Last updated: November 1, 2026

🗺️ Four-year roadmap · Year 4, Fall

About this course

This free course has 10 units and 6 labs. Those are the real counts, not a longer syllabus cut short.

A check is one number or code result on a course page that a script recomputes before the page is published. The printed number and the recomputed number have to match.

> This is a free self-study course outline written by Saving Planets. It is not a university course, it carries no academic credit, and no school is involved.
>
> Its scope follows a one-semester senior course in avionics and systems engineering. It is modeled on the topics and depth of MIT 16.842 Fundamentals of Systems Engineering (free on MIT OpenCourseWare) and the NASA Systems Engineering Handbook, which we link where they help. Neither MIT nor NASA endorses this page.
>
> What we add: every unit ties to real work with a cited public source (Landsat 9, Hubble, Dragonfly and the FAA's air traffic system), every number on the page is re-computed by a checking script before it goes live, and every lab has a free simulation or a spreadsheet.
>
> Work through it in order. Each unit has goals, key ideas, equations, step-by-step examples, practice with full answers, common mistakes, flashcards and a quiz. Your progress is saved only in this browser.

How this course helps save the planet

Earth-observing satellites, weather spacecraft and efficient air traffic all depend on avionics that work for years without a repair visit, and on systems engineering that makes thousands of parts behave as one.

Good requirements, redundancy and testing are what let a satellite keep measuring forests, ice and oceans long past its design life. Each unit ends with a short, sourced section. Values that are not from a source are labeled as sample or textbook values.

For instructors

You can teach this course, or let a student work through it alone. It is free. Saving Planets does not give a grade or school credit.

- This page is the whole course: 10 units and 6 labs (AERO 450).
- Plan on 15 weeks, about 6 to 9 hours a week, including the lab weeks.
- Follow the 15-week schedule. Read the unit, do the practice on paper, then open the answer. In a lab week, do the lab or the home version.
- A check is one number or code result on the page that a script recomputes before we publish. The number you see and the recomputed number have to match.
- Use Print this page, or download the PDF study guide. The formula sheet is near the end.
- Ask: how does this unit help people and the planet? Each unit has a green box with a sourced fact.
- Copy the teacher guide template and write in your class name, the time you have, and the questions you will ask. Open the teacher guide template

Before you start

Prerequisites

- Circuits: voltage, current, resistance and digital signals.
- Probability & Statistics: probability rules, exponential distribution and variance.
- Flight Dynamics & Controls: feedback, sensors and actuators.
- Intro to Programming: loops, functions and timing.

How to study

- Start every problem from the requirement it serves.
- Draw block diagrams and interfaces before computing anything.
- Keep probabilities as numbers between 0 and 1 and check that they stay there.
- Track units: bits, bytes, seconds, hertz, decibels.
- Ask “what happens if this part fails?” for every box you draw.
- Do every practice problem on paper before opening the answer, and retake the quizzes a few days later.

What you need

- A computer or tablet for the free PhET Circuit Construction Kit: DC simulation.
- Spreadsheet software (any free one works), or Python.
- The free NASA Systems Engineering Handbook in a web browser.
- A calculator.

Suggested 15-week schedule

About 6 to 9 hours a week: reading, practice problems and, in lab weeks, the lab.

