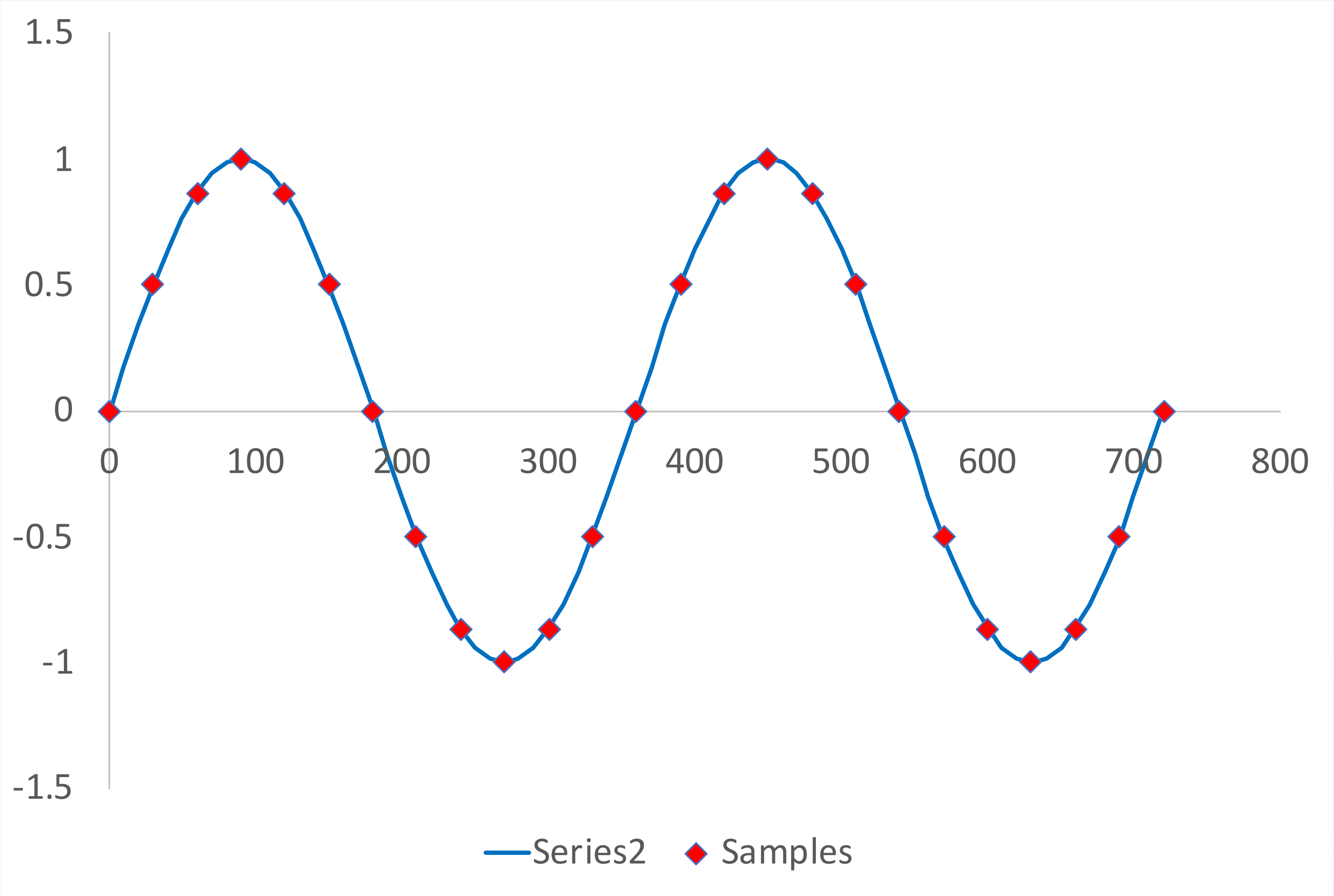
Analog and Digital Data



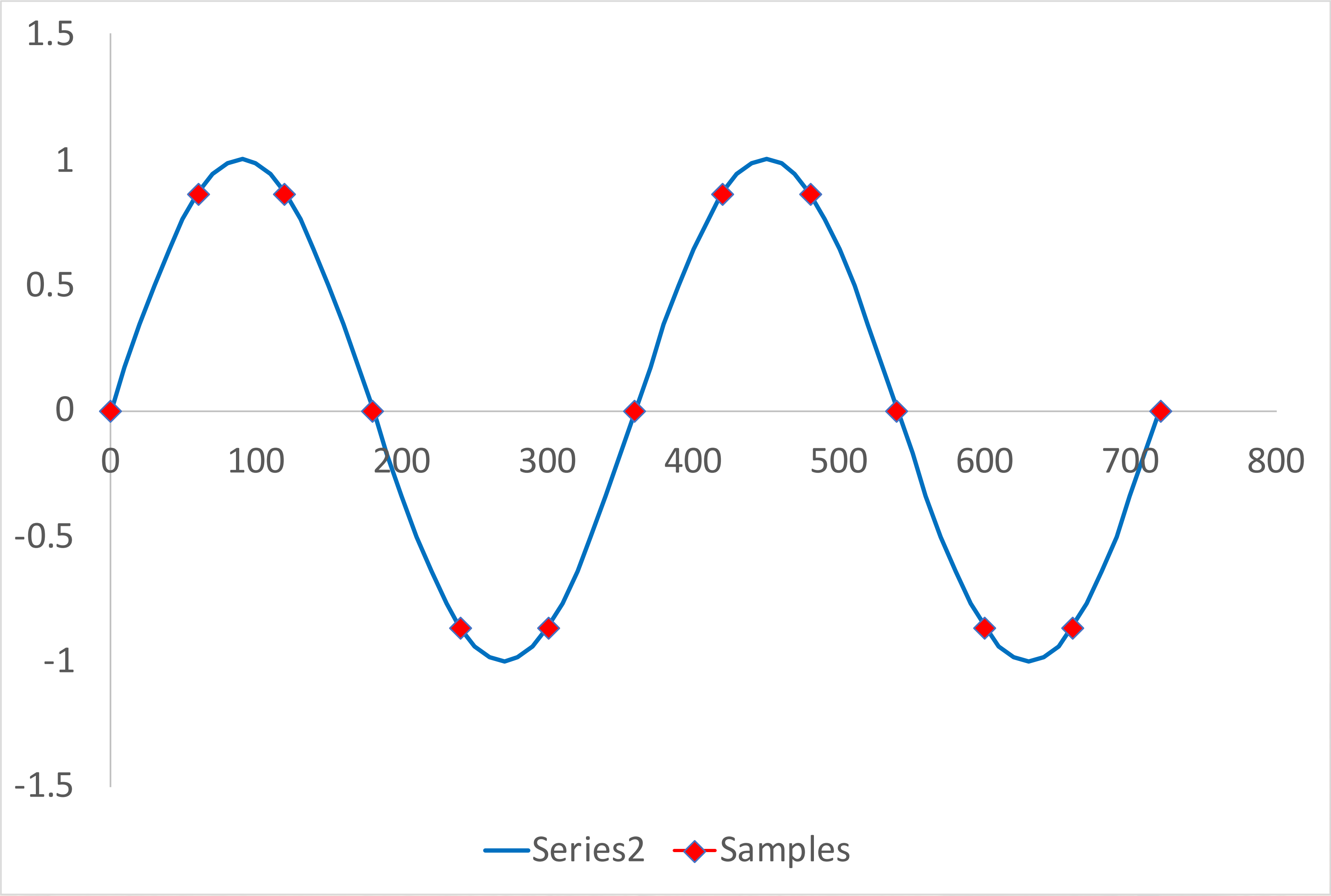
Analog and Digital Data with Noise



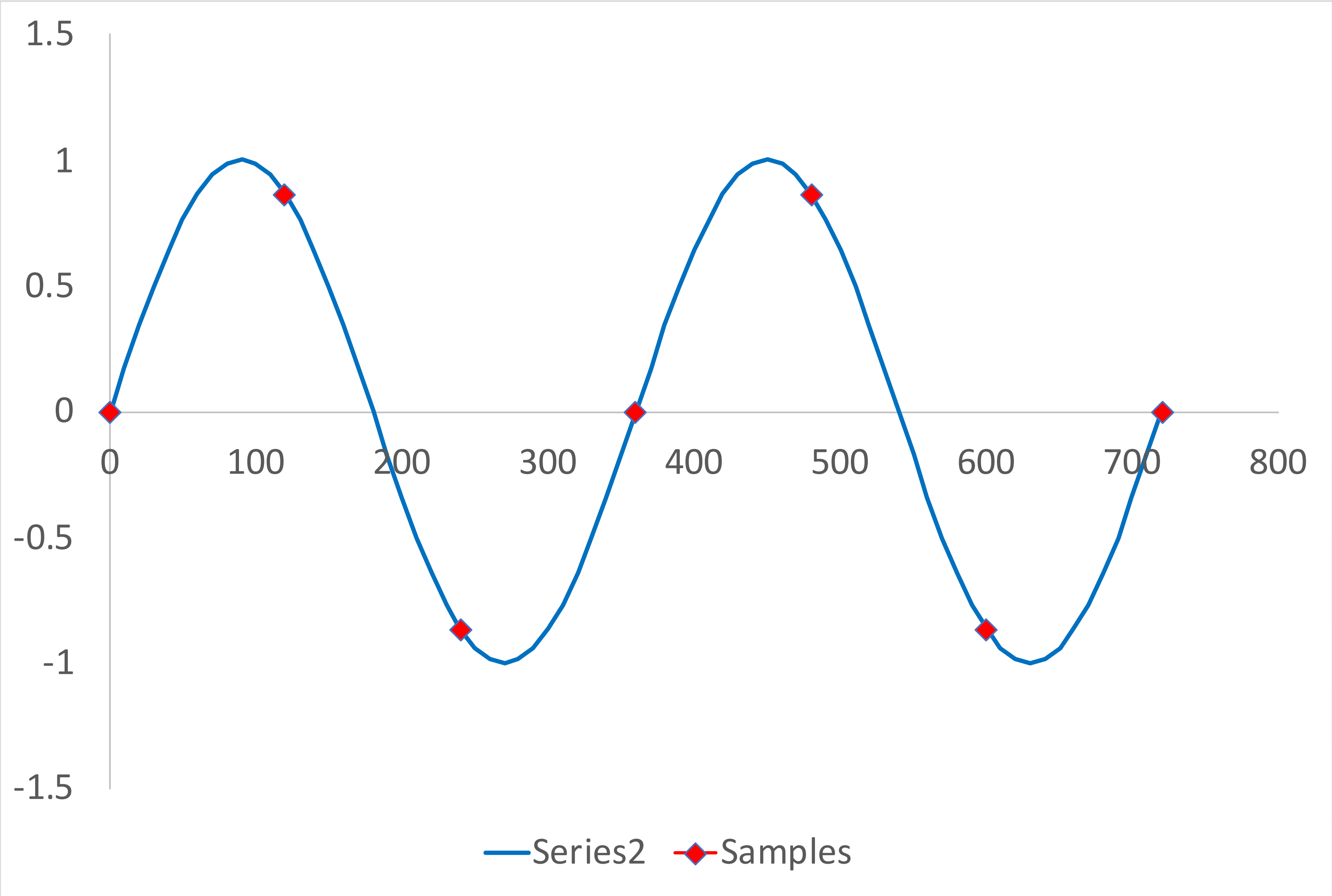
Sampling Every 30°



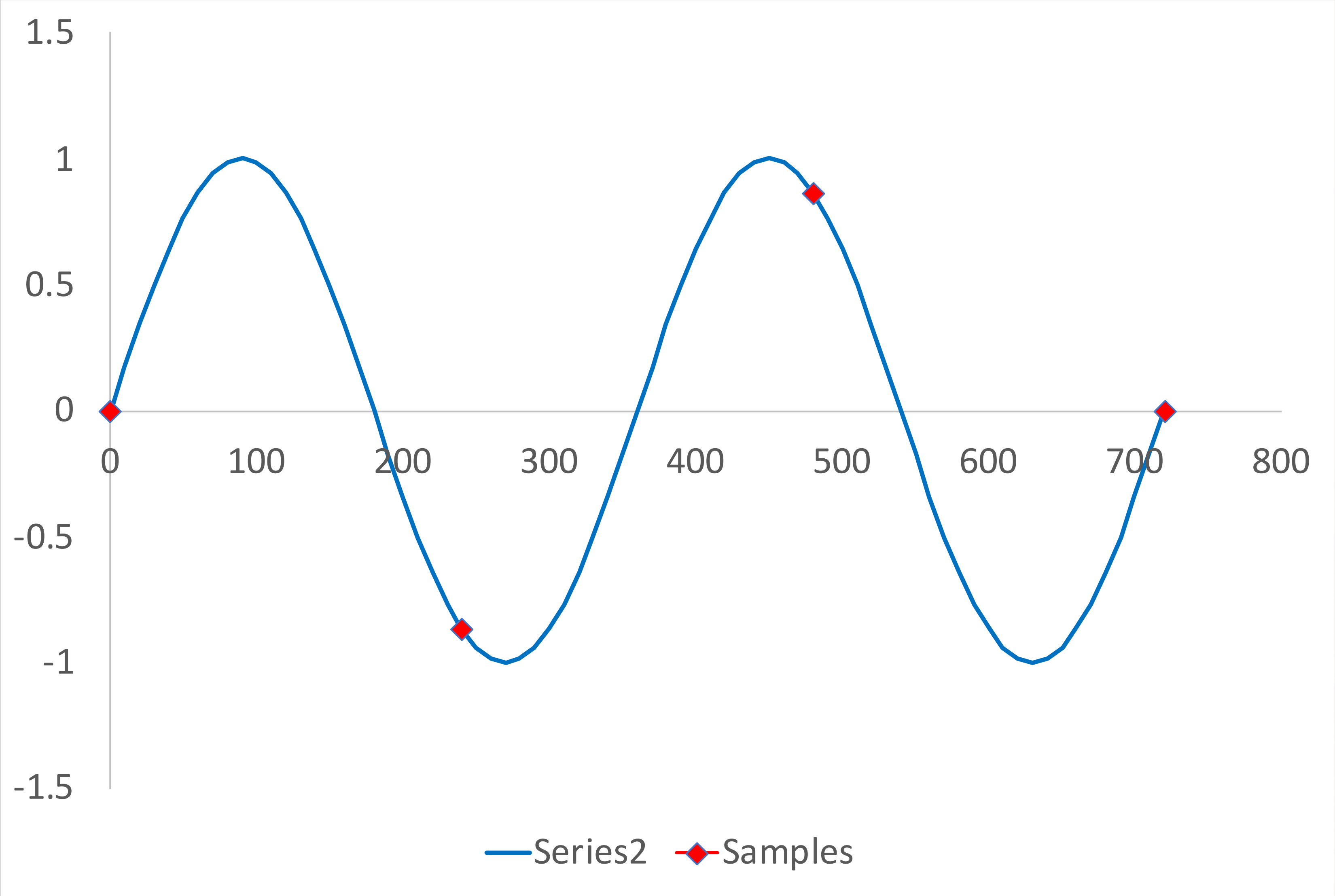
Sampling Every 60°



Sampling Every 120°



Sampling Every 240°



Shannon Sampling Limit

- For discrete measurements, can't reconstruct frequency greater than 1/2 the sampling rate
- Discretization error creates aliasing errors (frequencies that aren't really there)
  - Signal frequency f_{signal}
  - Sampling frequency f_{sample}
  - Alias frequencies $f_{\text{sample}} \pm f_{\text{signal}}$

Some Notes on Analog Sensors

- Analog sensors encode information in voltage (or sometimes current)
- Intrinsically can have infinite precision on signal measurement
- Practically limited by noise on line, precision of analog/digital encoder
- Differentiation between high level (signal variance~volts) and low level (signal variance~millivolts) sensors
- Advice: never do analog what you can do digitally

Proprioceptive Sensors

- Measure internal state of system in the environment
- Rotary position
- Linear position
- Velocity
- Accelerations
- Temperature

Proprioceptive Sensors

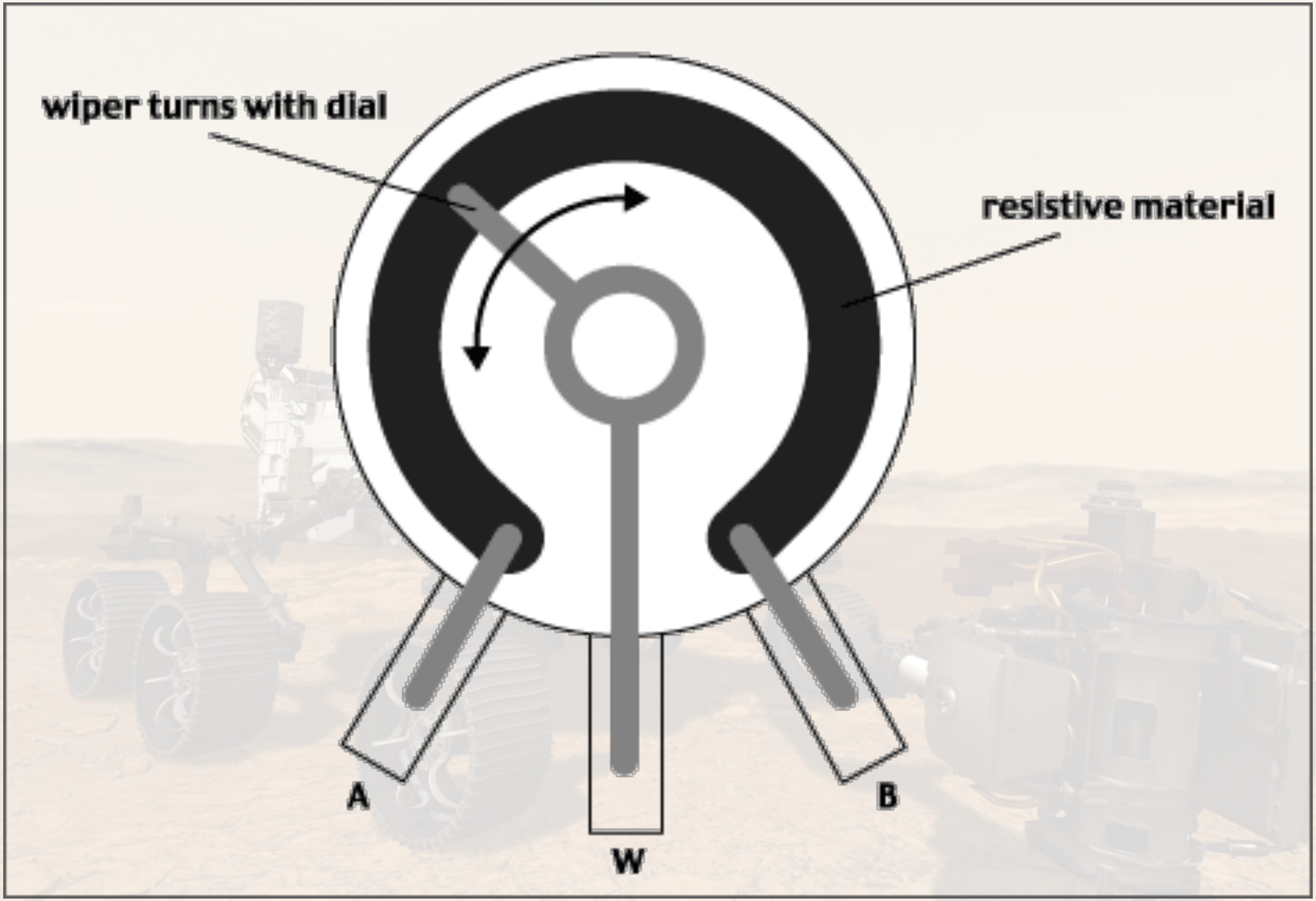
- Position and velocity (encoders, etc.)
- Location (GPS)
- Attitude
  - Inertial measurement units (IMU)
  - Accelerometers
  - Horizon sensors
- Force sensors

Representative Sensors

Absolute Encoders

- Measure absolute rotational position of shaft
- Should produce unambiguous position even immediately following power-up
- Rovers typically require continuous rotation sensors
- General rule of thumb: never do in analog what you can do digitally (due to noise, RF interference, cross-talk, etc.)

