# Robotic Sensors

- Discussion of Term Projects
- Sensors
  - Proprioceptive
  - Exteroceptive
  - Interoceptive

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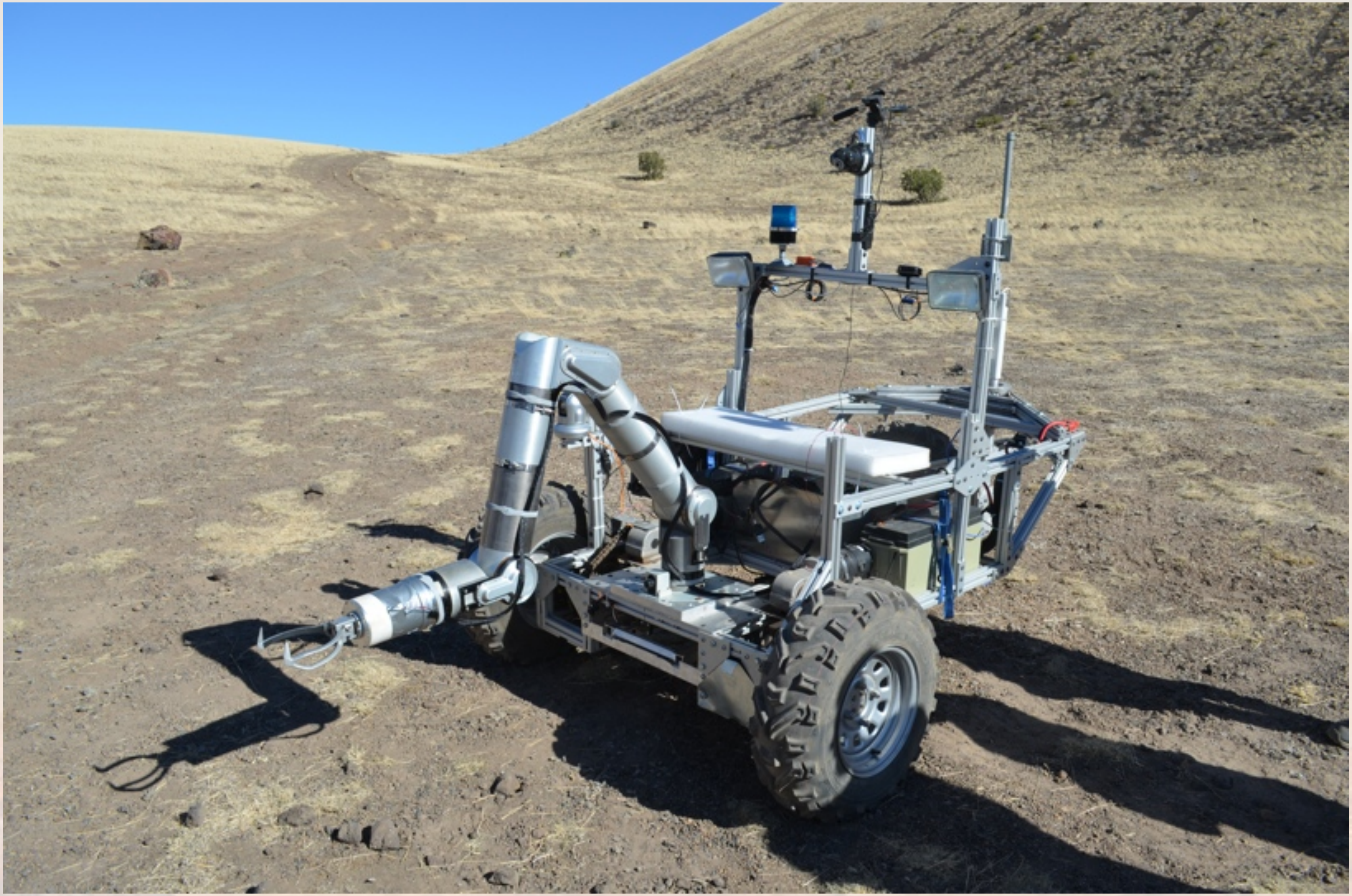
# Term Design Projects

- Astronaut assistance rover
- Sample collection rover
- Minimum pressurized exploration rover
- Others by special request

# AAR Design Project Statement

- Perform a detailed design of a small astronaut assistance rover, emphasizing mobility systems
  - Chassis systems (e.g., wheels, steering, suspension...)
  - Navigation and guidance system (e.g., sensors, algorithms...)
- Design for Moon, then assess feasibility of systems for Mars, and conversion to Earth analogue rover
- This is not a hardware project - focus is on detailed design (but may be built later!)

# RAVEN in Telerobotic Sample Config



# RAVEN in EVA Transport Config

# Level 1 Requirements (Performance)

1. Rover shall have a maximum operating speed of at least 15 km/hour on level, flat terrain
2. Rover shall be designed to accommodate a 0.3 meter obstacle at minimal velocity
3. Rover shall be designed to accommodate a 0.1 m obstacle at a velocity of 7.5 km/hour
4. Rover shall be designed to accommodate a 30° slope in any direction at a speed of at least 5 km/hour with positive static and dynamic margins

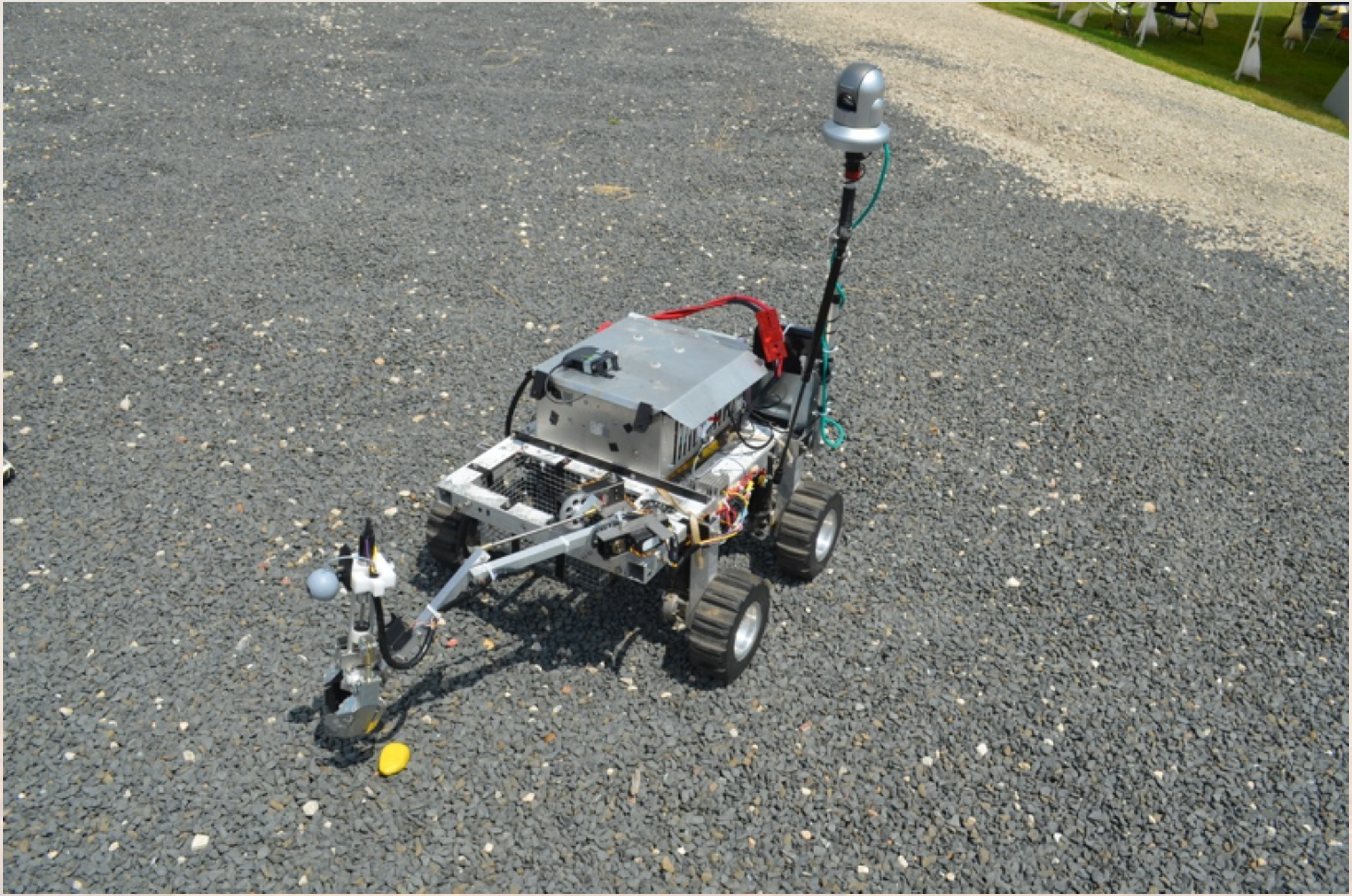
# Level 1 Requirements (Payload)

5. Rover shall be be designed for an instrument payload with a mass of 50 kg and volume of 0.25 $m^3$
6. Rover shall also accommodate a Ranger-classs sample-collection manipulator system with a mass of 50kg
7. Rover shall be designed to nominally transport a 95th percentile American male crew in full pressure suit
8. Rover shall be capable of carrying two 95th percentile crew in a contingency

# RoboOps Design Project Statement

- Design a small remotely operated rover to participate in the 2015 RoboOps competition
- Rover must be capable of rapid and highly robust maneuverability in all terrains at the JSC Rockyard
- Design will be implemented by a group of undergrads in the spring (although you can help, too, if you want!)

# RHEA – RoboOps 2012



# RoboOps Requirements

- Rovers must fit within a 1x1x0.5 meter volume to start and deploy to operational configuration
- Rover must be <45 kg; tactical advantages go to lighter rovers
- Rovers must operate without local interaction for one hour
- Rovers must be controlled via cell networks from participating university’s campus
- Rovers collect colored rocks to score points

# RoboOps Mobility Requirements

- Vehicle payload (exclusive of mobility system) will be 10 kg
- Vehicle shall be capable of at least 1 m/sec travel up 20° slope
- Vehicle shall have positive static (stationary) stability margins on 40° slope in any orientation
- Vehicle shall be capable of traversing 20cm obstacles
- Vehicle shall be capable of robust operation in loose sand, small gravel, and packed earth

# LWPR Design Project Statement

- Design a mobility chassis for a minimum pressurized rover for lunar exploration
- Design for the moon, and do design modifications for implementation on Earth
- Goal is to keep complete rover below 2000 kg

# NASA Space Exploration Vehicle

# TURTLE Interior

# LWPR Requirements

- Pressurized cabin (payload) is 2m in diameter x 2.5 m long, mass of 1200 kg
- Vehicle shall be designed for moon and assessed for operations on Mars and Earth
- Vehicle shall have positive static (stationary) margins at 35° slopes in any orientation
- Vehicle shall be capable of unrestricted operations on 20° slope
- Vehicle shall have a minimum max speed of 15 km/hr on flat terrain

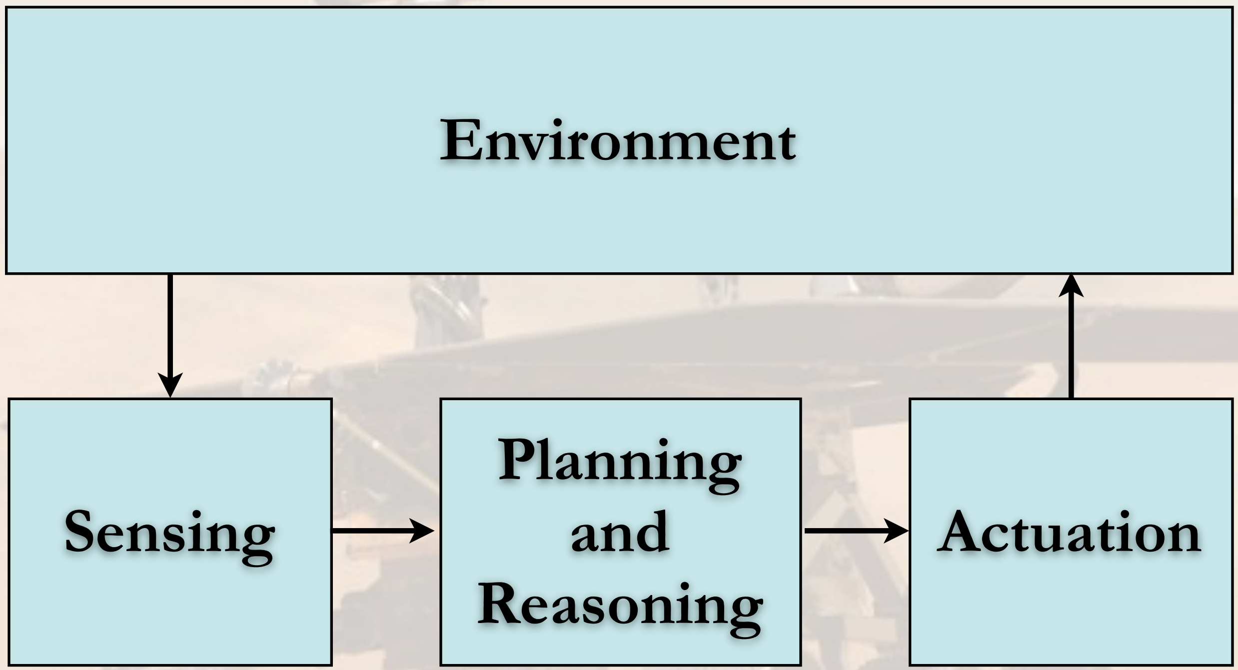
# LWPR Requirements

- Vehicle shall be capable of traversing a 50cm obstacle
- Vehicle shall be capable of operating reliably on loose sand