Week	Unit	Topics	Reading
1	The Systems Engineering Life Cycle and Requirements	Life cycle and requirements	NASA SE Handbook
2	Architecture, Interfaces and Integration	Architecture and interfaces; Lab A	MIT 16.842
3	Reliability and Redundancy	Reliability models	NASA SE Handbook
4	Reliability and Redundancy	Redundancy; Lab B	NASA Hubble
5	Safety Analysis: FMEA and Fault Trees	FMEA and fault trees; Lab C	NASA SE Handbook
6	Digital Avionics and Data Buses	Digital avionics	MIT 16.842
7	Digital Avionics and Data Buses	Data buses; Lab D; midterm practice	NASA Landsat 9
8	Navigation Sensors: IMUs, GNSS, Cameras and Lidar	Navigation sensors	NASA Dragonfly
9	Sensor Fusion and the Kalman Filter	Sensor fusion and Kalman filters; Lab E	MIT 16.842
10	Communication and Surveillance: ADS-B	Communication and ADS-B	FAA ADS-B
11	Real-Time Flight Software	Real-time software	MIT 16.842
12	Real-Time Flight Software	Fault protection; Lab F	NASA Hubble
13	Integration, Verification and Operations	Integration and verification	NASA SE Handbook
14	Integration, Verification and Operations	Testbeds and fault injection	NASA Dragonfly
15	Integration, Verification and Operations	Review; final practice	MIT 16.842

Your progress

Tick units and labs as you finish them, and take the quizzes. Progress and quiz scores are saved only in this browser, never sent to us.

Units

The Systems Engineering Life Cycle and Requirements

Stakeholders, the V-model, life-cycle phases and reviews, good requirements, technical performance measures and margins.

Learning objectives

By the end of this unit you can:

- Describe the V-model.
- Write verifiable requirements.
- Compute margins against a requirement.
- Track a technical performance measure.

Key concepts

- Systems engineering turns stakeholder needs into a system that works, on time and on budget, across its whole life.
- The V-model goes down the left side (requirements, architecture, design) and up the right (integration, verification, validation).
- A good requirement is necessary, clear, feasible and verifiable, with a number, a unit and a test method.
- Technical performance measures such as mass, power and data rate are tracked against allocations with margin.
- Reviews (concept, preliminary design, critical design) gate each phase; MIT 16.842 students prepare a preliminary-design-review-level design.

Key equations

$$\text{Margin} = \frac{C - N}{N}$$

```
Margin=(C-N)/(N)
```

Margin over need

$$m_{alloc} = m_{est}(1 + M)$$

```
m_alloc=m_est(1+M)
```

Allocation with margin

$$S = \sum w_i s_i$$

```
S= w_is_i
```

Weighted trade score

$$\sum w_i = 1$$

`w_i=1`

Weights sum to one

Worked examples, step by step

Example 1.1 NASA requires Landsat 9 to collect at least 400 scenes a day; it collects 740. Find the margin.

1. (740 − 400)/400.

Answer: 85% above the requirement.

Example 1.2 An avionics box is estimated at 12 kg. Allocate with 25% margin (sample values).

1. 12 × 1.25.

Answer: 15 kg.

Example 1.3 Option A scores 7 (cost) and 8 (reliability); B scores 9 and 6. Weights 0.3 and 0.7. Which wins?

1. A = 2.1 + 5.6 = 7.7.
2. B = 2.7 + 4.2 = 6.9.

Answer: A, 7.7 to 6.9.

Practice problems

Work each on paper first, then check.

1. Landsat 9 design life is 5 years and consumables last 10 years. Ratio?

   2.

2. Allocate 400 W of power at 30% margin.

   520 W.

3. Rewrite “the radio shall be fast” as a verifiable requirement.

   For example: “The radio shall downlink at least 300 Mbit/s, verified by test.”

4. Which side of the V holds verification?

   The right side.

Common misconceptions

Myth: Requirements describe the design.
Actually: They state what is needed, not how.

Myth: Margin is waste.
Actually: It absorbs growth and surprises.

Myth: Verification and validation are the same.
Actually: Verification: built right; validation: right thing built.

Flashcards

V-model

Decompose down, integrate and verify up.

Requirement

Verifiable need.

TPM

Tracked technical performance measure.

PDR

Preliminary design review.

Verification

Built right.

Validation

Right thing built.

Self-check quiz

1. Landsat 9 margin...

85%

74%

40%

185%

85%. (740 − 400)/400.

2. 12 kg + 25%...

15 kg

13 kg

12.25 kg

16 kg

15 kg. Multiply.