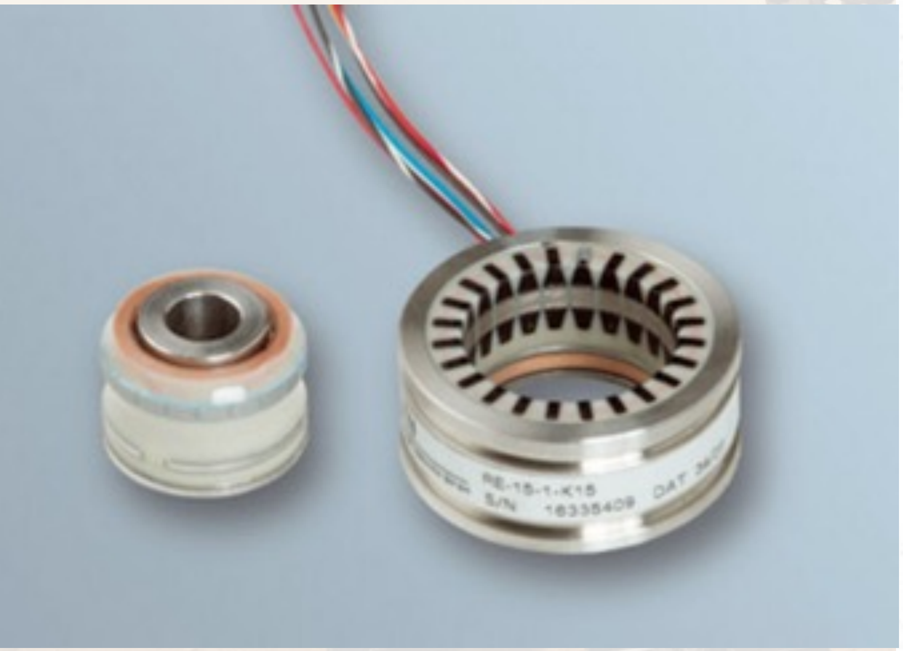
Potentiometers

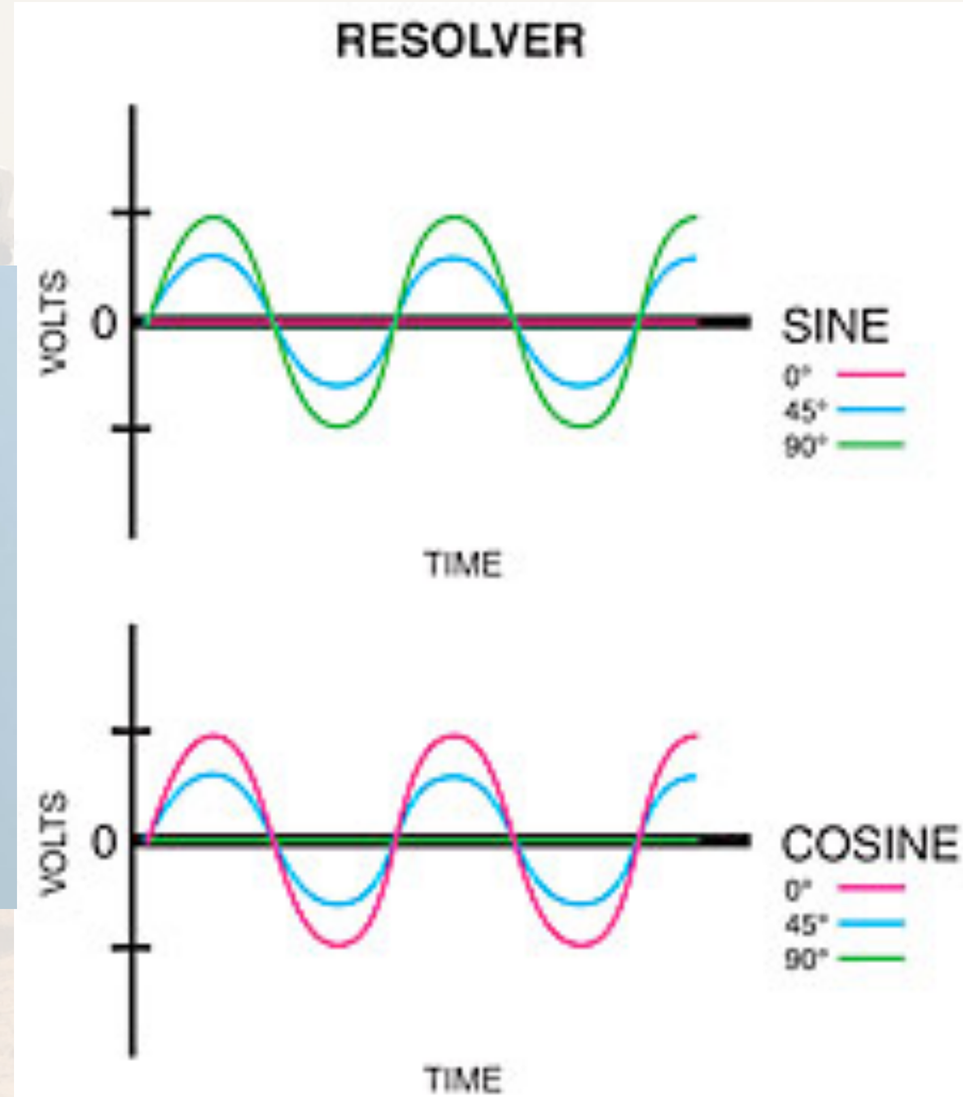


Potentiometers

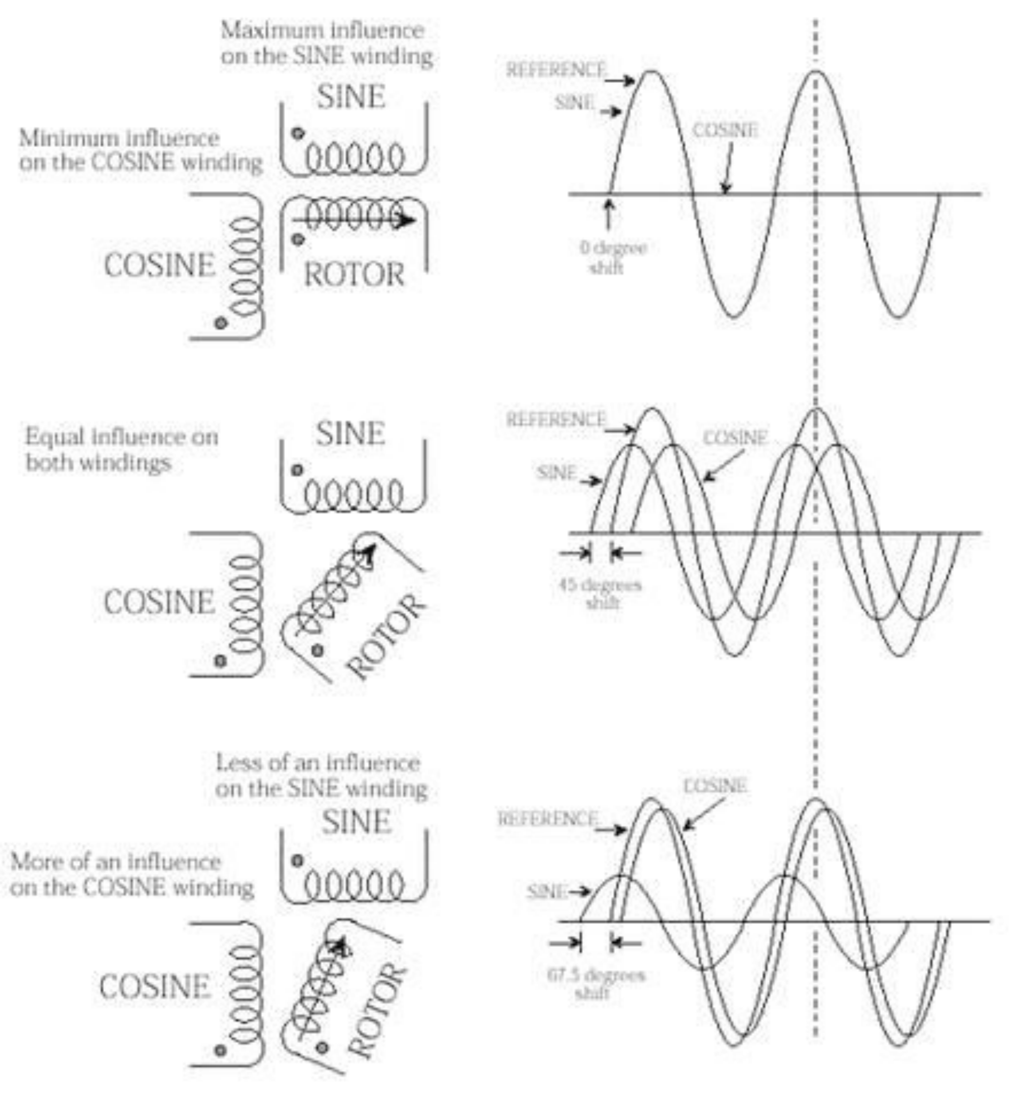
- Advantages
  - Very simple (three wires)
  - Unambiguous absolute position readout
  - Generally easy to integrate
  - Low cost
- Disadvantages
  - Analog signal
  - Data gap at transition every revolution
  - Accuracy limited to precision of resistive element
  - Wear on rotating contactor
  - Liable to contamination damage

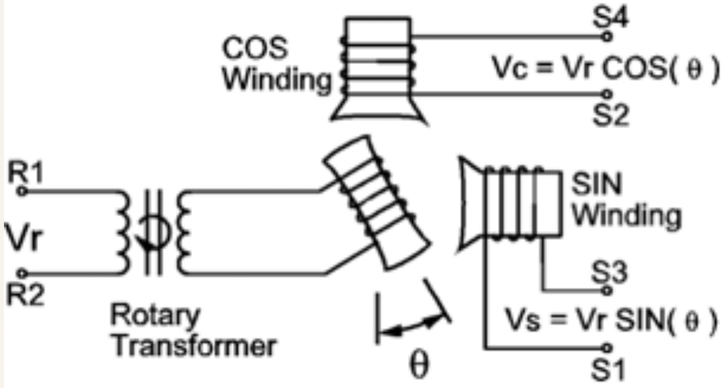
Resolvers

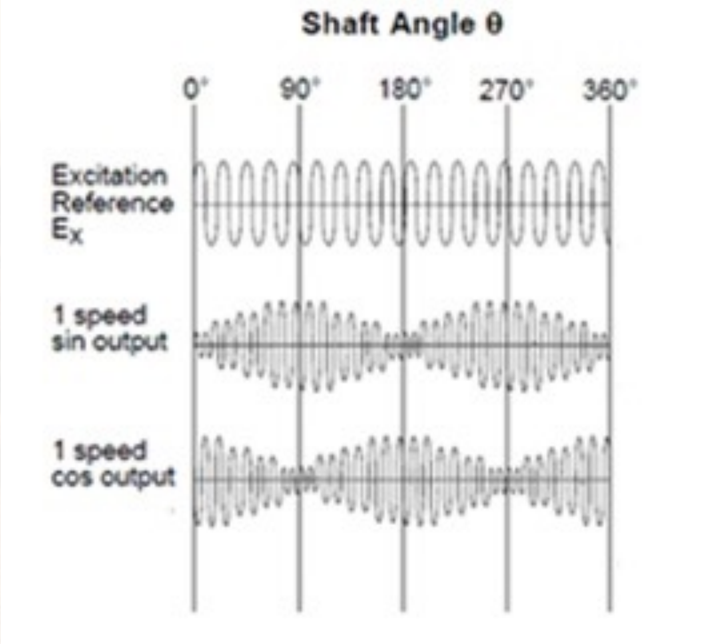




Resolvers


Maximum influence on the SINE winding
SINE
Minimum influence on the COSINE winding
COSINE
ROTOR
REFERENCE
SINE
COSINE
0 degree shift
Equal influence on both windings
SINE
COSINE
ROTOR
REFERENCE
SINE
COSINE
45 degrees shift
Less of an influence on the SINE winding
SINE
More of an influence on the COSINE winding
COSINE
ROTOR
COSINE
REFERENCE
SINE
67.5 degrees shift


COS Winding
S4
Vc = Vr COS(θ)
S2
R1
Vr
R2
Rotary Transformer
SIN Winding
S3
Vs = Vr SIN(θ)
S1
θ


Shaft Angle θ
0°
90°
180°
270°
360°
Excitation Reference Ex
1 speed sin output
1 speed cos output

Resolvers

- Advantages
  - Non-contact (inductively coupled)
  - Unambiguous absolute position reading
  - Similar technology to synchros
- Disadvantages
  - AC signal
  - Analog
  - Requires dedicated decoding circuitry
  - Expensive