# Suggested Content for all Term Projects

- Terramechanics analysis
- Wheel configuration (number, shape) trade studies
- Steering approach and analysis
- Static stability
- Suspension dynamics
- Actuator specification (torque, speed)
- Calculation of power requirements
- Overall configuration graphics
- Opportunities for individual initiatives

# Fundamental Elements of Robotics

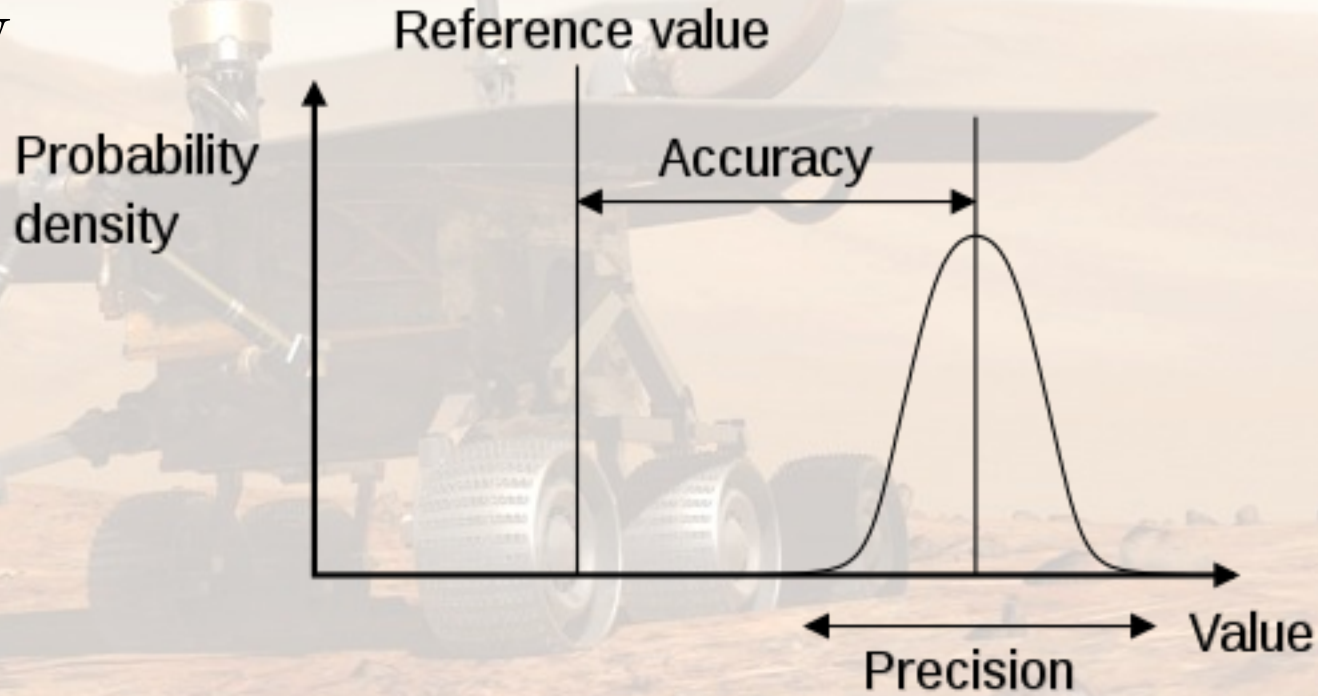


# Sensor Components

- 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



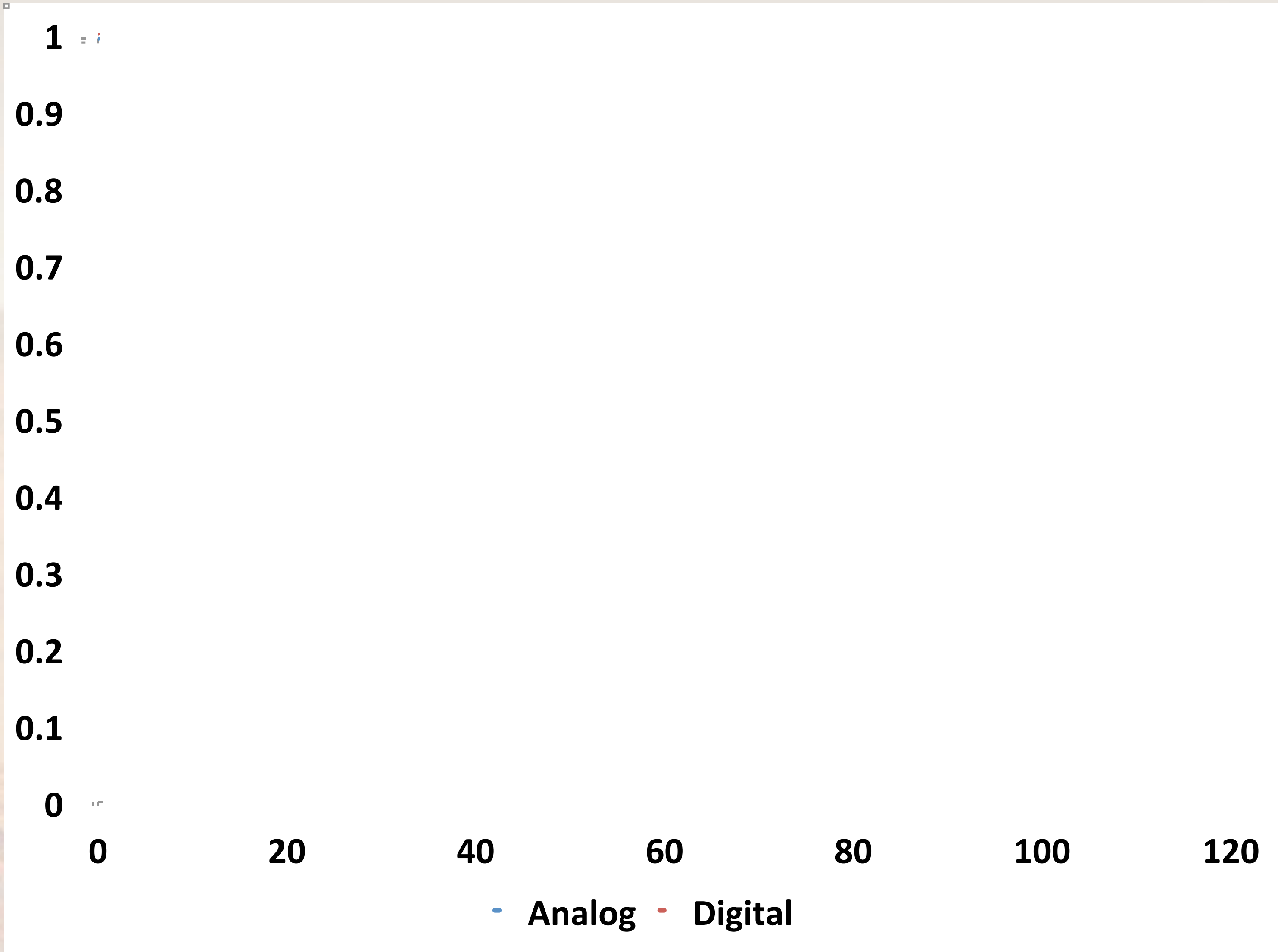
# Some Notes on Data and Noise

- 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

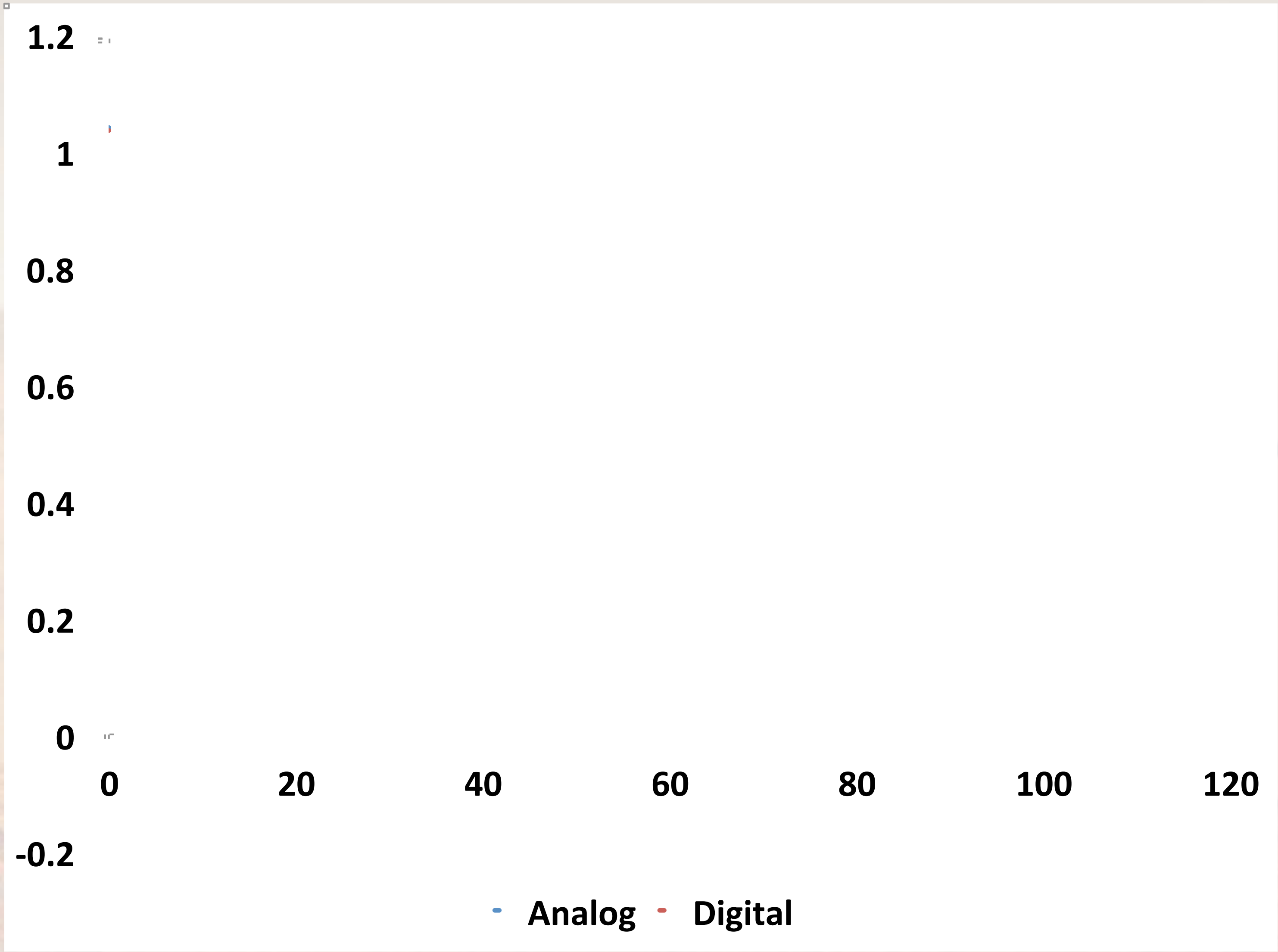
# Shannon Sampling Limit

- 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 $f_{\text{signal}}$
  - Sampling frequency $f_{\text{sample}}$
  - Alias frequencies $f_{\text{sample}} \pm f_{\text{signal}}$