3. Trade winner...

A

B

tie

neither

A. 7.7 > 6.9.

4. A good requirement is...

verifiable

vague

a design

optional

verifiable. Testable.

Try this quiz again

How this helps save the planet

NASA lists Landsat 9's requirements, including at least 400 scenes a day and a 5-year design life; Landsat 9 collects 740 scenes a day, almost double the minimum, and carries enough fuel to operate for at least 10 years.

With Landsat 8, it observes the same place every 8 days, enabling near-weekly tropical deforestation alerts, water-quality monitoring and crop reports, payoffs of requirements written and met with margin.

On Saving Planets: Earth Observation · Spacecraft Design

Sources: NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

Free learning resources

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook, Sections 3–4.
- MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/): Free MIT lectures.

Watch the lecture

Lecture 21: Systems Engineering for Space Shuttle Payloads (https://ocw.mit.edu/courses/16-885j-aircraft-systems-engineering-fall-2005/resources/lecture-21/) (in English)

MIT 16.885J Aircraft Systems Engineering (Fall 2005), MIT OpenCourseWare. License: CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/) · Terms of use (https://ocw.mit.edu/pages/privacy-and-terms-of-use/). Linked for free study only; Saving Planets is not affiliated with or endorsed by this university.

☐ **I finished this unit**

Architecture, Interfaces and Integration

Functional and physical architecture, interface control, N² diagrams, model-based systems engineering and why interfaces grow fast.

Learning objectives

By the end of this unit you can:

- Map functions to components.
- Count potential interfaces.
- Read an N² diagram.
- Explain model-based systems engineering.

Key concepts

- A functional architecture says what the system does; a physical architecture says which boxes do it.
- Every pair of components could need an interface, so potential interfaces grow as n(n − 1)/2.
- An N² diagram puts components on the diagonal and the data or power between them off the diagonal.
- Interface control documents fix connectors, signals, timing and data formats so teams can build in parallel.
- NASA notes its handbook update includes Model-Based Systems Engineering, which keeps requirements, architecture and analyses in one connected model.

Key equations

$$I = \frac{n(n-1)}{2}$$

```
I=(n(n-1))/(2)
```

Potential two-way interfaces

$$N_{cells} = n(n-1)$$

```
N_cells=n(n-1)
```

Off-diagonal N² cells

$$B = \sum_{i} r_i$$

```
B=_i r_i
```

Total bus load

$$U = B / B_{max}$$

`U=B/B_max`

Bus utilization

Worked examples, step by step

Example 2.1 An avionics suite has 8 boxes. How many potential interfaces?

1. 8 × 7/2.

Answer: 28.

Example 2.2 Add 4 boxes (n = 12).

1. 12 × 11/2.

Answer: 66, more than double.

Example 2.3 Three boxes send 20, 35 and 15 kbit/s on a 100 kbit/s bus. Utilization?

1. 70/100.

Answer: 70%.

Practice problems

Work each on paper first, then check.

1. Off-diagonal N² cells for n = 8?

   56.

2. Interfaces for n = 4?

   6.

3. Why keep bus utilization below 100%?

   Room for growth, retries and timing jitter.

4. What is an ICD?

   Interface control document.

Common misconceptions

Myth: Interfaces grow linearly.

Actually: They grow roughly as n^2.

Myth: Architecture is just a parts list.

Actually: It includes functions and connections.

Myth: MBSE replaces engineers.

Actually: It connects their work.

Flashcards

Architecture

Functions mapped to components.

N² diagram

Interface matrix.

ICD

Interface control document.

MBSE

Model-based systems engineering.

Integration

Joining components.

Bus load

Sum of data rates.

Self-check quiz

1. Interfaces for 8 boxes...

28

56

16

64

28. n(n − 1)/2.

2. For 12 boxes…

66

132

24

144

66. 12 × 11/2.