Rotary Binary Encoder

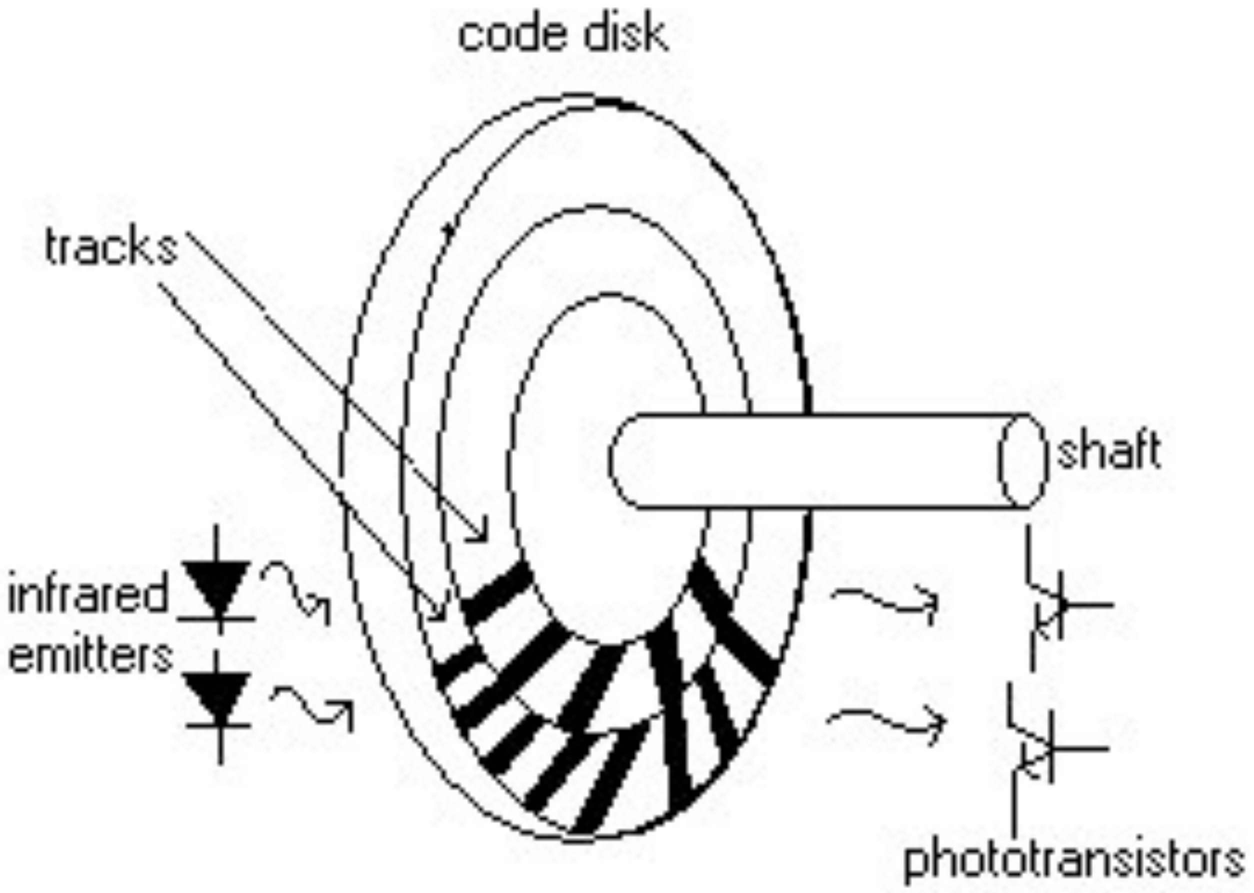


Fig 1. A rotary optical encoder

Binary Absolute Position Encoders

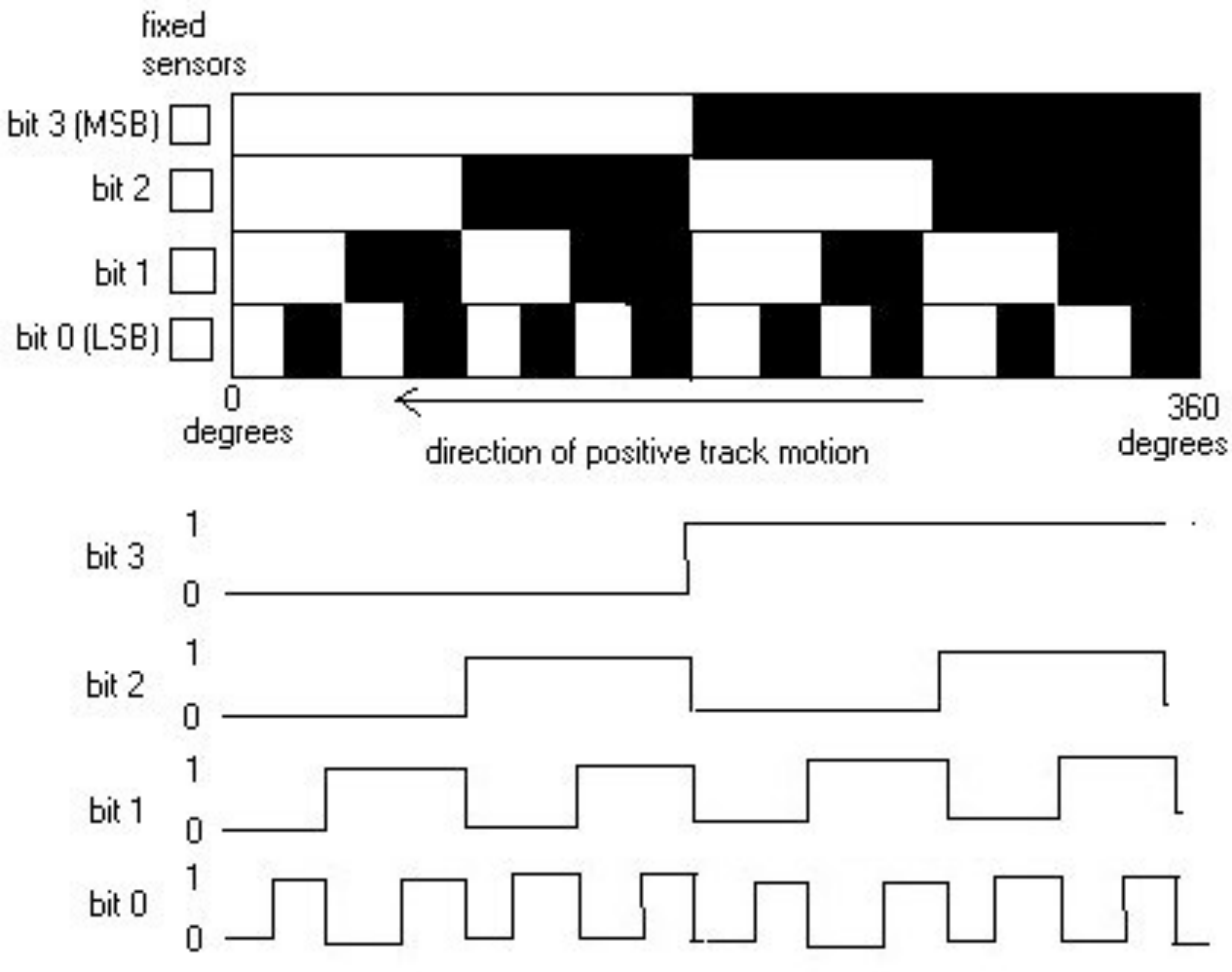


Fig 3 4-Bit binary code absolute encoder disk track patterns

Gray Code Absolute Position

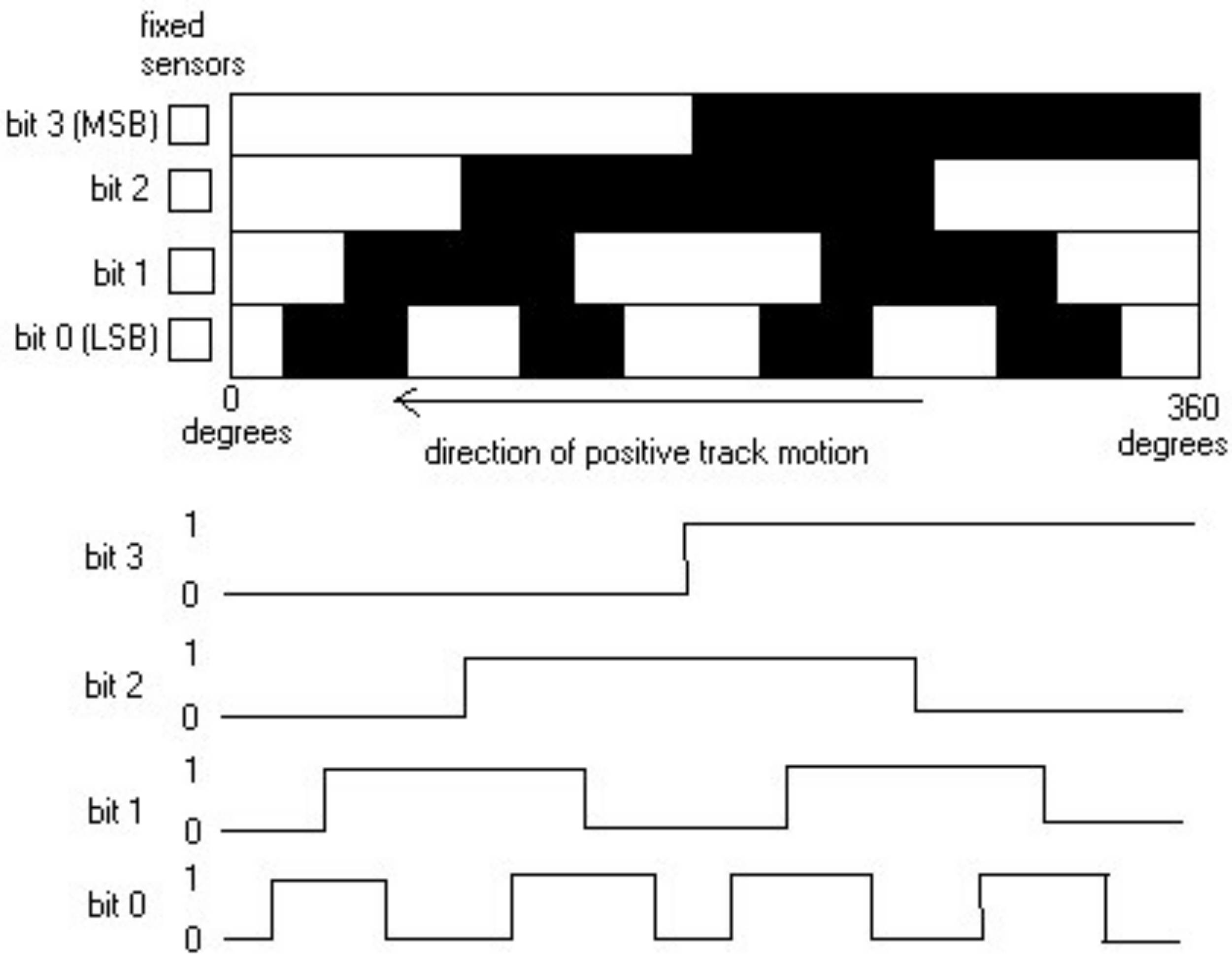


Fig 2. 4-Bit gray code absolute encoder disk track patterns

Absolute Encoder Gray Codes

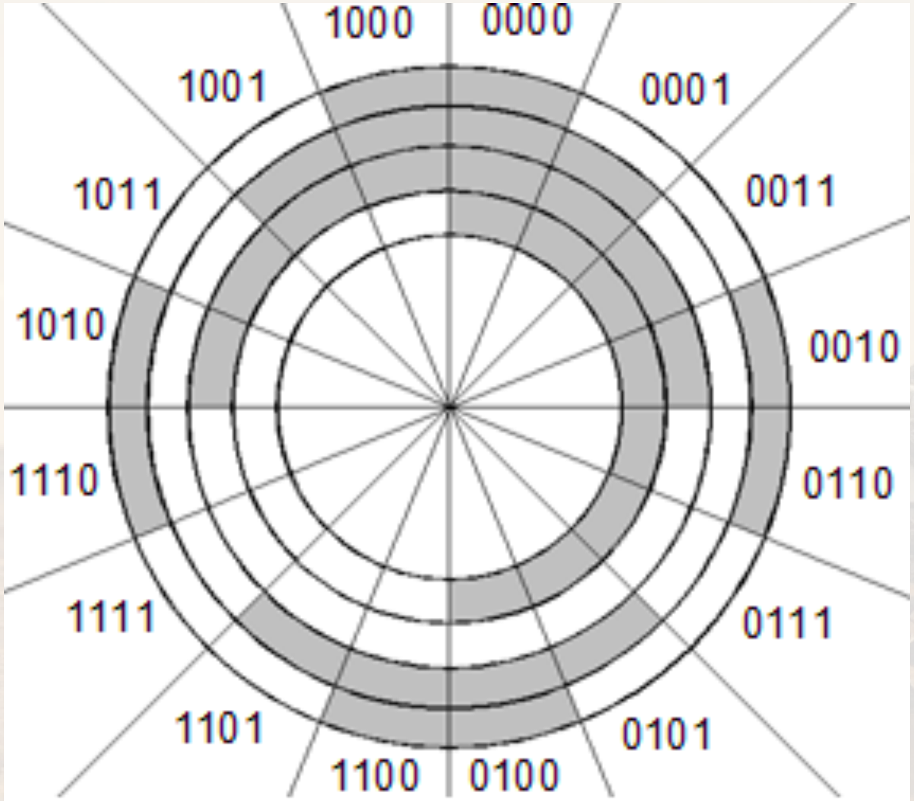
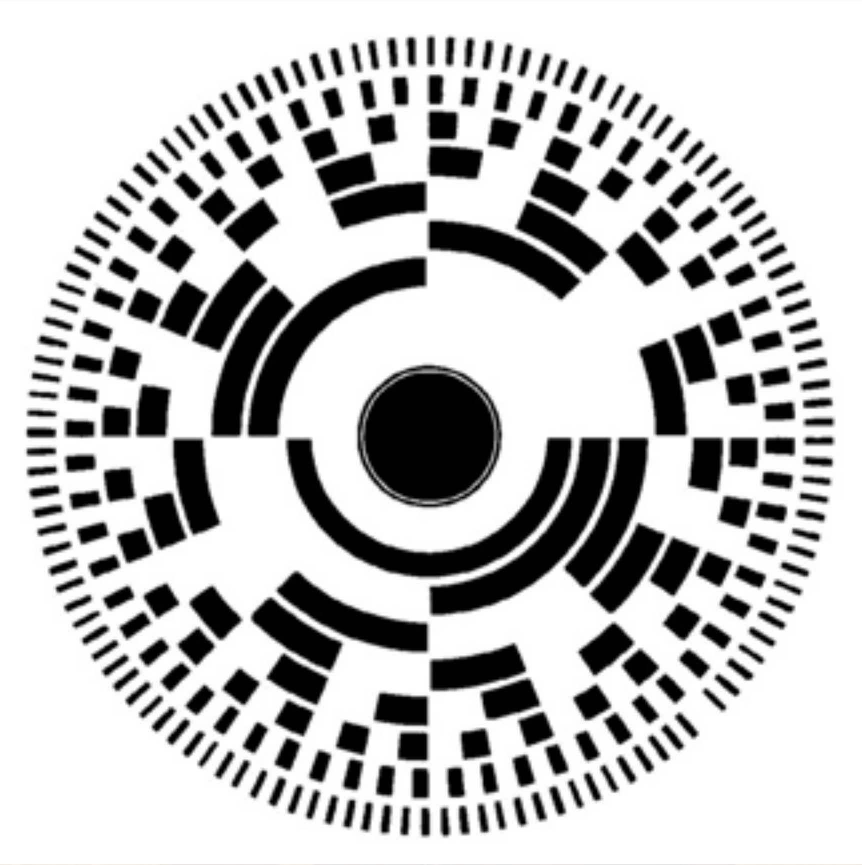


Fig. 1



Optical Absolute Encoders

- Advantages
  - No contact (low/no friction)
  - Absolute angular position to limits of resolution
    - 8 bit = 256 positions/rev = 1.4° resolution
    - 16 bit = 65,536 positions = 0.0055° resolution
- Require decoding (look-up table) of Gray codes
- Number of wires ~ number of bits plus two

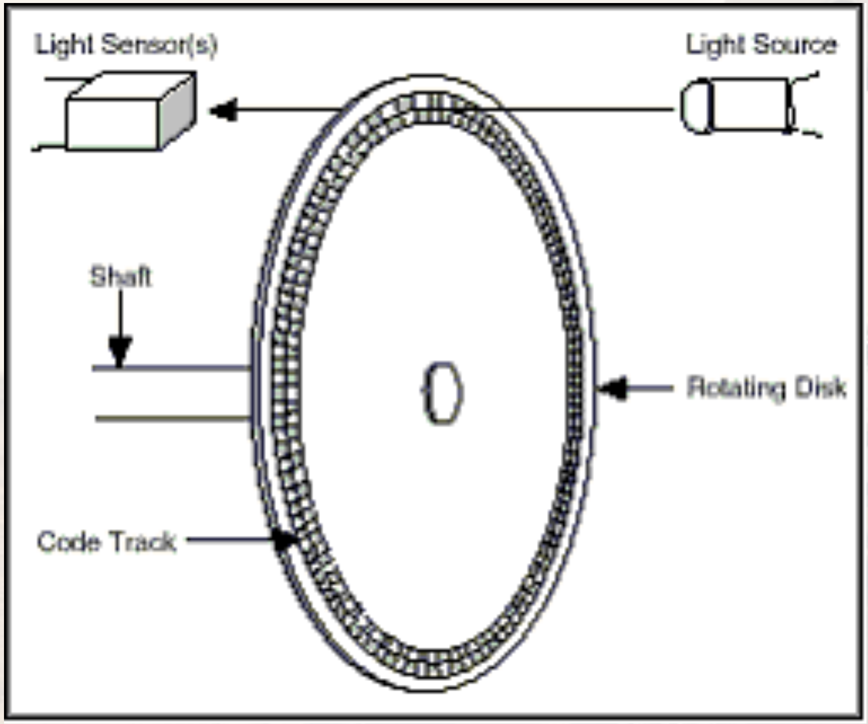
Magnetic Absolute Encoders

- Advantages
  - No contact (low/no friction)
  - Absolute angular position to limits of resolution
    - 8 bit = 256 positions/rev = 1.4° resolution
    - 16 bit = 65,536 positions = 0.0055° resolution
  - Robust to launch loads
- Require decoding (frequently on chip)
- Choice of output reading formats (analog, serial, parallel)