# Analog and Digital Data



# Analog and Digital Data with Noise



# 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

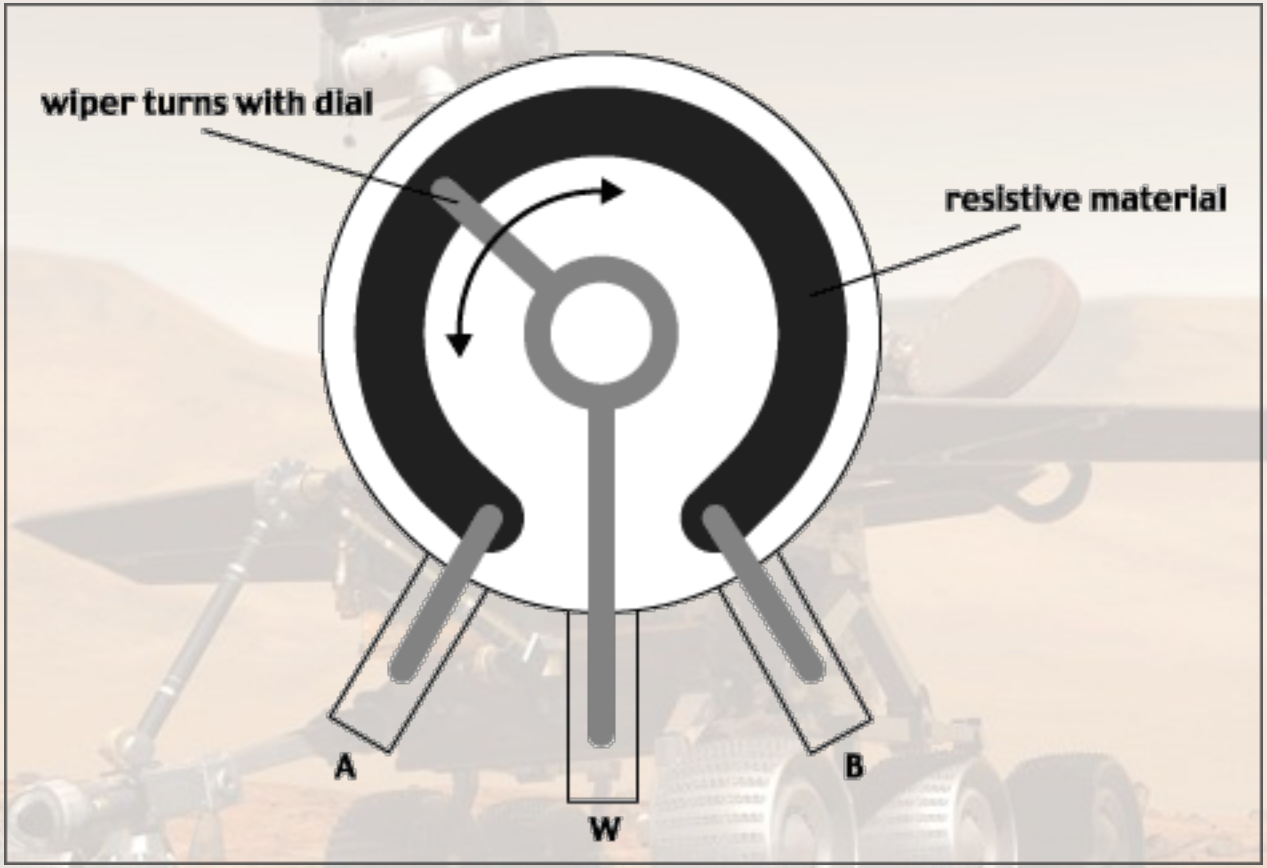
- Position and velocity (encoders, etc.)
- Location (GPS)
- Attitude
  - Inertial measurement units (IMU)
  - Accelerometers
  - Horizon sensors
- Force sensors

# 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.)

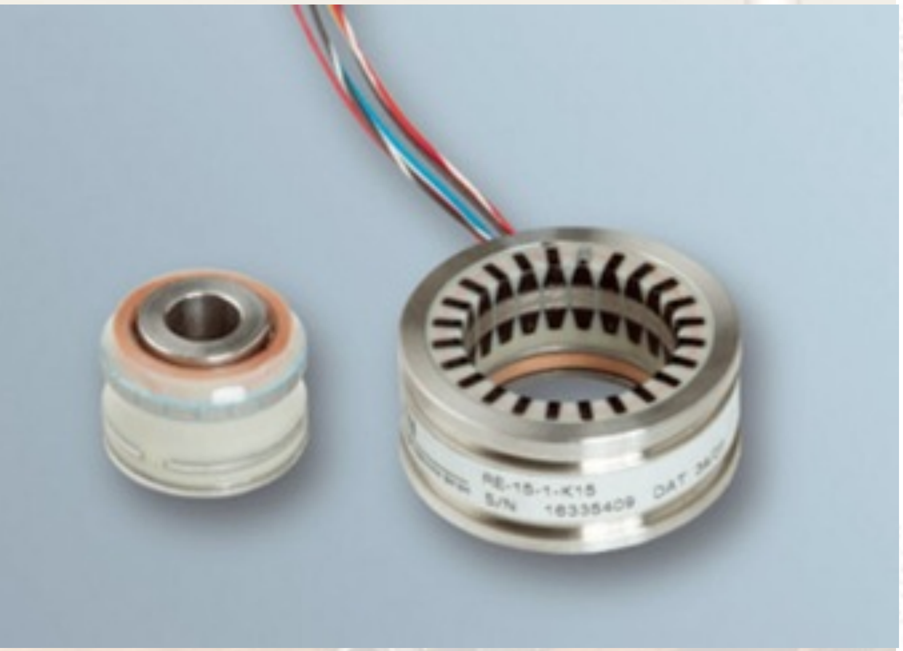
# Potentiometers

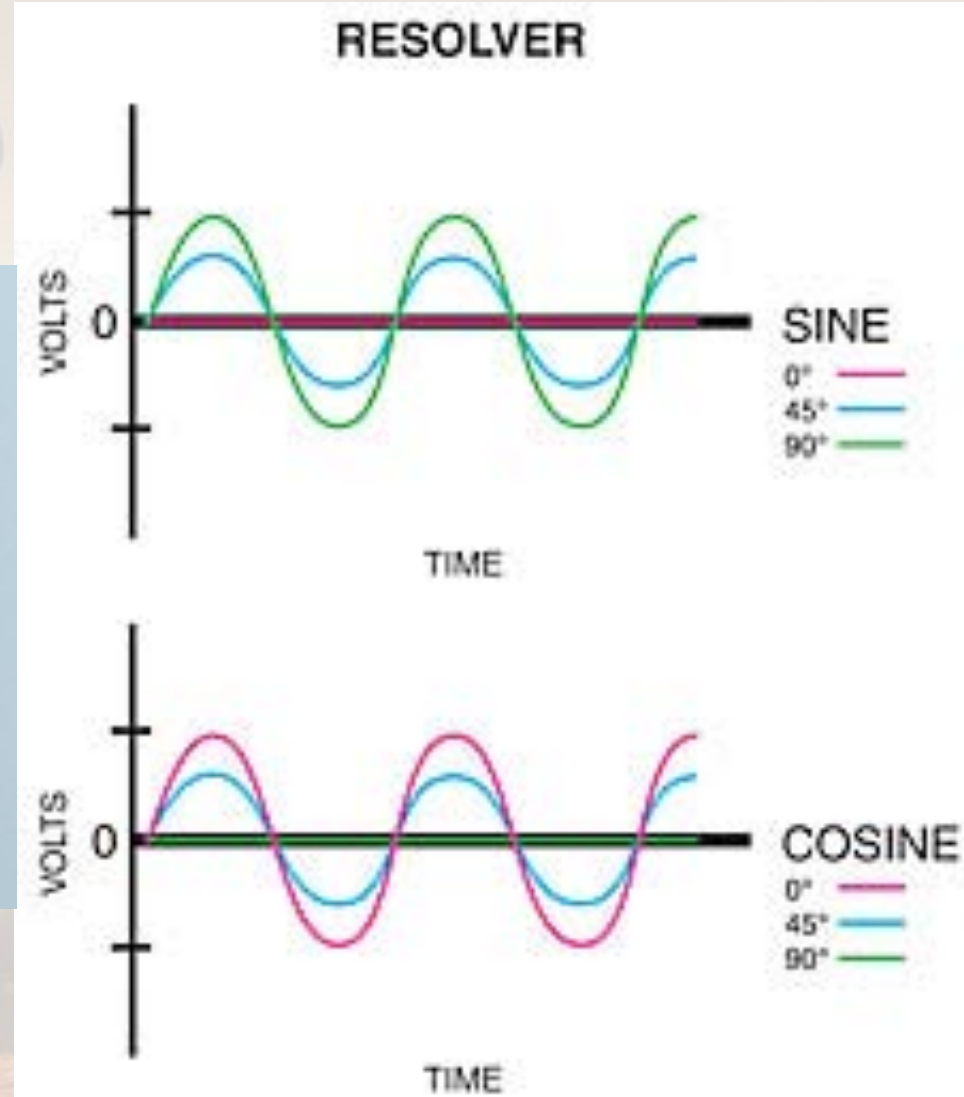


# Potentiometers

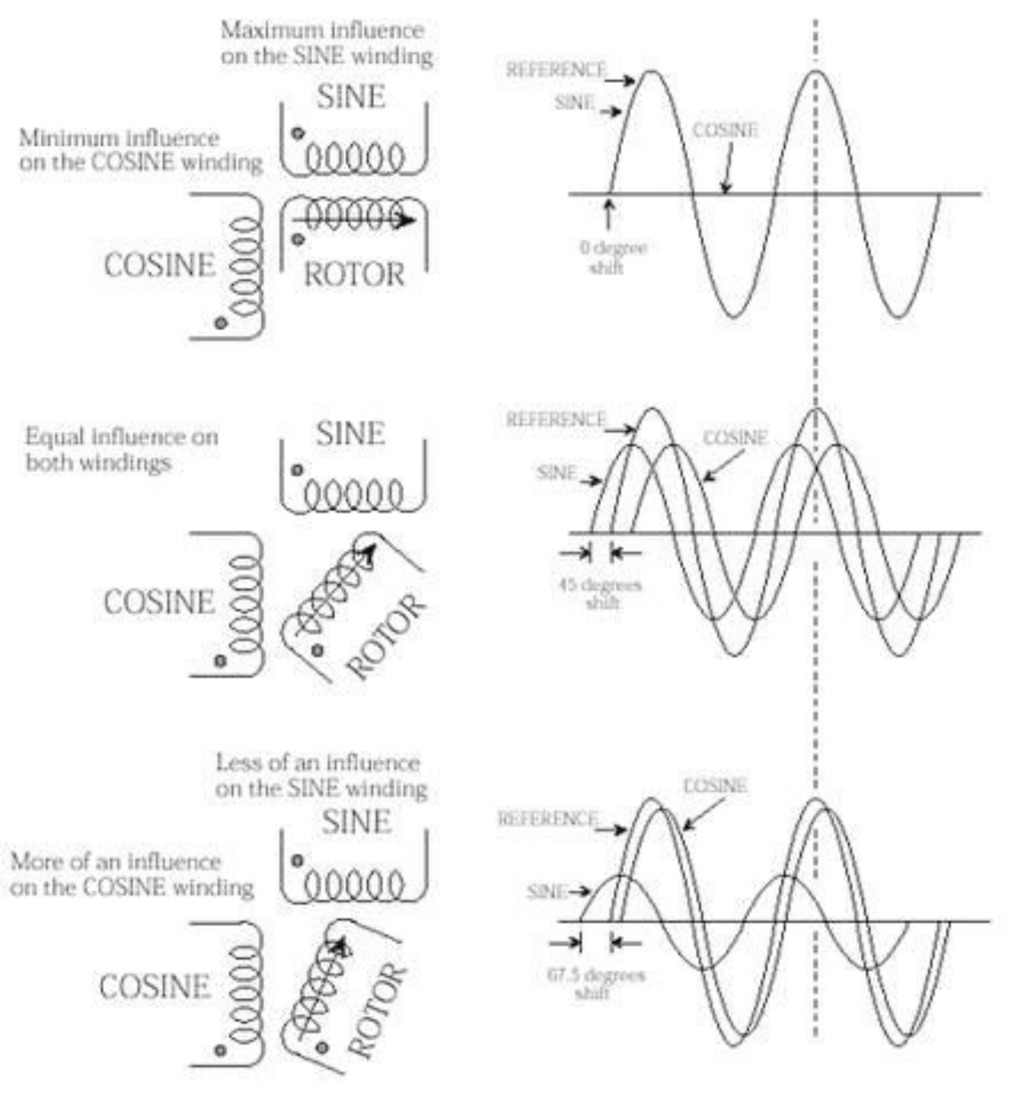
- Advantages
  - Very simple (three wires)
  - Unambiguous absolute position readout
  - Generally easy to integrate
  - Low cost
- Disadvantages
  - Analog signal
  - Data gap at transition every revolution
  - Accuracy limited to precision of resistive element
  - Wear on rotating contactor
  - Liable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