3. Bus utilization…

70%

35%

100%

7%

70%. 70/100.

4. MBSE means…

model-based systems engineering

mass budget

mission baseline

mean bus error

model-based systems engineering. NASA.

Try this quiz again

How this helps save the planet

NASA says its Systems Engineering Handbook was updated to include Model-Based Systems Engineering, drawing on lessons from missions and mishaps.

Clear interfaces let instrument and spacecraft teams build in parallel, which is how Earth-observing missions such as Landsat 9 reach orbit on schedule.

On Saving Planets: Spacecraft Design · Earth Observation

Sources: NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/)

Free learning resources

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook, Section 4.
- MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/): Free MIT lectures.

Watch the lecture

Session 8: Systems Integration and Interface Management (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/resources/session-8-systems-integration-and-interface-management/) (in English)

MIT 16.842 Fundamentals of Systems Engineering (Fall 2015), MIT OpenCourseWare. License: CC BY-NC-SA 4.0 (https://creativecommons.org/licenses/by-nc-sa/4.0/) · Terms of use (https://ocw.mit.edu/pages/privacy-and-terms-of-use/). Linked for free study only; Saving Planets is not affiliated with or endorsed by this university.

- [ ] **I finished this unit**

Reliability and Redundancy

Failure rates, exponential reliability, MTBF, series and parallel systems, triple modular redundancy, k-of-n systems and availability.

Learning objectives

By the end of this unit you can:

- Compute reliability from a failure rate.
- Combine series and parallel blocks.
- Compute 2-of-3 voting reliability.
- Compute availability.

Key concepts

- With a constant failure rate λ, reliability falls as e^(−λt) and the mean time between failures is 1/λ.
- Series systems fail if any part fails, so reliabilities multiply.
- Parallel (redundant) systems fail only if all parts fail.
- Triple modular redundancy votes 2 of 3; it beats a single unit early in life but not after R drops below 0.5.
- Availability is the fraction of time a system works: MTBF/(MTBF + MTTR).

Key equations

$$R(t) = e^{-\lambda t}$$

`R(t)=e^- t`

Exponential reliability

$$R_s = \prod R_i,\ R_p = 1 - \prod (1 - R_i)$$

`R_s= R_i,\ R_p=1-(1-R_i)`

Series and parallel

$$R_{2/3} = 3R^2 - 2R^3$$

`R_2/3=3R^2-2R^3`

Two-of-three voting

$$A = \frac{MTBF}{MTBF + MTTR}$$

A=(MTBF)/(MTBF+MTTR)

Availability

Worked examples, step by step

Example 3.1 A unit has $\lambda = 10^{-5}$ per hour. Reliability over 10,000 h?

1. e^(−0.1).

Answer: 0.905.

Example 3.2 Two such units in parallel?

1. $1 - (1 - 0.9048)^2$.

Answer: 0.991.

Example 3.3 Three units voting 2 of 3?

1. $3(0.9048)^2 - 2(0.9048)^3$.

Answer: 0.975.

Practice problems

Work each on paper first, then check.

1. MTBF for $\lambda = 10^{-5}$ /h?

   100,000 h.

2. Single, dual and TMR at 50,000 h?

   0.607, 0.845, 0.657.

3. Availability with MTBF 1000 h and MTTR 2 h?

   0.998.

4. Hubble needs one of three working gyros. Which model?

   1-of-3 (parallel).

Common misconceptions

Myth: Redundancy always helps.

Actually: TMR loses to a single unit once R < 0.5.

Myth: MTBF is guaranteed life.

Actually: It is a mean; many fail sooner.

Myth: Series reliability adds.

Actually: It multiplies.

Flashcards

Failure rate

Failures per hour.

MTBF

Mean time between failures.

Redundancy

Backup units.

TMR

Triple modular redundancy, 2-of-3 voting.

Availability

Fraction of time working.

k-of-n

Works if k of n work.