Incremental Encoders

- Measure change in position, not position directly
- Have to be integrated to produce position
- Require absolute reference (index pulse) to calibrate
- Can be used to calculate velocities
- Generally optical or magnetic (no contact)

Incremental Encoder Principles



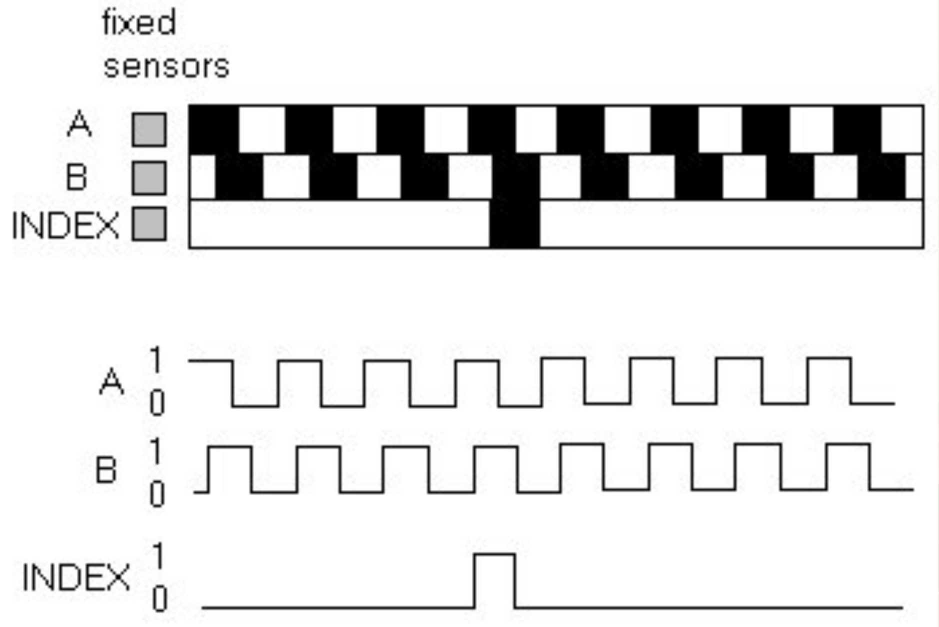


Fig 5. Incremental encoder disk track patterns

Quadrature Incremental Encoder

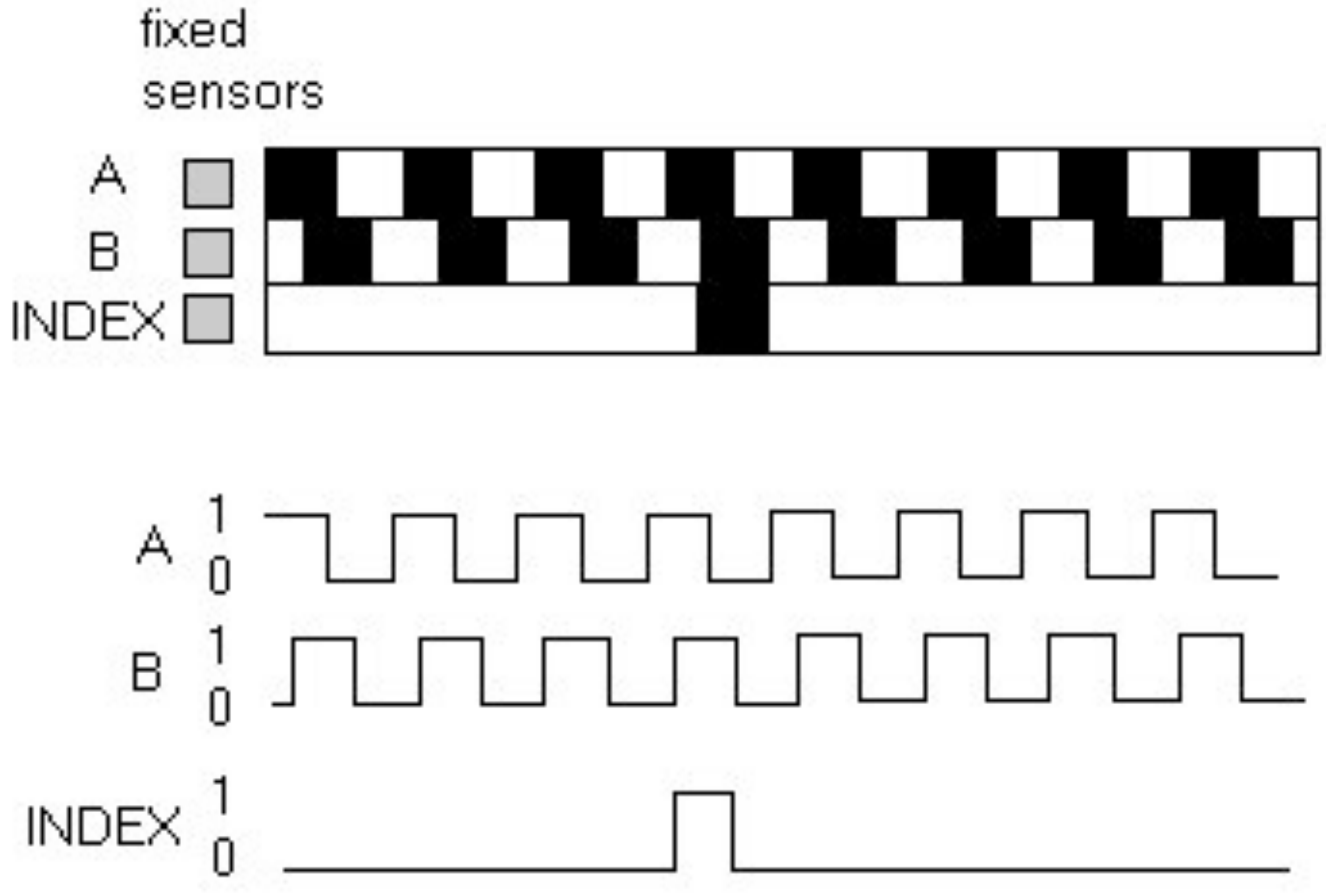


Fig 5. Incremental encoder disk track patterns

Incremental Encoder Interpretation

- Position
  - Count up/down based on quadrature (finite state machine)
  - Resolution based on location, gearing, speed
    - 256 pulse encoder (1024 with quadrature)
    - Output side – 0.35 deg
    - Input side 160:1 gearing – 0.0022 deg = 7.9 arcsec
- Velocity
  - Pulses/time period
    - High precision for large number of pulses (high speed)
    - 90 deg/sec, input side – 41 pulses/msec (2.5% error)
  - Time/counts
    - High precision for long time between pulses (low speed)
    - 1 deg/sec, output side – 350 msec/pulse

Velocity Measurement

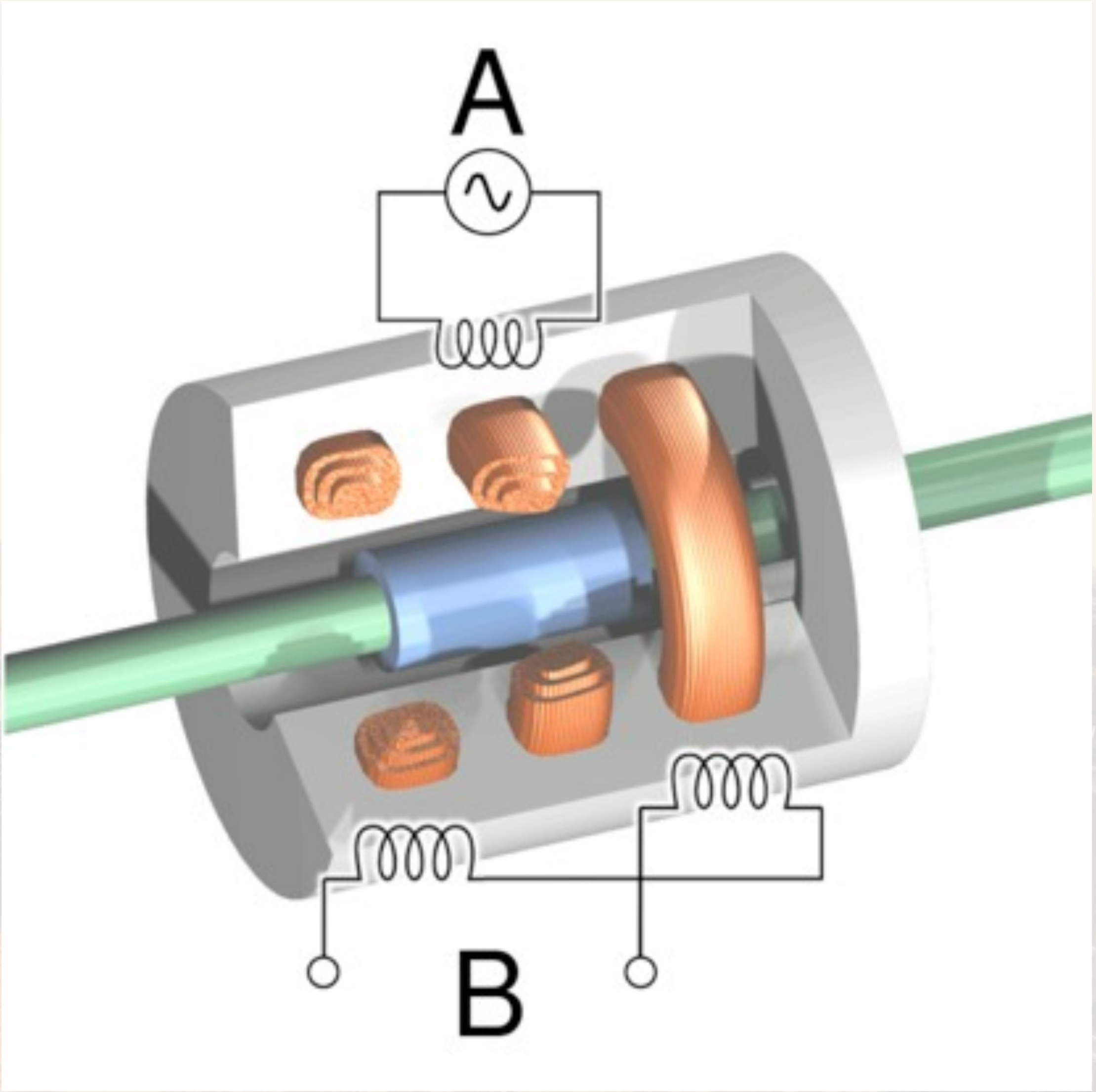
- Number of bits/unit time
  - High precision for rapid rotation
  - Low resolution at slow rotation
  - For n bit encoder reading k bits/interval

$$\omega = \frac{k}{2^n} \frac{2\pi}{\Delta t_{CLK}} \langle \frac{rad}{sec} \rangle$$

- Amount of time between encoder bits
  - High precision for rapid rotation
  - Low resolution for slow rotation

$$\omega = \frac{1}{2^n} \frac{2\pi}{\Delta t_{pulses}} \langle \frac{rad}{sec} \rangle$$

Linear Variable Displacement



Exterioceptive Sensors

- Measure parameters external to system
- Pressure
- Forces and torques
- Vision
- Proximity
- Active ranging
  - Radar
  - Sonar
  - Lidar

Exteroceptive Sensors

- Vision sensors
  - Monocular
  - Stereo/multiple cameras
  - Structured lighting
- Ranging systems
  - Laser line scanners
  - LIDAR
  - Flash LIDAR
  - RADAR
  - SONAR