# Resolvers

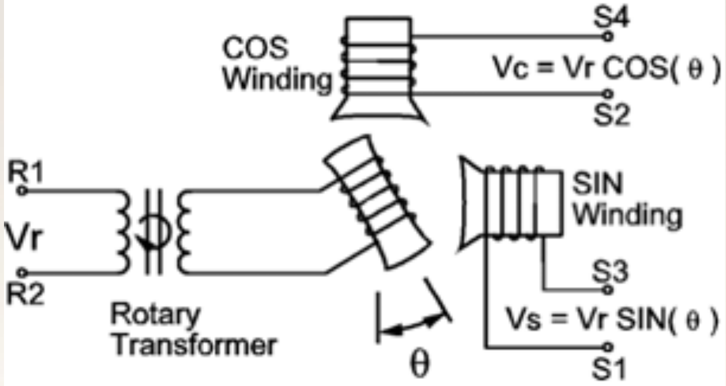




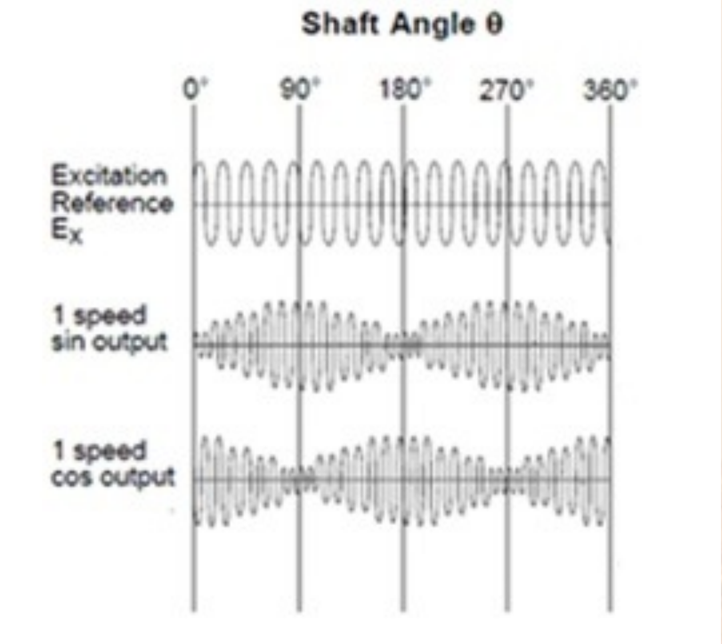
# Resolvers



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
θ
SIN Winding
S3
Vs = Vr SIN( θ )
S1