Self-check quiz

1. R(10,000 h)...

0.905

0.990

0.1

0.5

0.905. e^(−0.1).

2. Parallel pair…

0.991

0.819

0.905

1

0.991. 1 − 0.095^2.

3. TMR…

0.975

0.905

0.991

0.857

0.975. $3R^2 - 2R^3$.

4. MTBF…

100,000 h

10,000 h

1000 h

10^{-5} h

100,000 h. 1/λ.

Try this quiz again

How this helps save the planet

NASA says Hubble received six new gyroscopes in 2009, three remained operational, and when one returned faulty readings NASA moved Hubble to one-gyro mode while keeping another in reserve.

Launched in 1990, Hubble has more than doubled its expected design lifetime; redundancy planned decades earlier keeps a working observatory in orbit instead of a replacement.

On Saving Planets: Flight Dynamics & Controls · Spacecraft Design

Sources: NASA Science: NASA to change how it points Hubble Space Telescope (https://science.nasa.gov/missions/hubble/nasa-to-change-how-it-points-hubble-space-telescope/)

Free learning resources

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook.
- NASA Science: NASA to change how it points Hubble Space Telescope (https://science.nasa.gov/missions/hubble/nasa-to-change-how-it-points-hubble-space-telescope/): NASA Hubble gyro story.

- [ ] **I finished this unit**

UNIT 4 · WEEK 5

Safety Analysis: FMEA and Fault Trees

Hazards, failure modes and effects analysis, risk priority numbers, fault trees with AND and OR gates, and safety-critical design.

Learning objectives

By the end of this unit you can:

- Run a simple FMEA.
- Compute a risk priority number.
- Evaluate AND and OR gates.
- Choose mitigations.

Key concepts

- FMEA works bottom-up: for each part, list how it can fail, the effect, and how it will be detected.
- A risk priority number multiplies severity, occurrence and detection scores (each 1–10, textbook scale).
- A fault tree works top-down from an unwanted event; OR gates add risk, AND gates (redundancy) shrink it.
- For small independent probabilities, an OR gate is nearly the sum and an AND gate is the product.
- Lessons from accidents shape practice; NASA notes its handbook drew on the Columbia Accident Investigation Board and other reports.

Key equations

$$RPN = S \times O \times D$$

```
RPN=S× O× D
```

Risk priority number

$$P_{OR} = 1 - \prod (1 - p_i)$$

```
P_OR=1-(1-p_i)
```

OR gate

$$P_{AND} = \prod p_i$$

```
P_AND= p_i
```

AND gate

$$P_{OR} \approx \sum p_i$$

Rare-event approximation

Worked examples, step by step

Example 4.1 A sensor failure scores S = 8, O = 4, D = 5. RPN?

1. 8 × 4 × 5.

Answer: 160.

Example 4.2 Either of two faults ($p = 10^{-3}$ and 2×10^{-3}) causes loss of data. Probability?

1. 1 − (0.999)(0.998).

Answer: 2.998×10^{-3}.

Example 4.3 Loss needs both faults (redundant design).

1. $10^{-3} \times 2 \times 10^{-3}$.

Answer: 2×10^{-6}.

Practice problems

Work each on paper first, then check.

1. Better detection drops D to 2. New RPN?

   64.

2. Rare-event approximation for the OR gate?

   3×10^{-3}.

3. Which gate does redundancy create?

   AND.

4. Top-down or bottom-up: fault tree?

Top-down.

Common misconceptions

Myth: RPN is a probability.

Actually: It is a ranking score.

Myth: OR gates multiply.

Actually: AND gates multiply.

Myth: Redundant parts fail independently.

Actually: Common causes can fail both.

Flashcards

FMEA

Failure modes and effects analysis.

RPN

Severity × occurrence × detection.

Fault tree

Top-down logic of failure.

OR gate

Any input causes the event.

AND gate

All inputs needed.

Common cause

One event failing several parts.