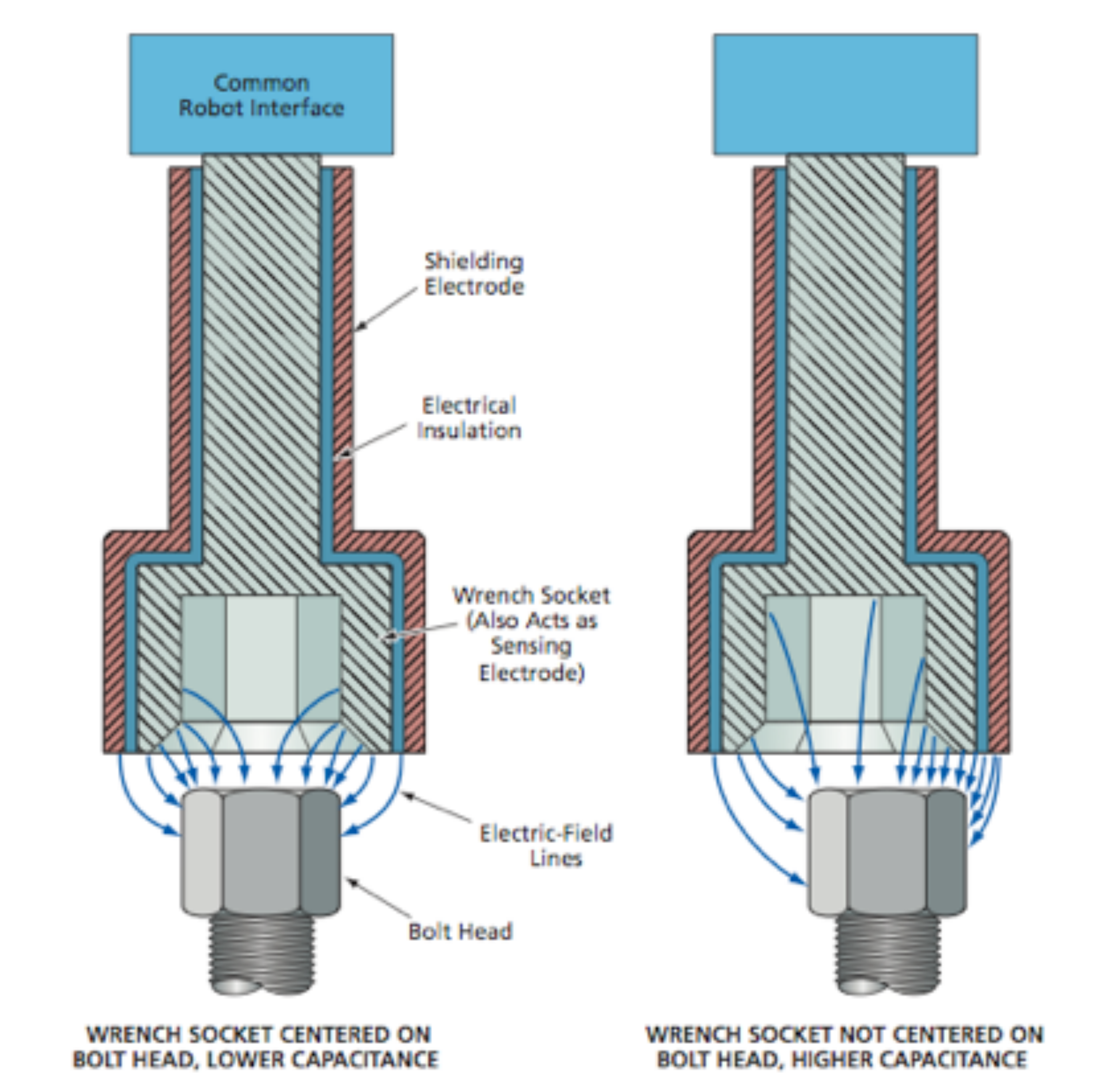
Switches

- Used to indicate immediate proximity, contact
  - End of travel/hard stops
  - Contact with environment
- Technologies
  - Mechanical switches
  - Reed (magnetic) switches
  - Hall effect sensors

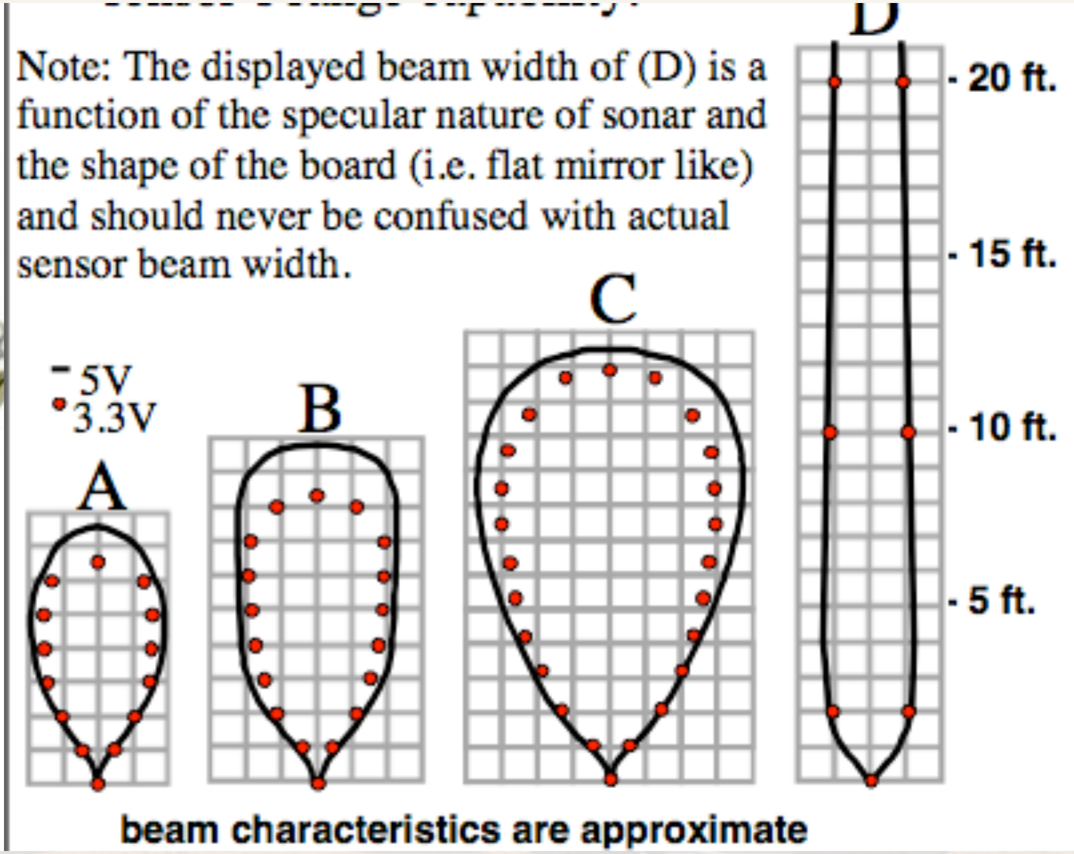
Proximity Sensors

- Technologies
  - Magnetic sensors
  - Phototransistor / LED
  - Capaciflector
  - Whiskers