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

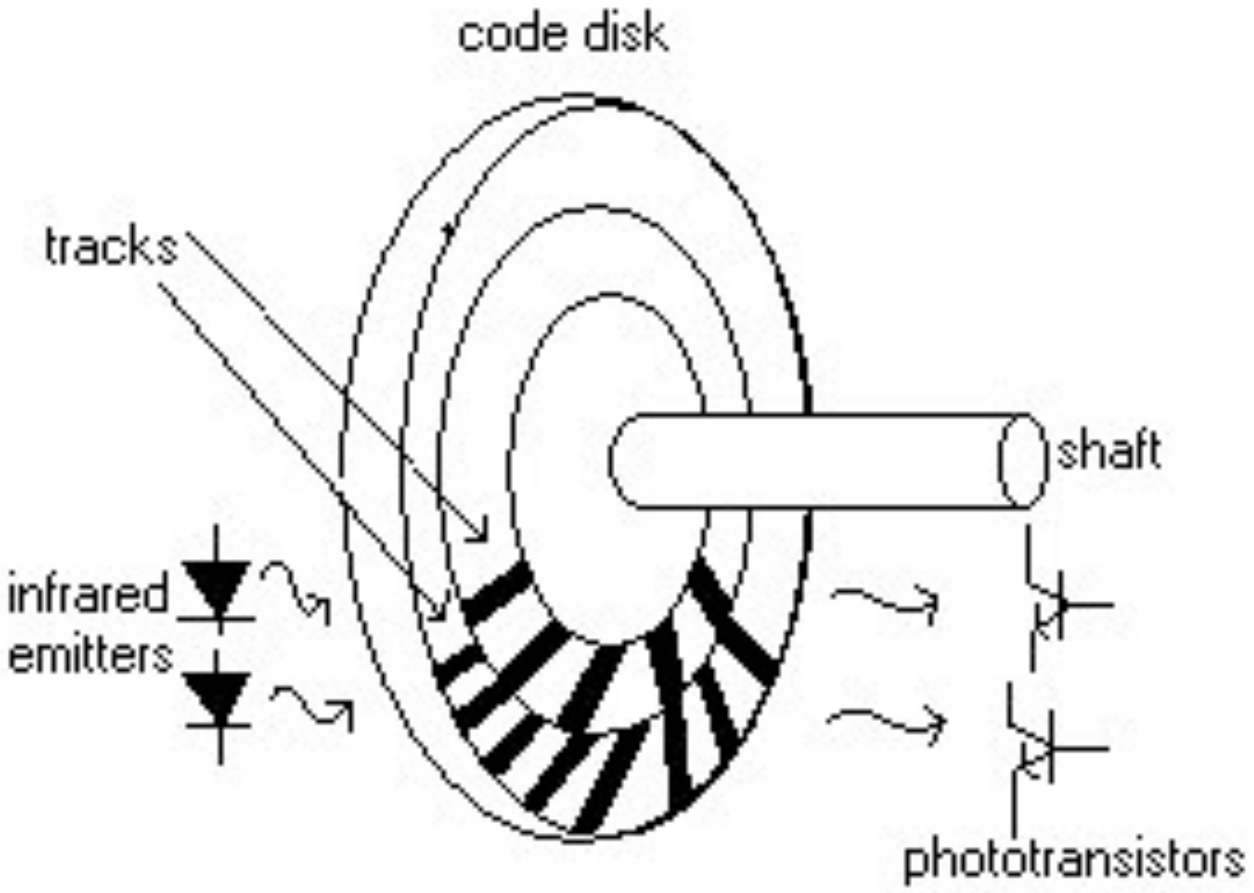



Fig 1. A rotary optical encoder

# Binary Absolute Position Encoders

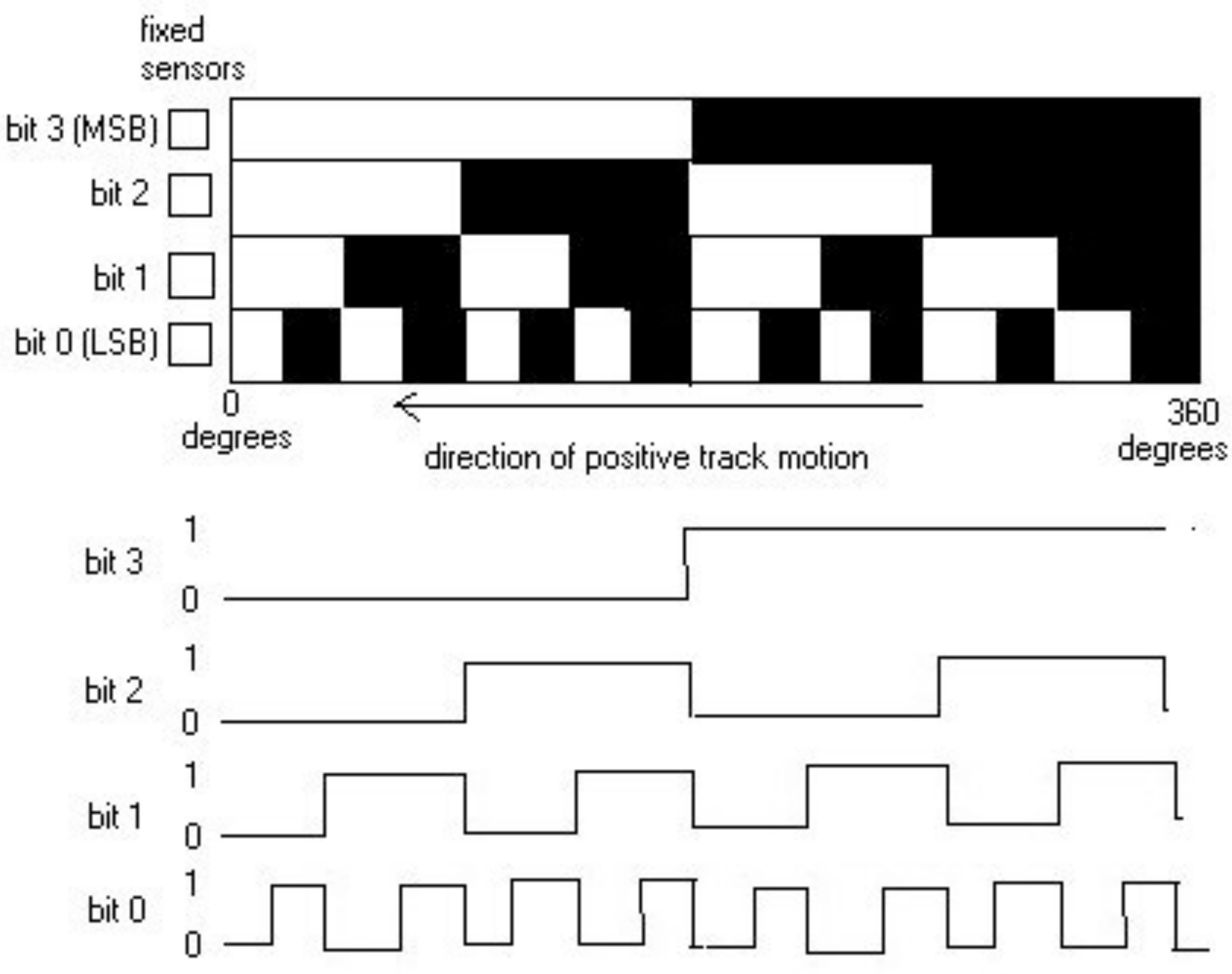



Fig 3 4-Bit binary code absolute encoder disk track patterns

# Gray Code Absolute Position Encoders

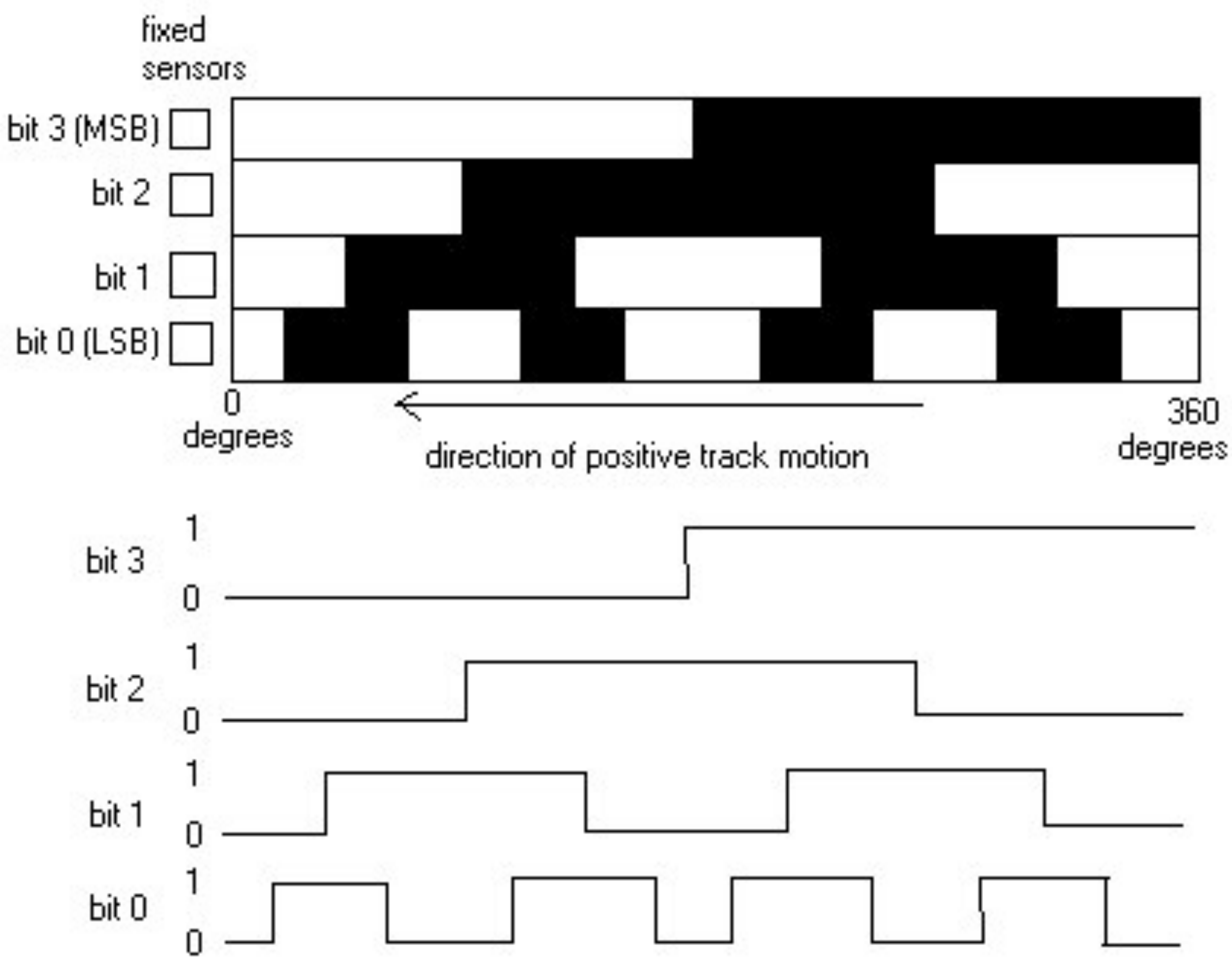



Fig 2. 4-Bit gray code absolute encoder disk track patterns

# Absolute Encoder Gray Codes

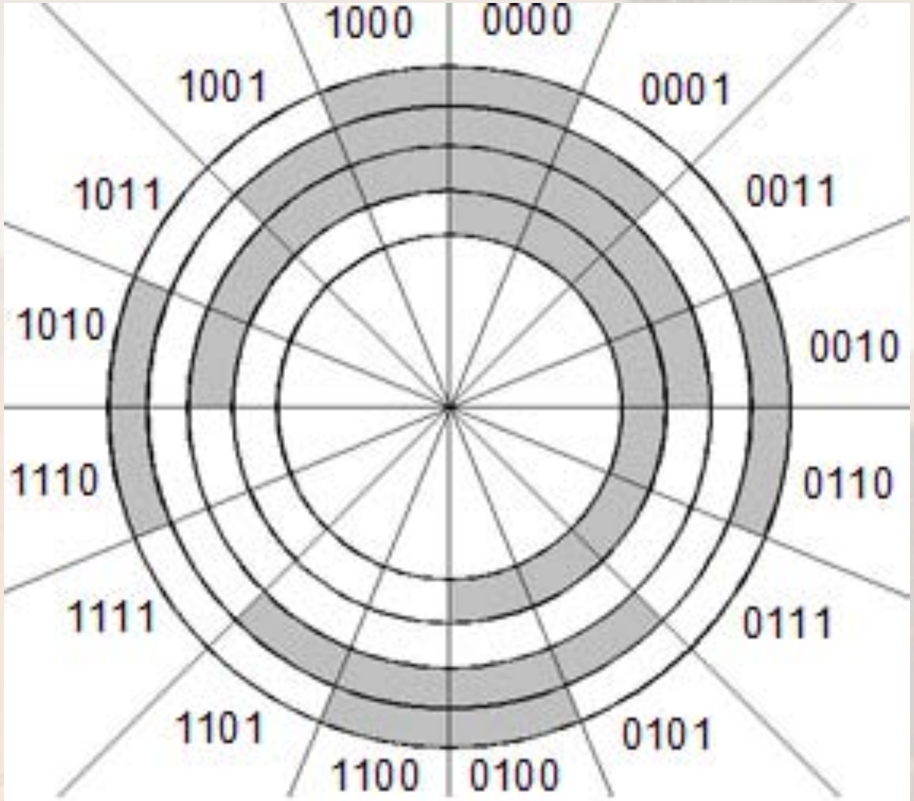
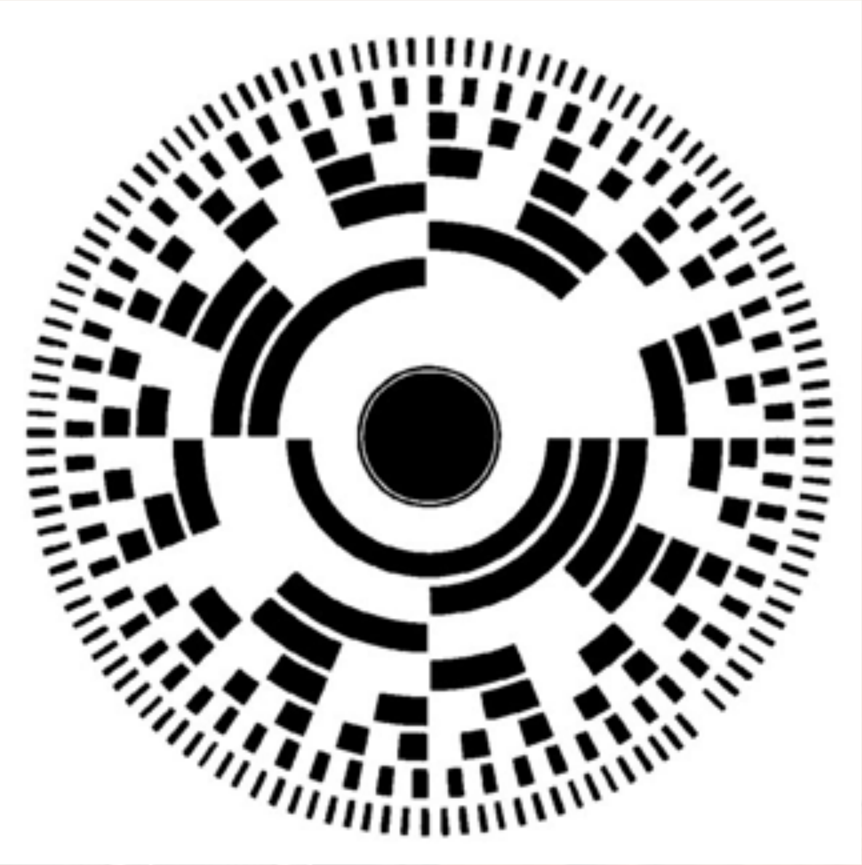



Fig. 1



# 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

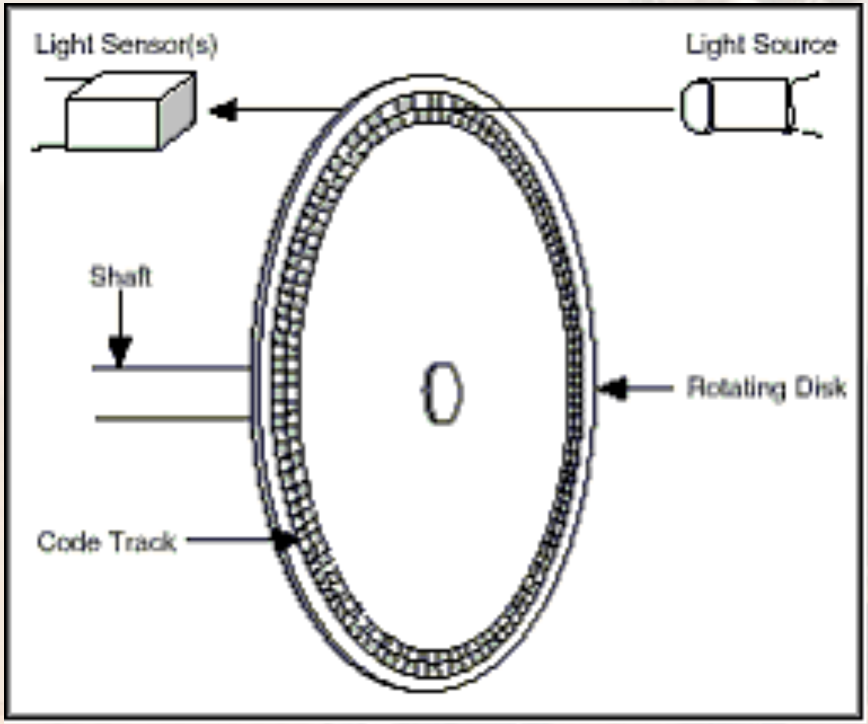
# Magnetic Absolute Encoders

- 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



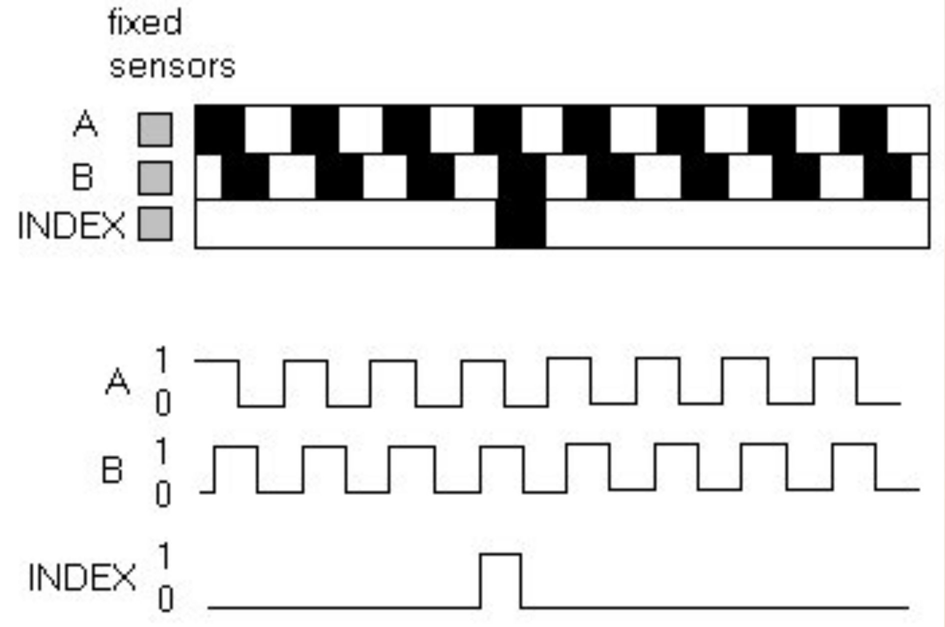




Fig 5. Incremental encoder disk track patterns

# Quadrature Incremental Encoder

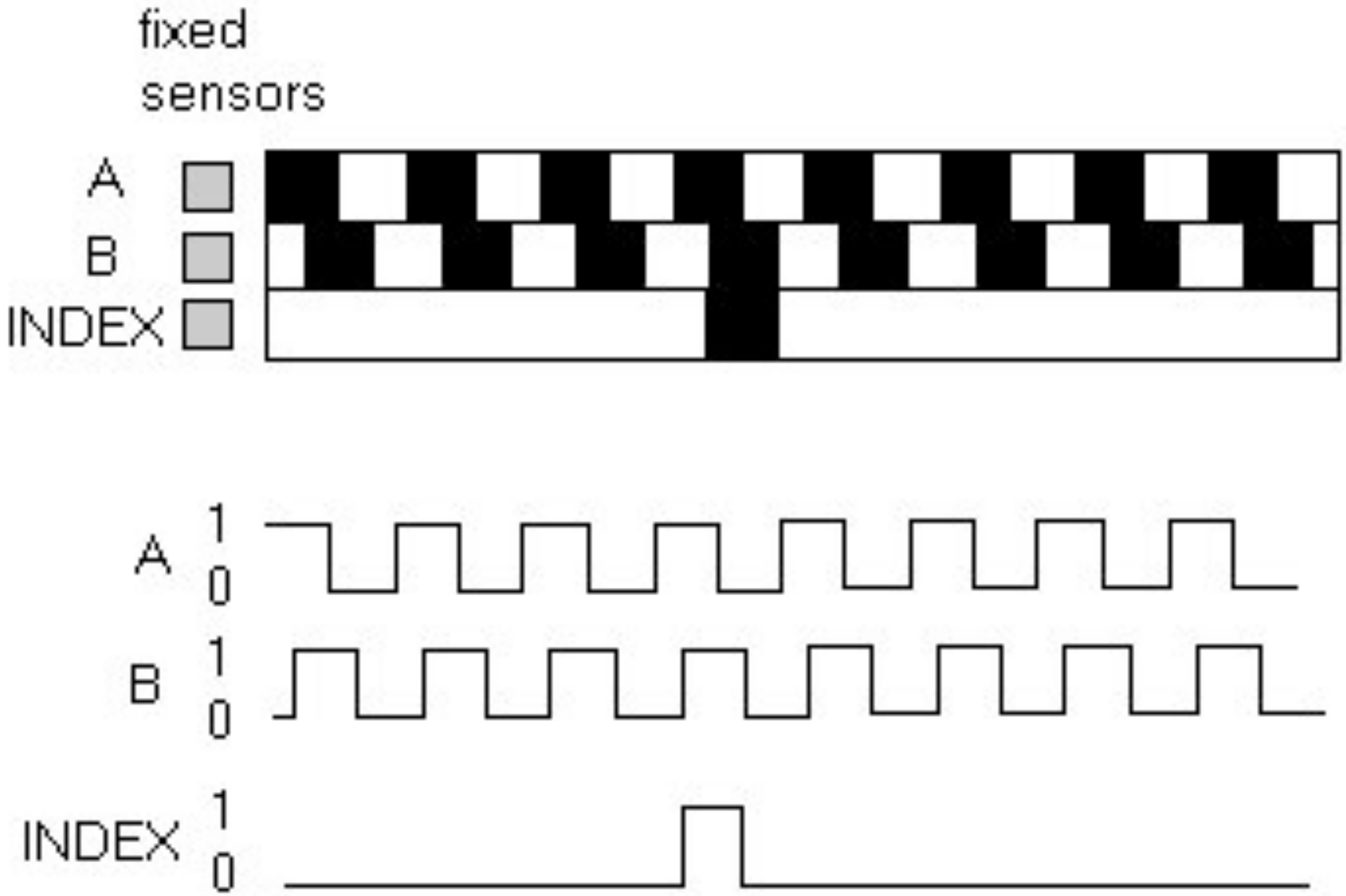
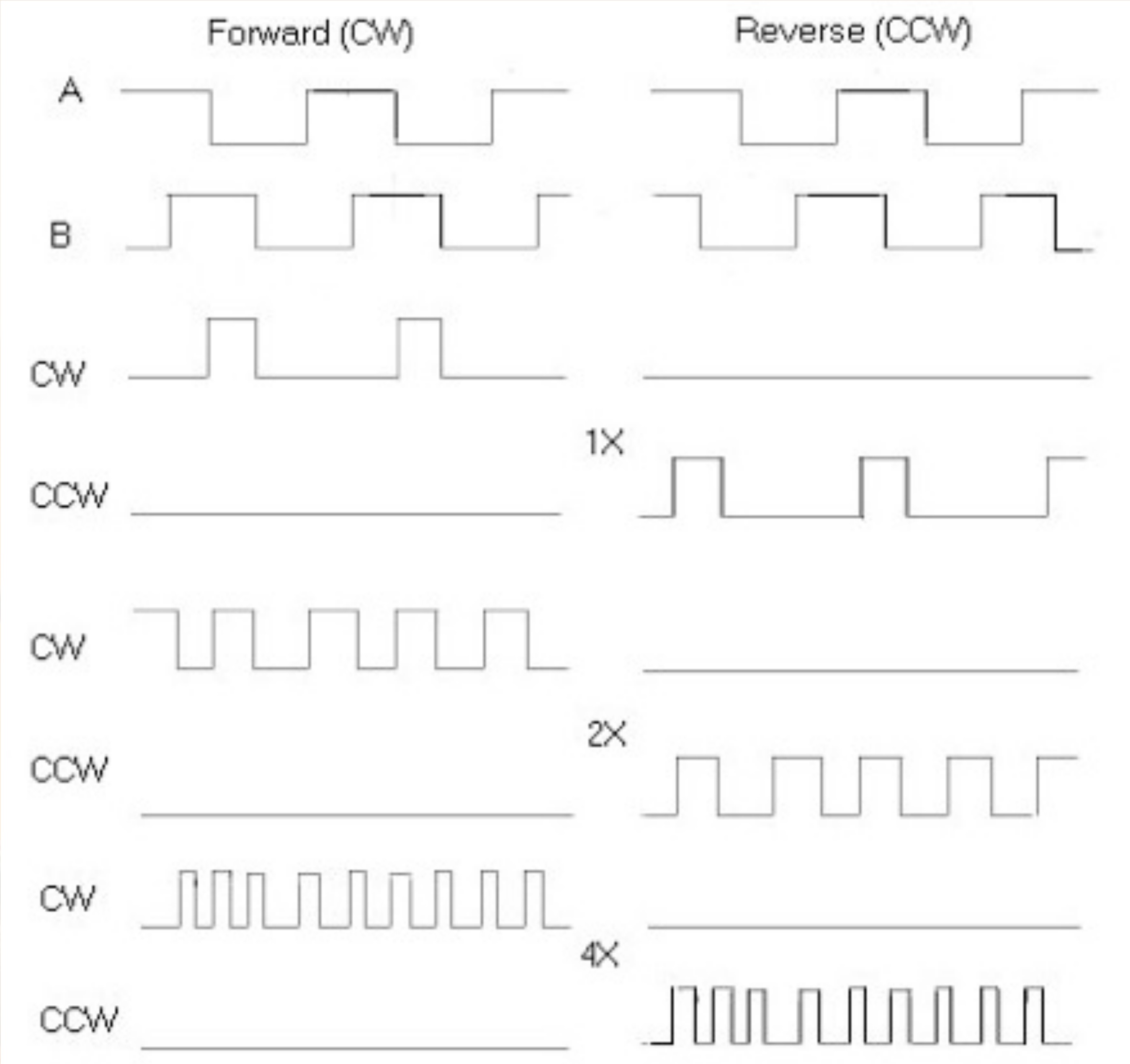