Capaciflector

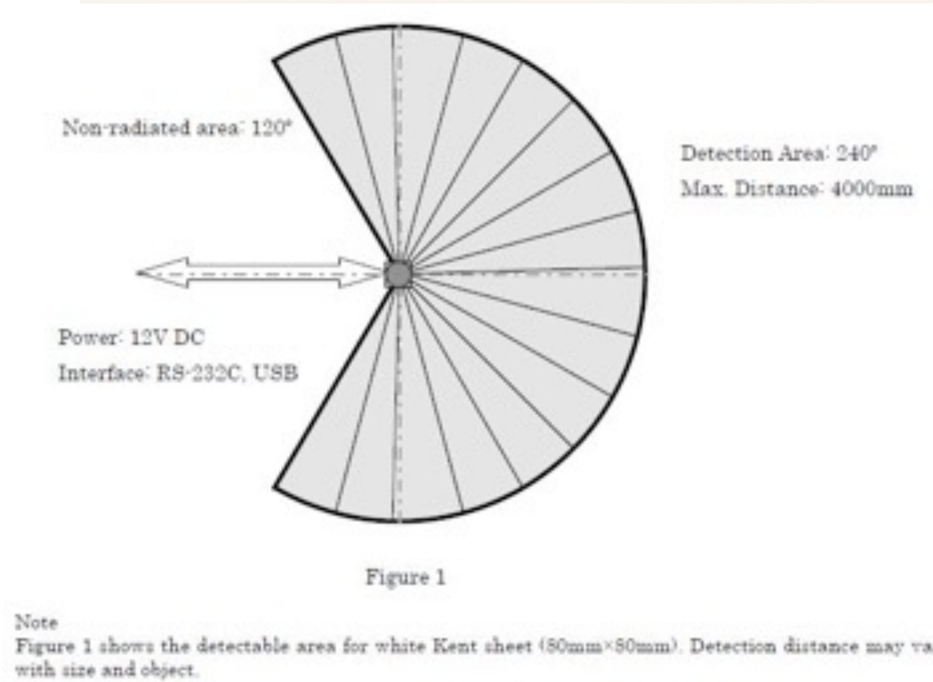


Sonar Rangefinder Systems

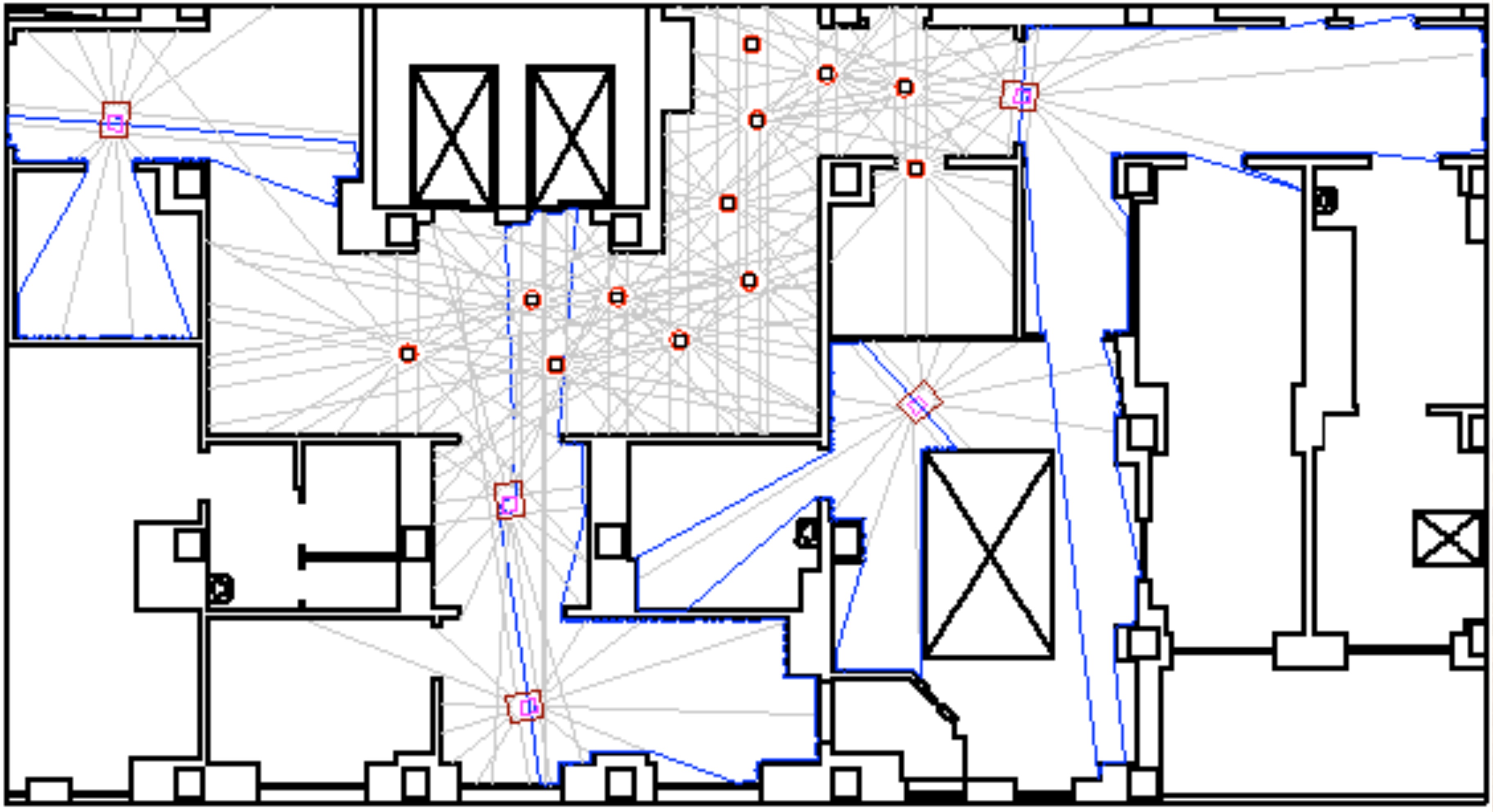


Computer Vision Cameras

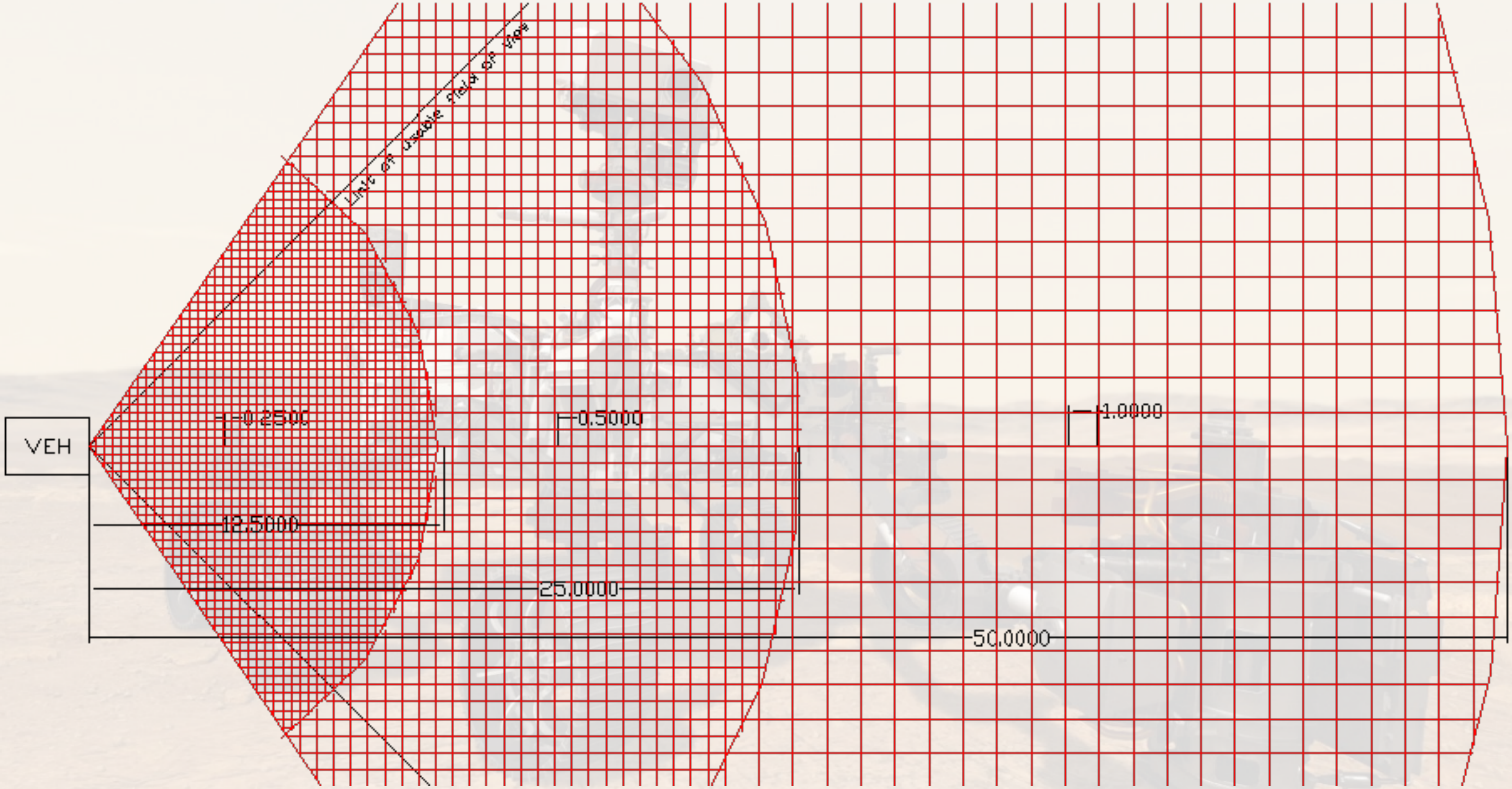
Scanning Laser Rangefinder



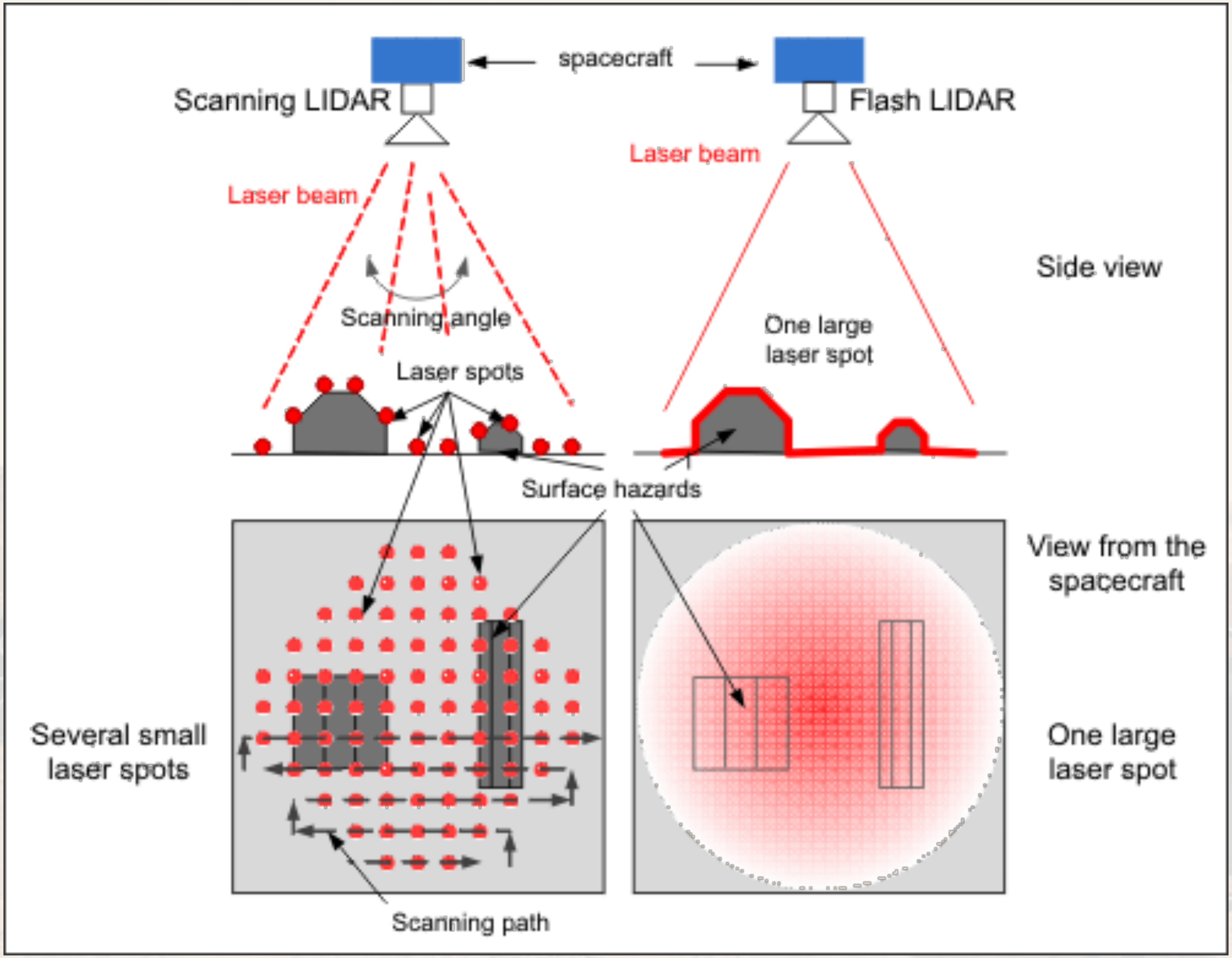
Line Scanner Area Map



Scanning Laser Rangerfinder FOV

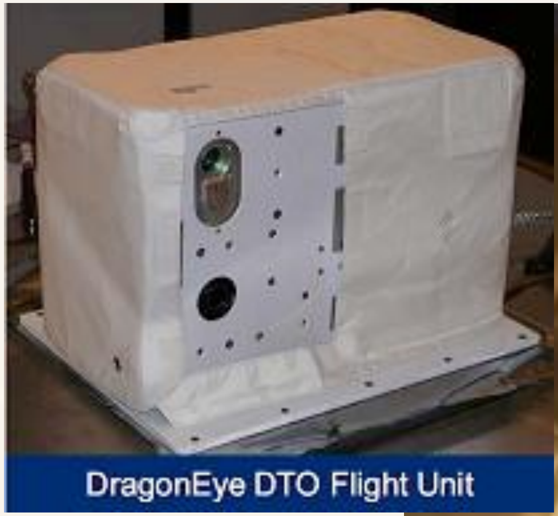


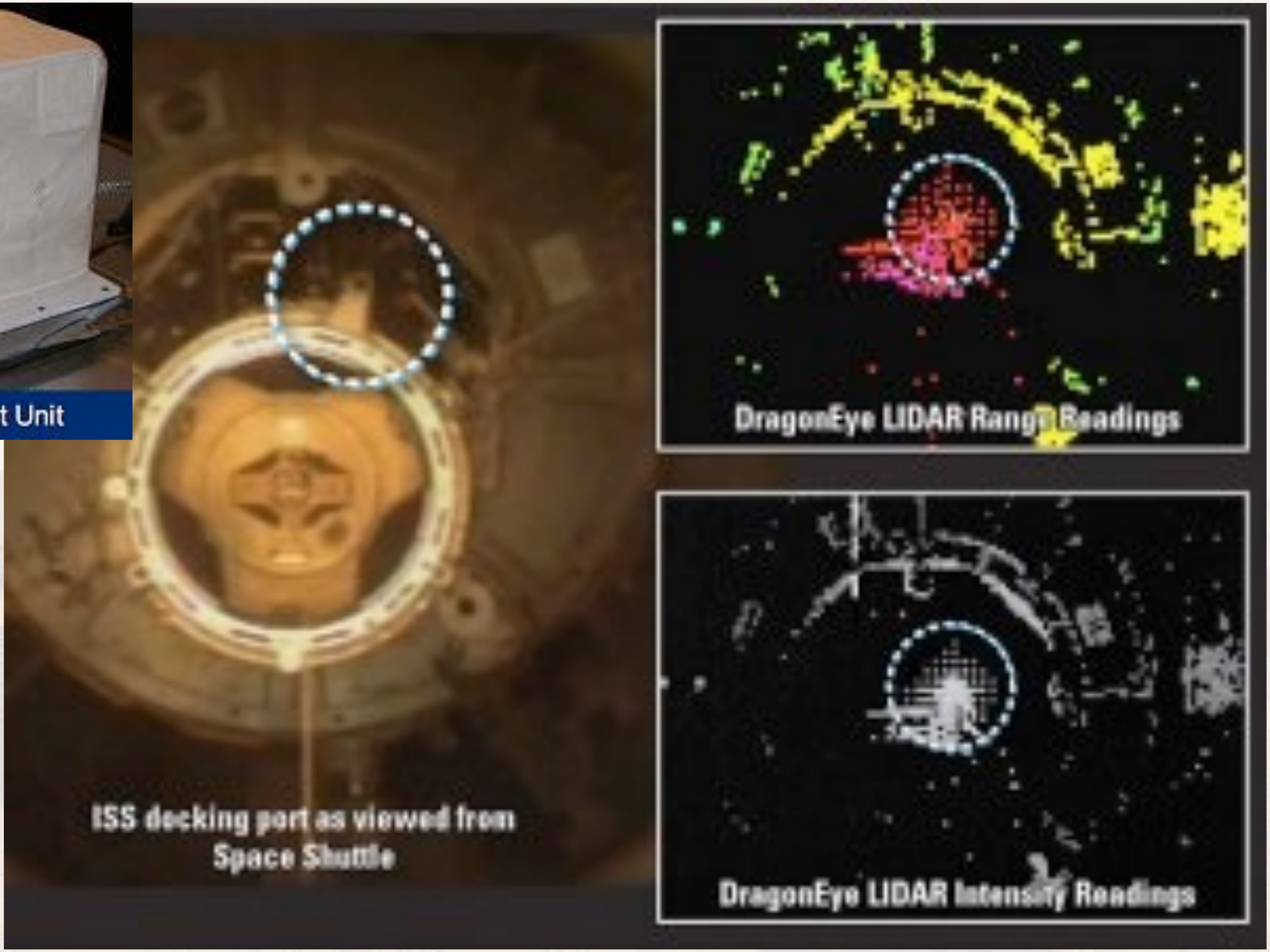
LIDAR Types



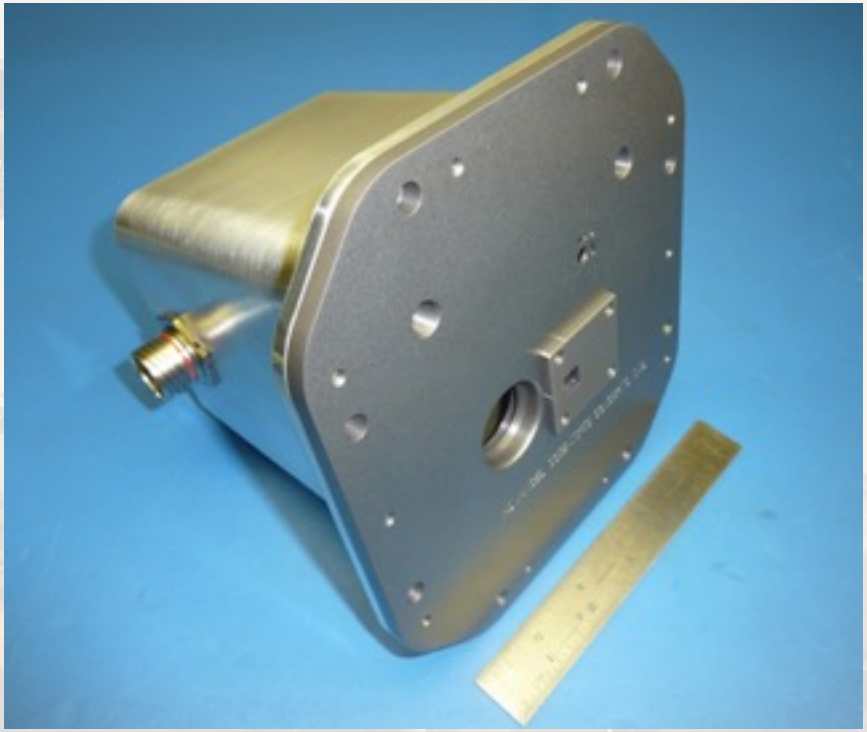
spacecraft
Scanning LIDAR
Flash LIDAR
Laser beam
Laser beam
Side view
Scanning angle
One large
laser spot
Laser spots
Surface hazards
View from the
spacecraft
Several small
laser spots
One large
laser spot
Scanning path