Fig 5. Incremental encoder disk track patterns

# 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

# Quadrature Direction Sensing



# Velocity Measurement

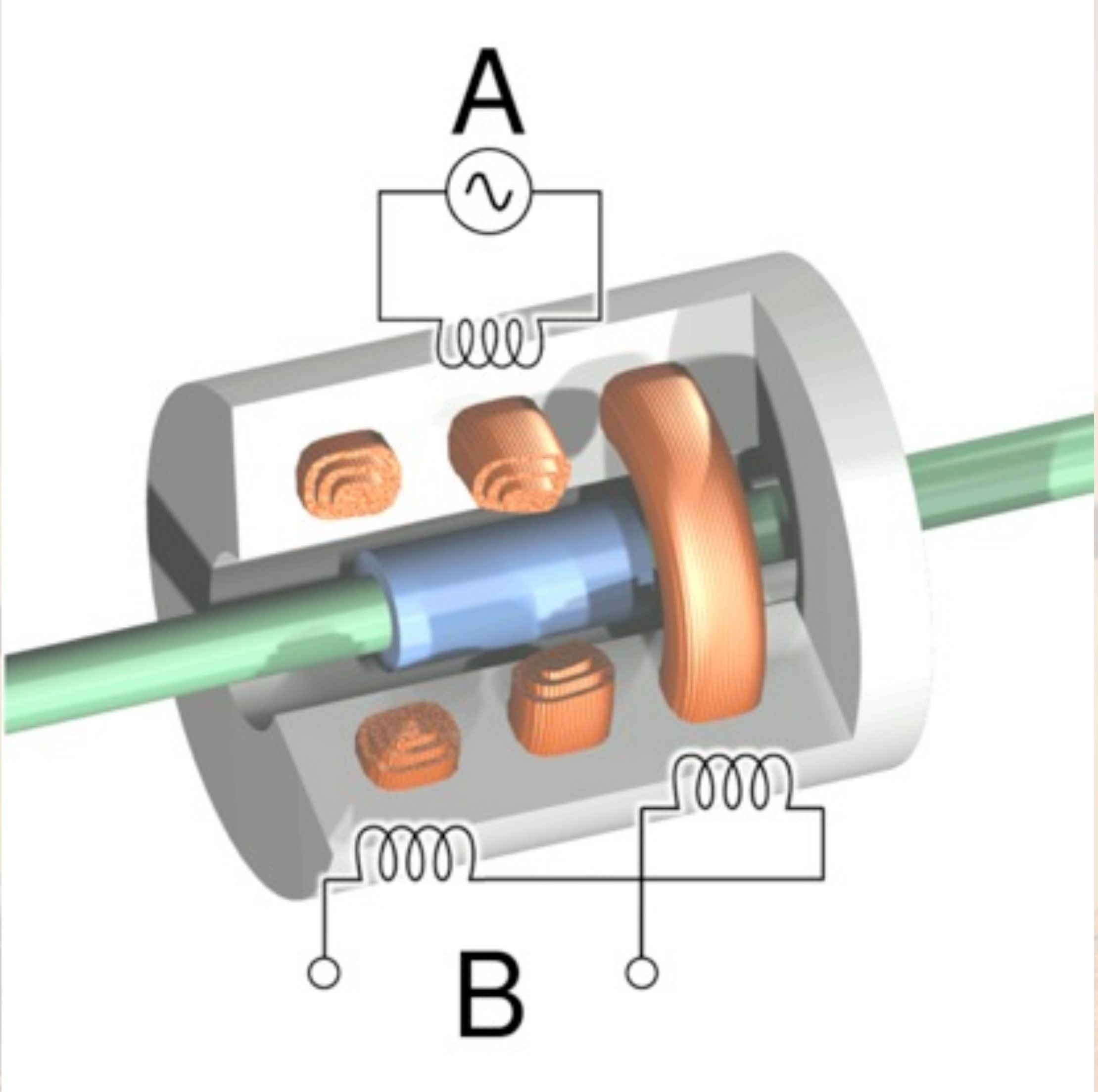
- Number of bits/unit time
  - High precision for rapid rotation
  - Low resolution at slow rotation
  - For n bit encoder reading k bits/interval