SpaceX DragonEye Flash LIDAR





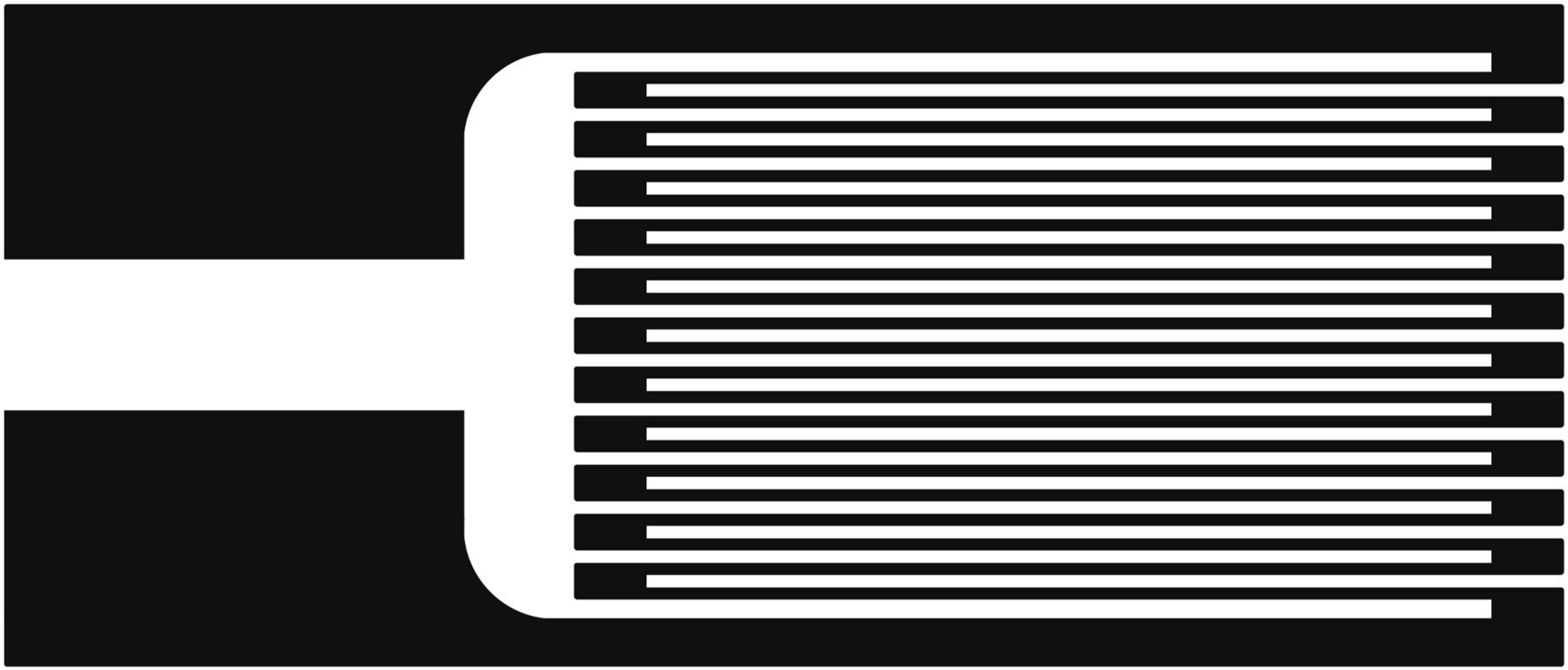
Flash LiDAR



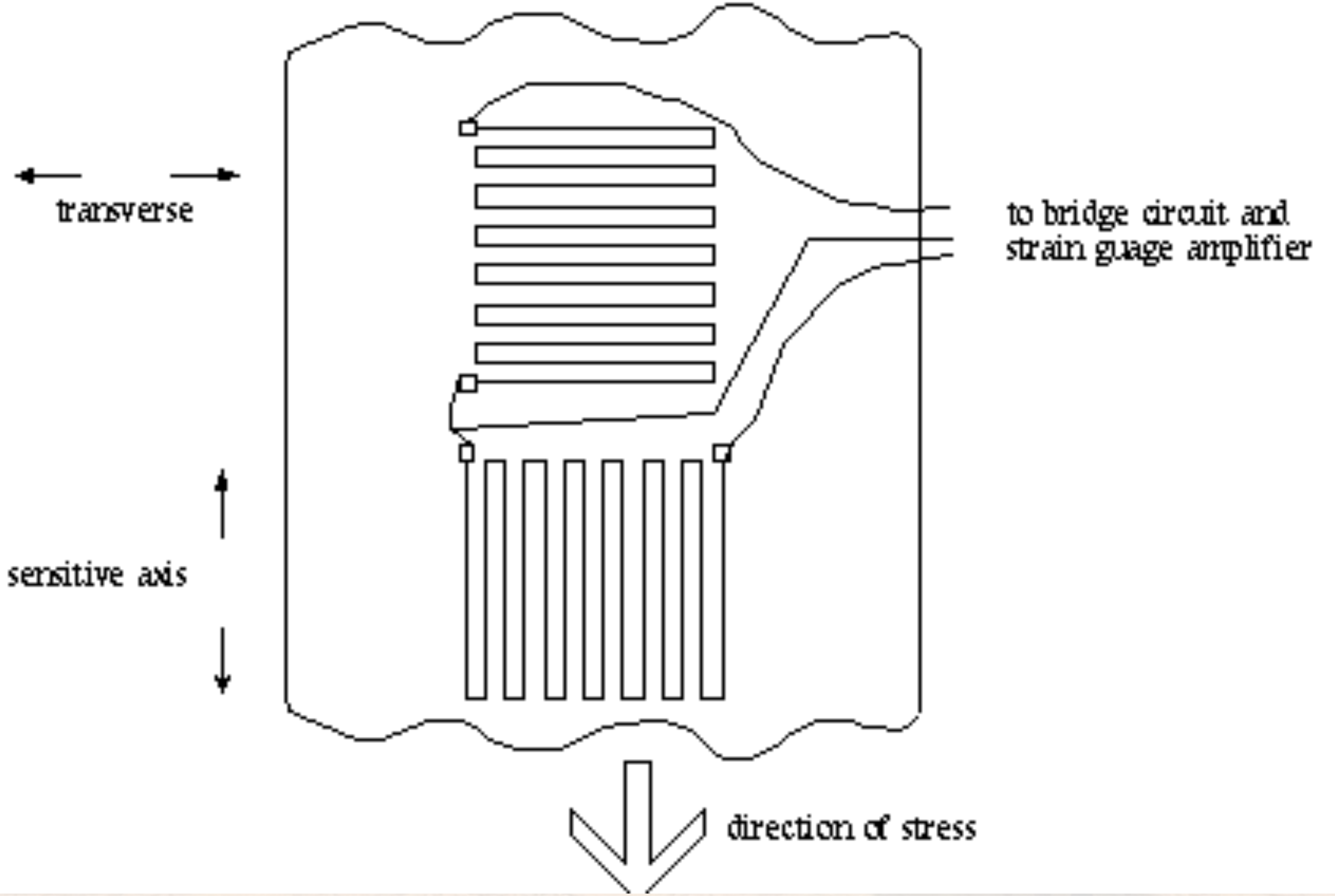
Interoceptive Sensors

- Electrical (voltage, current)
- Temperature
- Battery charge state
- Stress/strain (strain gauges)
- Sound

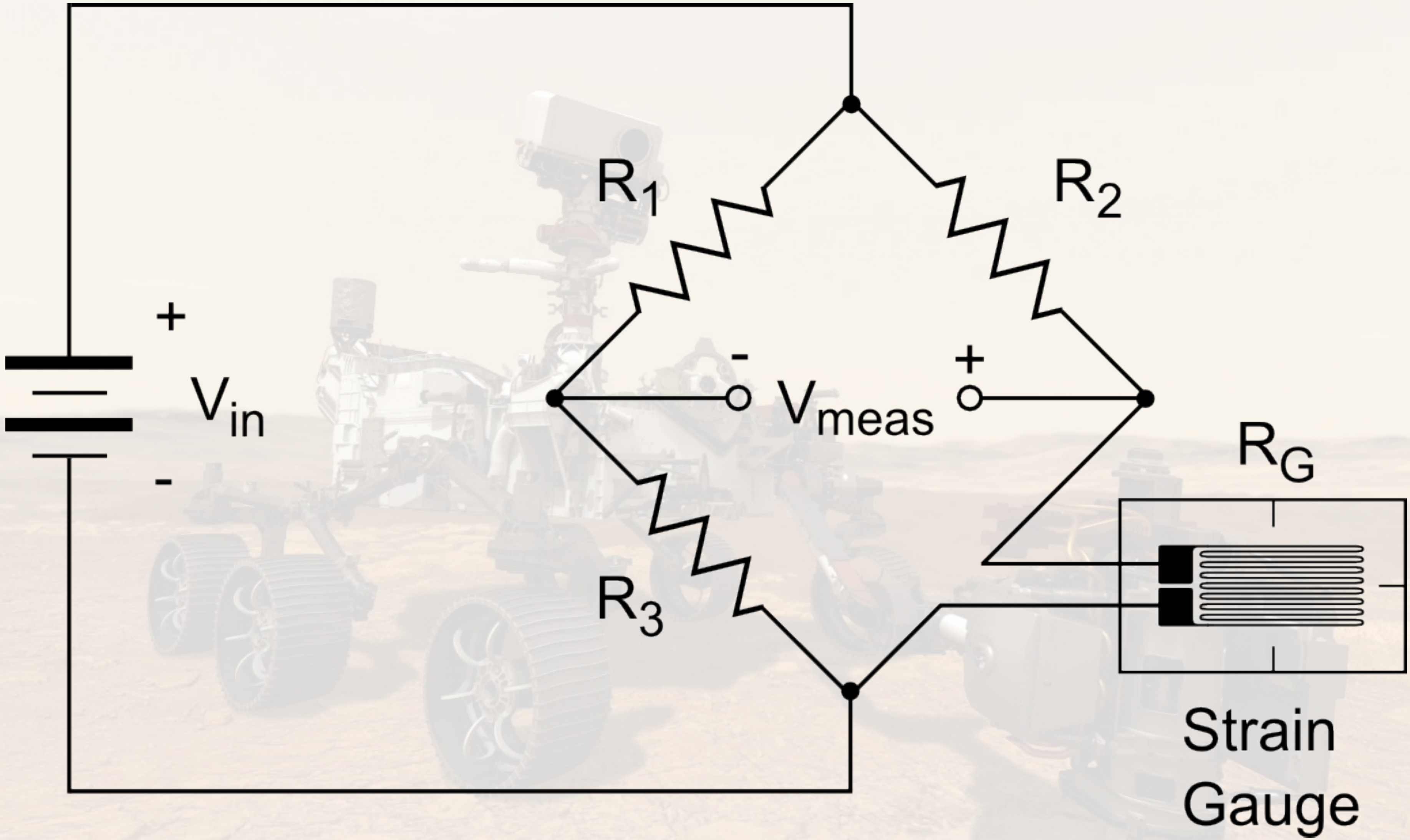
Strain Gauges



Strain Gauge with “Dummy” Gauge



Wheatstone Bridge



Temperature Sensors

- Contact
  - Thermistors
  - Resistant Temperature Detectors (RTDs)
  - Thermocouples
- Non-contact
  - Infrared
  - Thermal generators (thermopiles)

Sensor Guidelines for Flight Systems

- Instrument every flight-critical activity
- Provide sufficient sensor redundancy to differentiate between sensor failure and system failure
  - Redundant sensors
  - Reinforcing sensors
- Interrogate sensors well beyond Shannon's limit (cannot reconstruct data without at least two samples/cycle)