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

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

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

# Linear Variable Displacement Transformer



# Exteroceptive 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

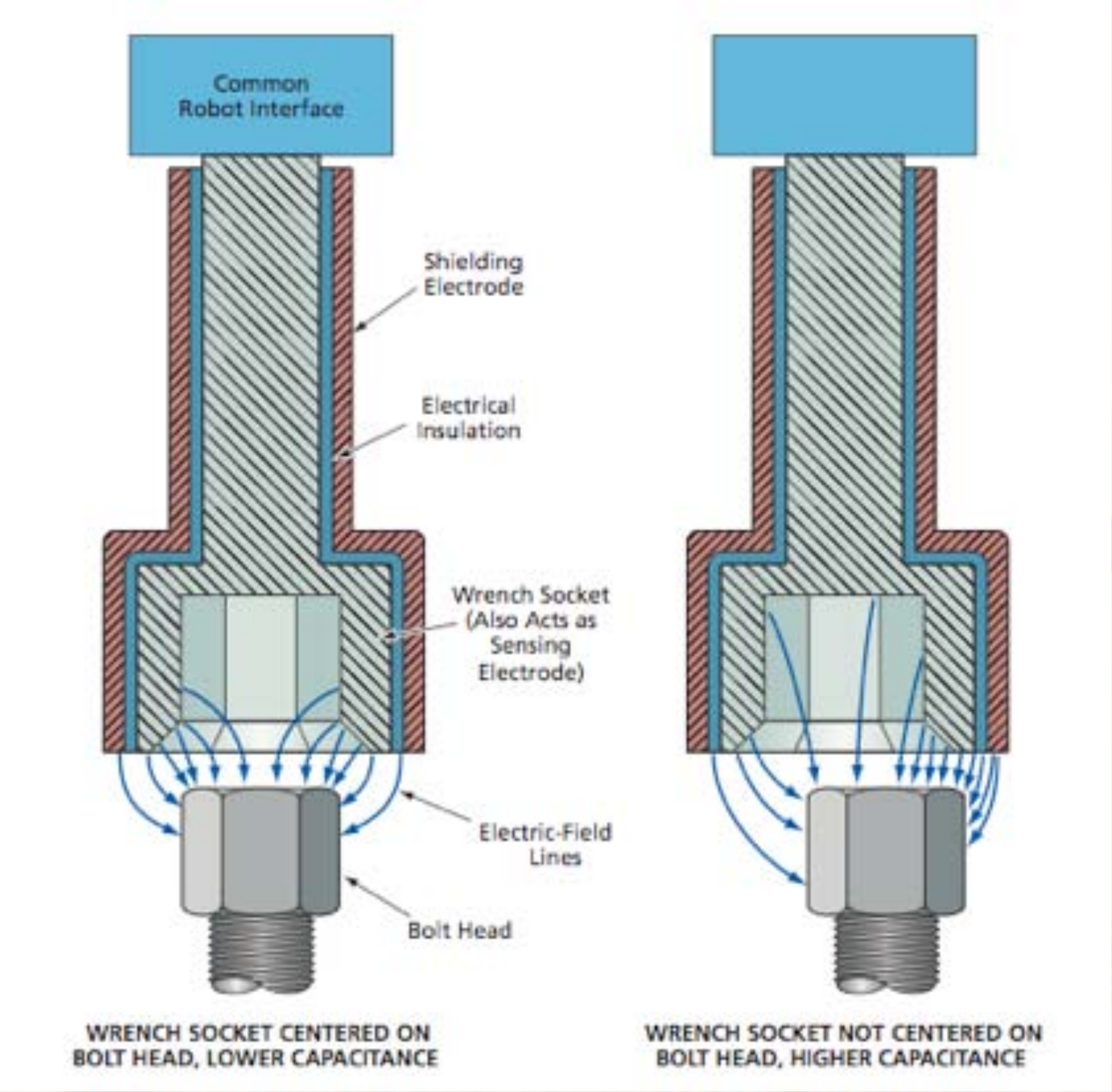
# Switches

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

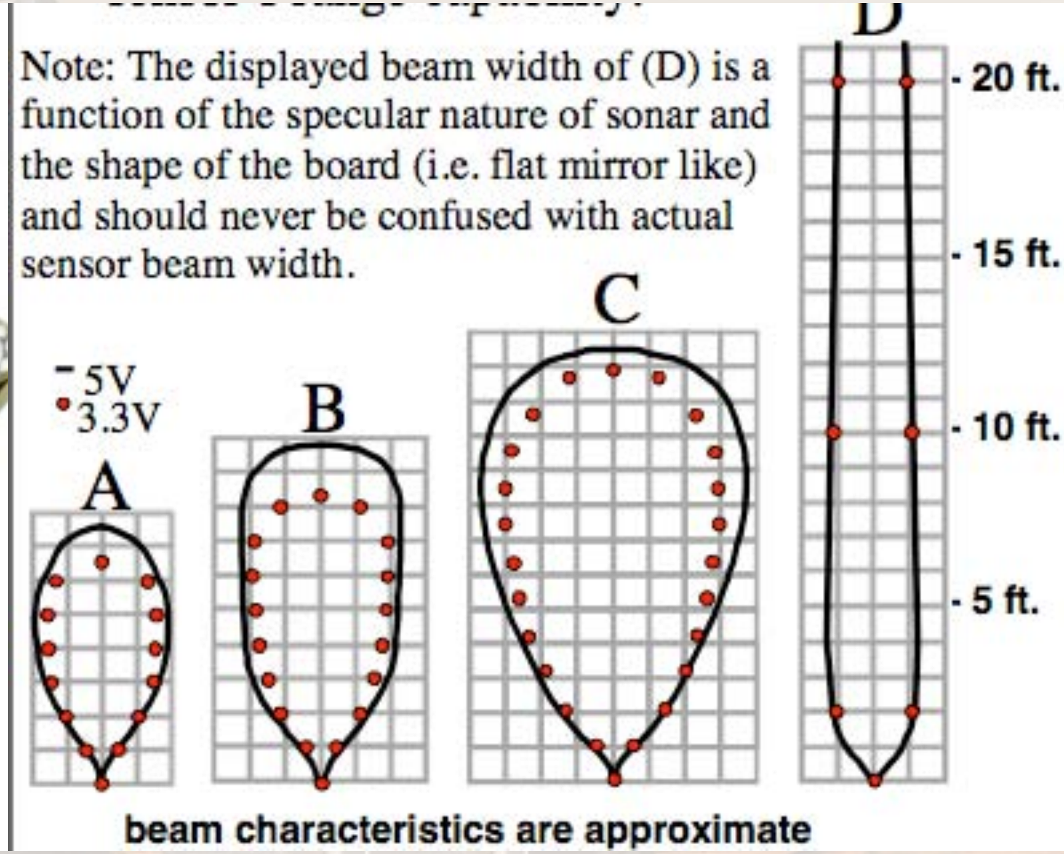
# Proximity Sensors

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

# Capaciflector

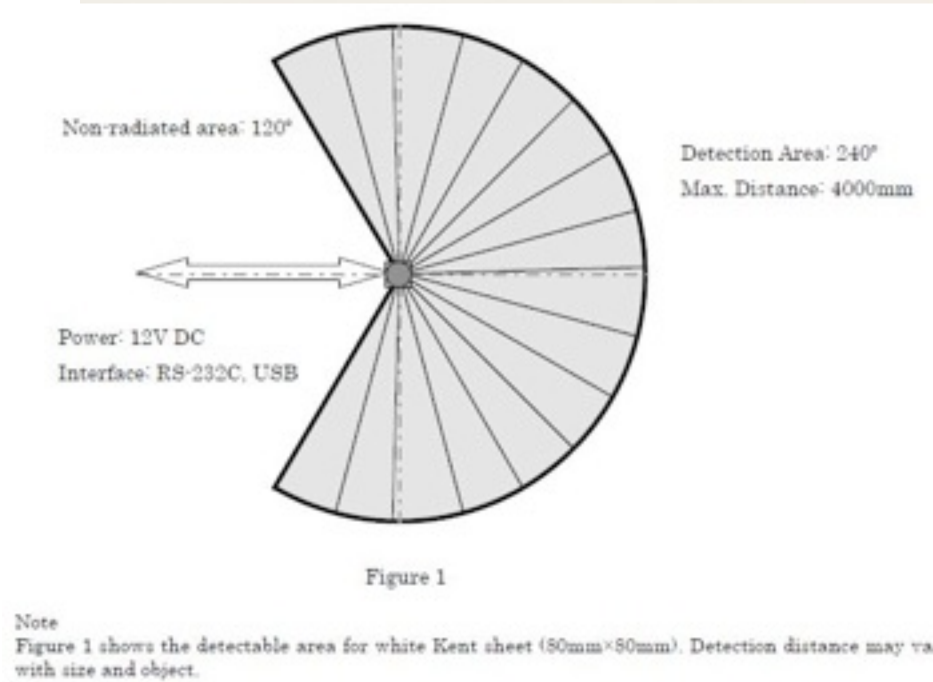


# Sonar Rangefinder Systems

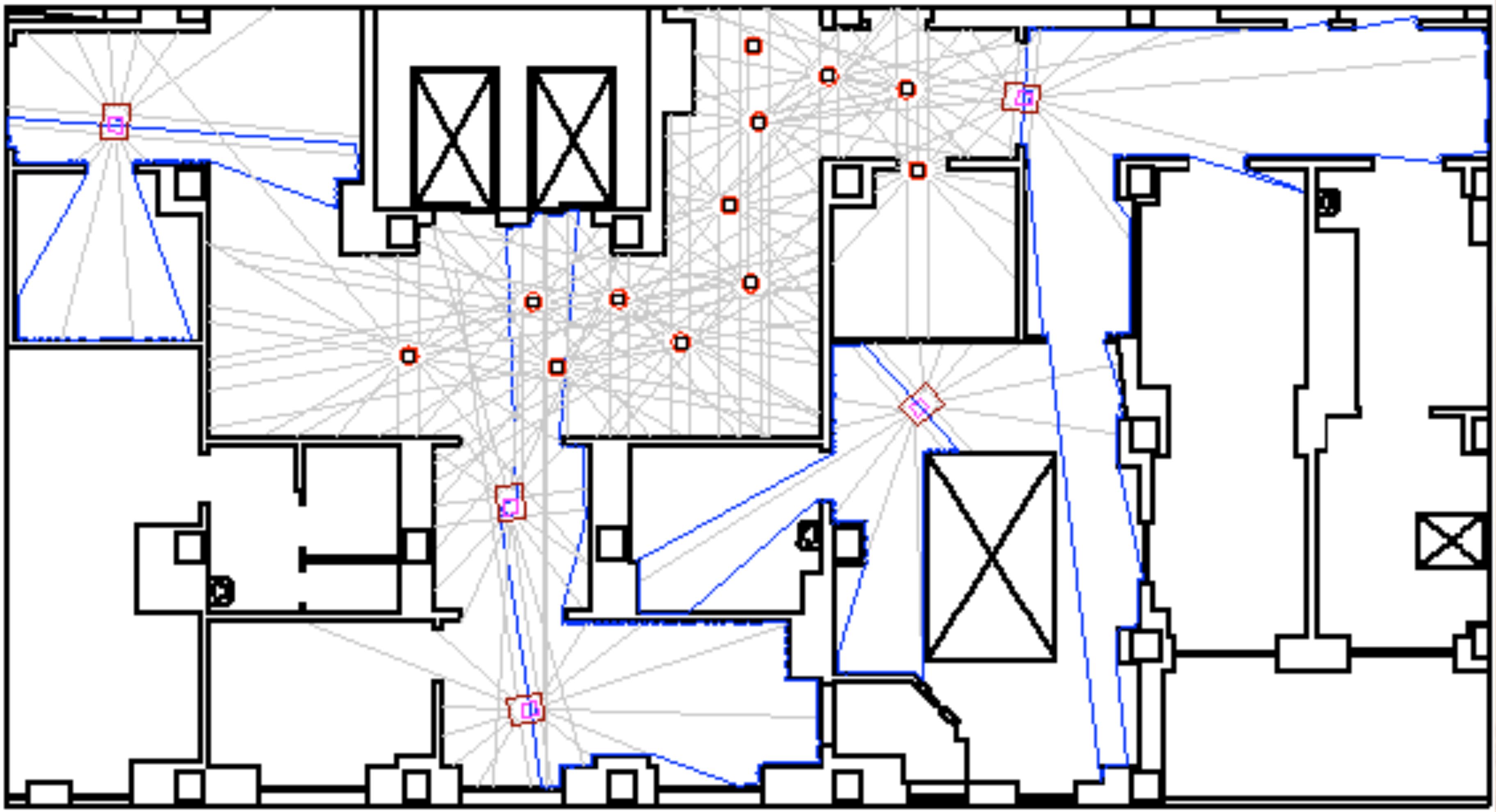



# Computer Vision Cameras

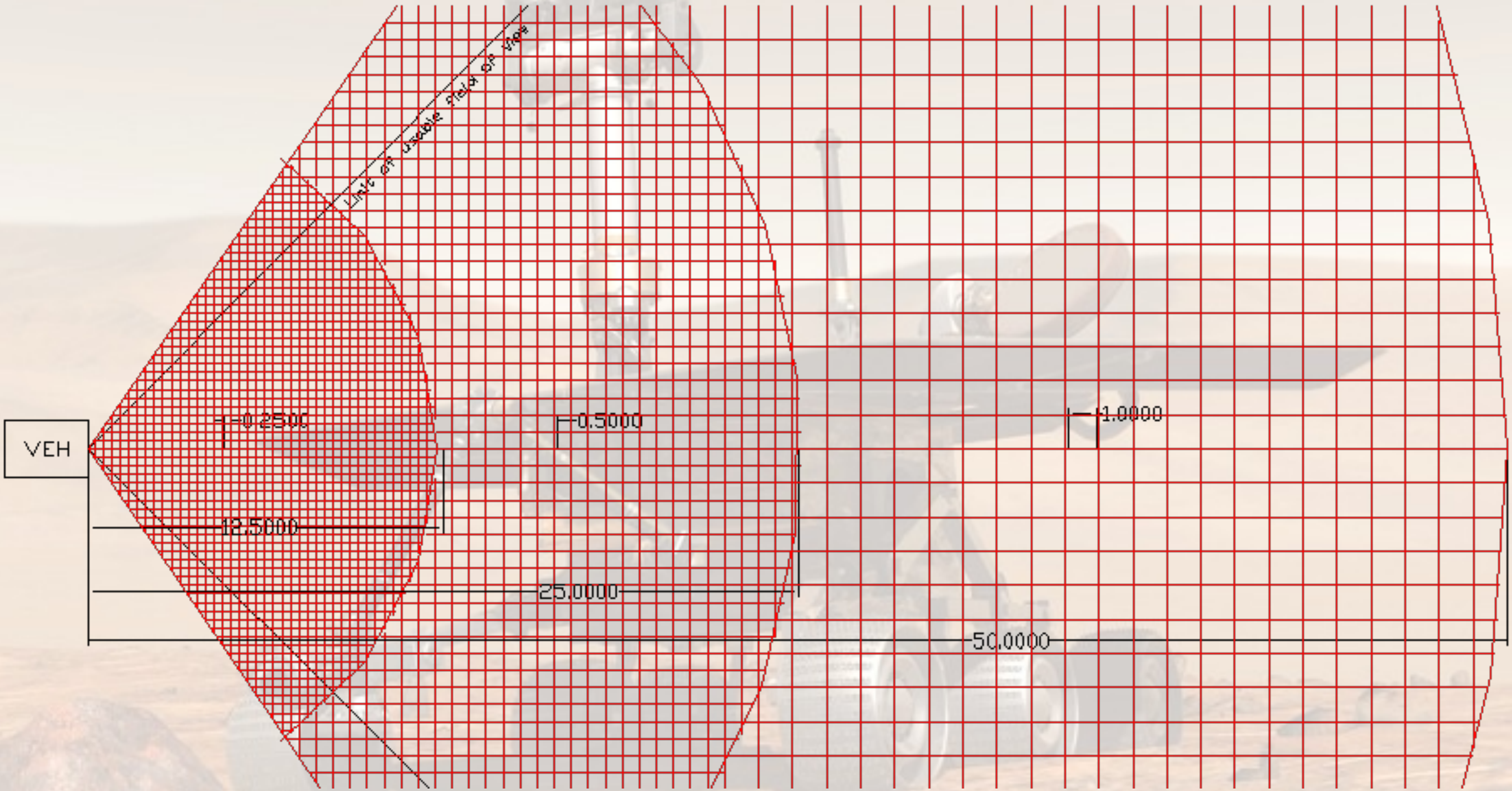
# Scanning Laser Rangefinder



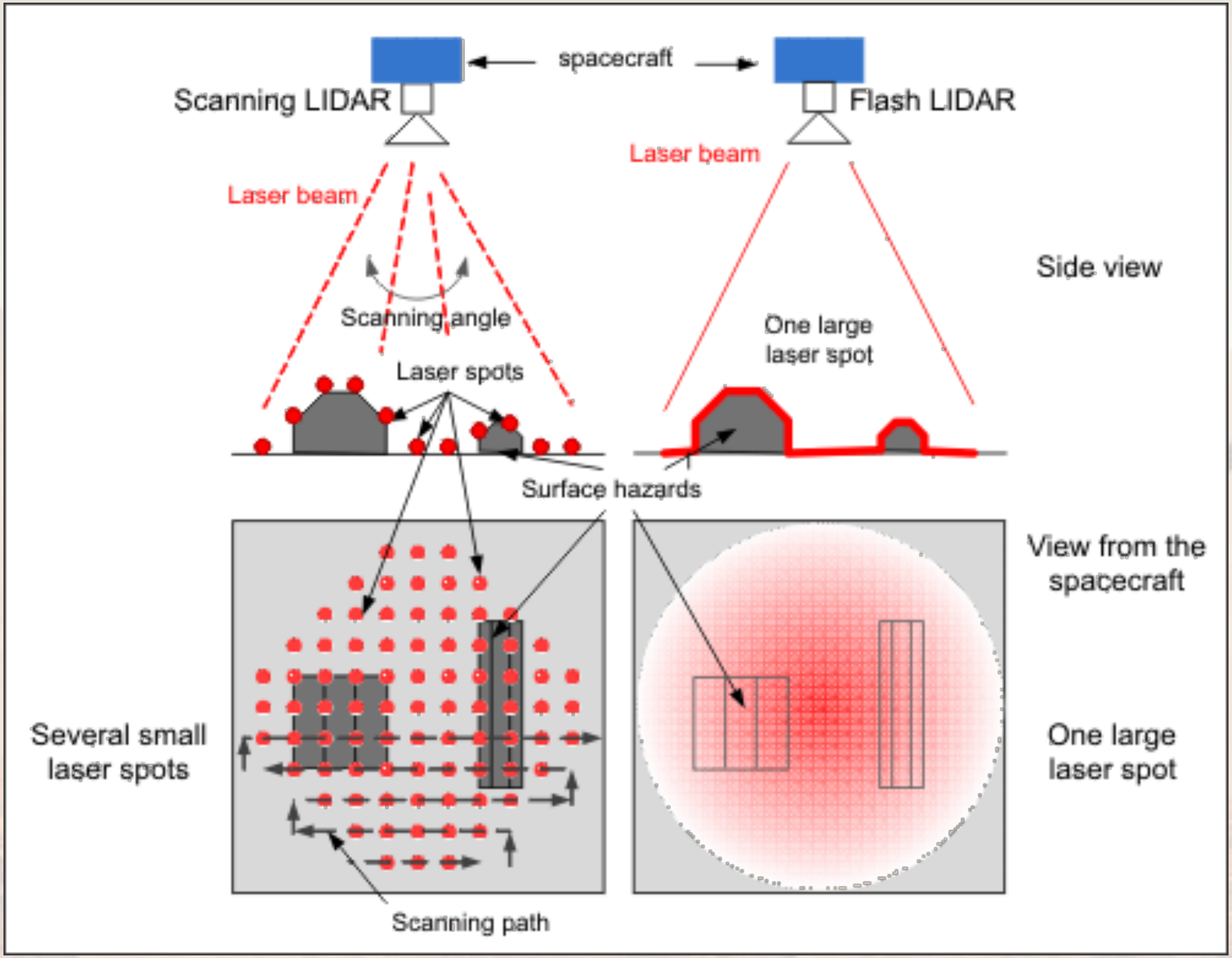
# Line Scanner Area Map



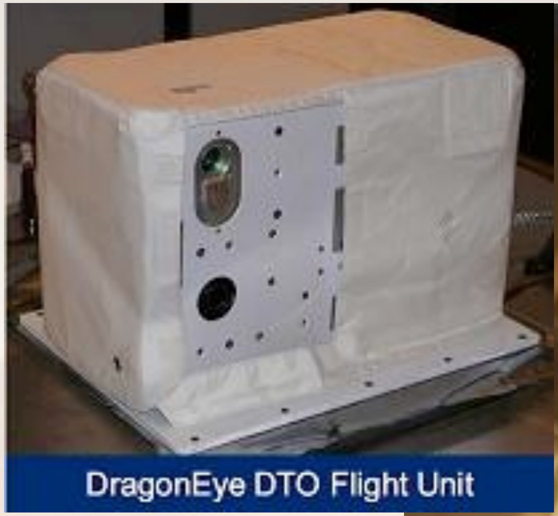
# Scanning Laser Rangerfinder FOV

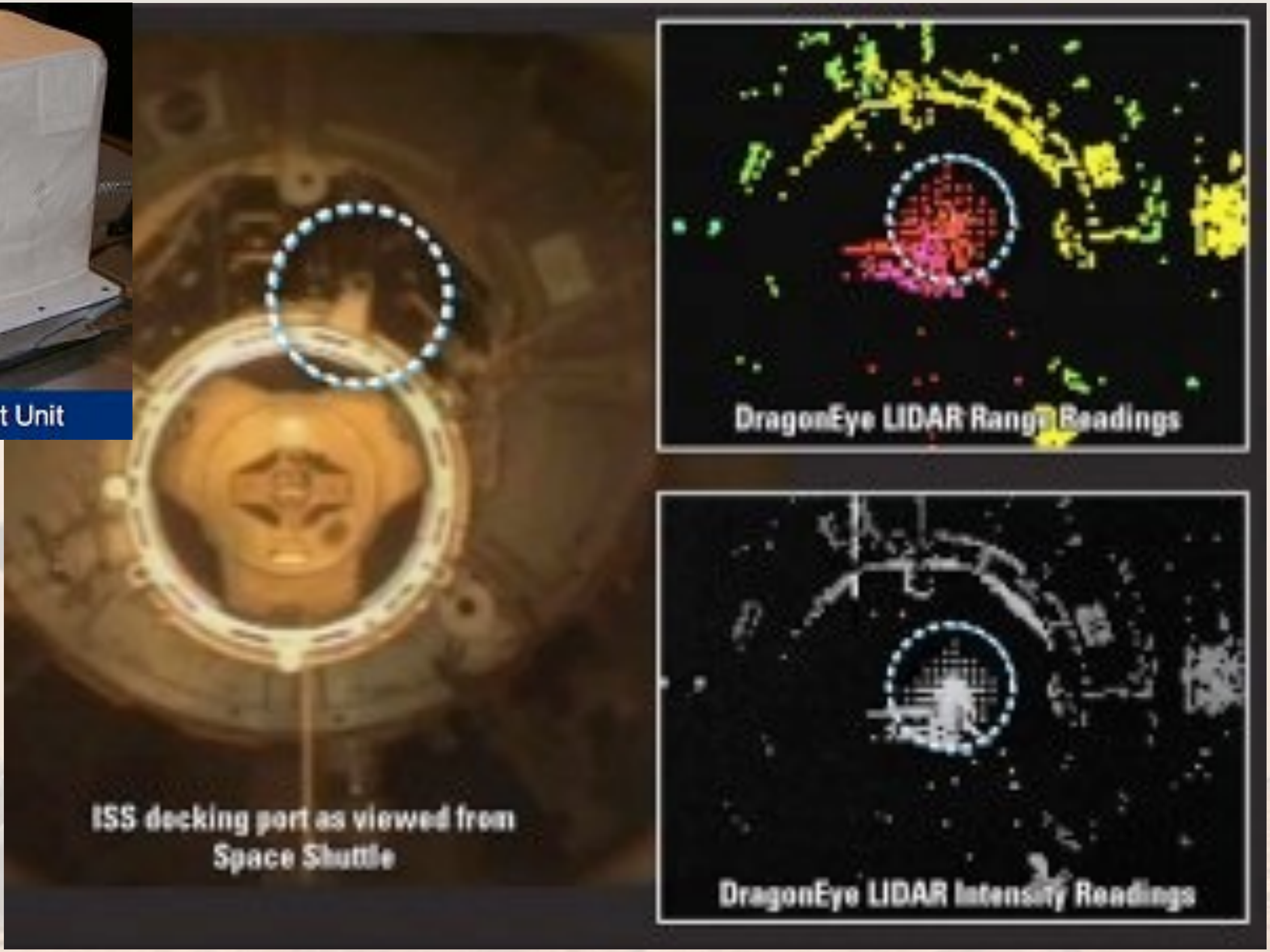


# LIDAR Types

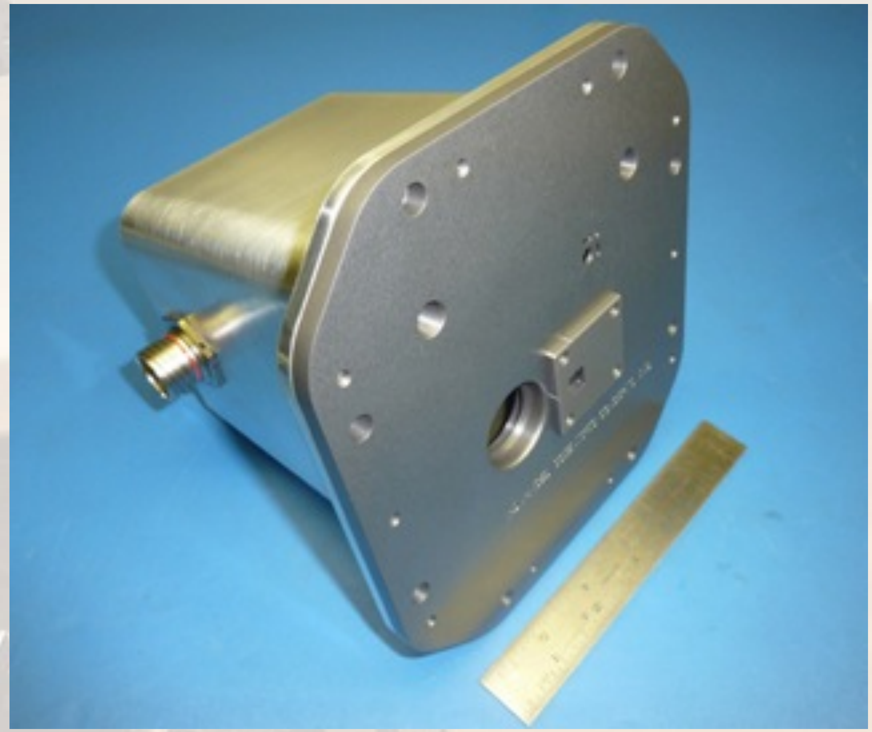

spacecraft
Scanning LIDAR
Flash LIDAR
Laser beam
Laser beam
Side view
Scanning angle
One large
laser spot
Laser spots
Surface hazards
View from the
spacecraft
Several small
laser spots
One large
laser spot
Scanning path

# SpaceX DragonEye Flash LIDAR

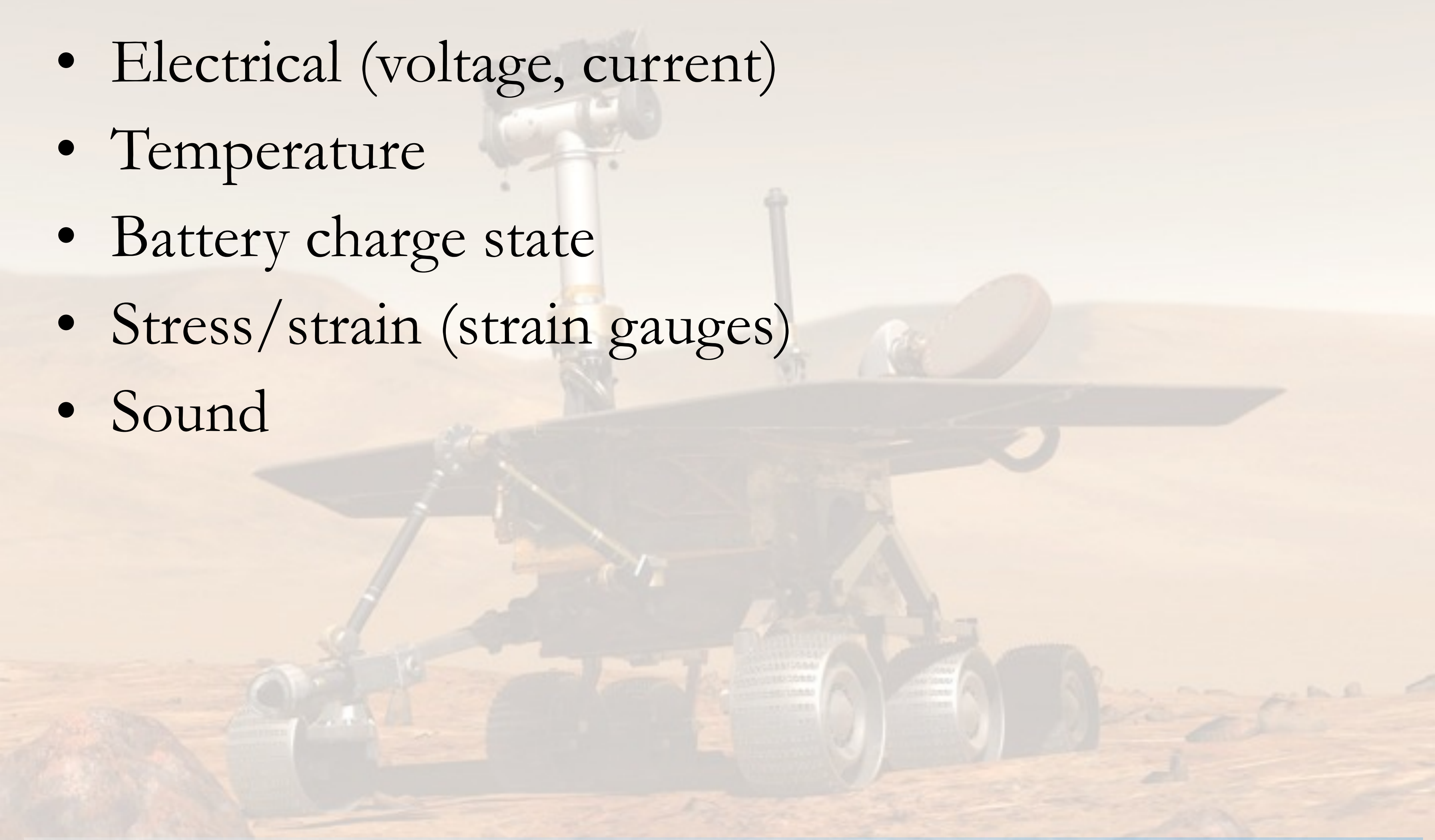


# Flash LiDAR

# Interoceptive Sensors



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

# 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)