Self-check quiz

1. RPN...

160

17

40

320

160. 8 × 4 × 5.

2. OR gate...

$\approx 3 \times 10^{-3}$

2×10^{-6}

10^{-3}

0.5

$\approx 3 \times 10^{-3}$. $1 - \prod(1 - p)$.

3. AND gate...

2×10^{-6}

3×10^{-3}

10^{-3}

2×10^{-3}

2×10^{-6}. Product.

4. FMEA works...

bottom-up

top-down

sideways

randomly

bottom-up. Part by part.

Try this quiz again

How this helps save the planet

NASA says lessons documented by the Columbia Accident Investigation Board, the NASA Integrated Action Team and others, plus mishaps in ground operations and commercial

spaceflight, shaped its systems engineering handbook.

The same safety tools protect the satellites that track wildfires, storms and sea ice. Probabilities in this unit are sample values.

On Saving Planets: Solutions · Earth Observation

Sources: NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/)

Free learning resources

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook, Section 6.
- MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/): Free MIT lectures.

☐ **I finished this unit**

Digital Avionics and Data Buses

Binary data, analog-to-digital conversion, quantization, serial data buses (ARINC 429, MIL-STD-1553), message timing and data volume.

Learning objectives

By the end of this unit you can:

- Compute ADC resolution and SNR.
- Compute message transmission time.
- Compare bus types.
- Estimate data volume.

Key concepts

- An N-bit converter divides its input range into 2^N levels; one step is the least significant bit.
- Ideal quantization SNR is about 6.02N + 1.76 dB.
- ARINC 429 is a one-transmitter, many-receiver bus at 100 kbit/s high speed (textbook value); MIL-STD-1553 is a command/response bus at 1 Mbit/s (textbook value).
- Message time is bits divided by bit rate; overhead and gaps add to it.
- Higher radiometric resolution (more bits) shows finer differences but makes more data.

Key equations

$$\Delta V = \frac{V_{FS}}{2^N}$$

`Δ V=_FS2^N`

ADC step

$$SNR \approx 6.02N + 1.76 \text{ dB}$$

Quantization SNR

$$t = \frac{bits}{R_b}$$

`t=(bits)/(R_b)`

Transmission time

$$L = 2^N$$

`L=2^N`

Number of levels

Worked examples, step by step

Example 5.1 A 12-bit ADC spans 10 V. Step size?

1. 10/4096.

Answer: 2.44 mV.

Example 5.2 Its ideal SNR?

1. 6.02 × 12 + 1.76.

Answer: 74.0 dB.

Example 5.3 A 32-bit ARINC 429 word at 100 kbit/s takes how long?

1. 32/100,000.

Answer: 0.32 ms.

Practice problems

Work each on paper first, then check.

1. Landsat 9 has 14-bit radiometric resolution. Levels?

   16,384.

2. SNR for 8 bits?

   49.9 dB.

3. Same 32-bit word on a 1 Mbit/s bus?

   0.032 ms.

4. Step for 16 bits over 10 V?

   0.153 mV.

Common misconceptions

Myth: More bits means more accuracy automatically.

Actually: Noise and calibration also limit it.

Myth: Bit rate equals data rate of useful data.

Actually: Overhead takes a share.

Myth: One bus fits all.

Actually: Pick by timing, integrity and cost.

Flashcards

ADC

Analog-to-digital converter.

LSB

Least significant bit step.

ARINC 429

One-way avionics bus.

MIL-STD-1553

Command/response bus.

Quantization

Rounding to levels.

Bit rate

Bits per second.

Self-check quiz

1. 12-bit step over 10 V...

2.44 mV

24.4 mV

0.244 mV

10 mV

2.44 mV. 10/4096.

2. 12-bit SNR…

74.0 dB

72 dB

49.9 dB

98 dB

74.0 dB. 6.02N + 1.76.

3. ARINC word time…

0.32 ms

3.2 ms

32 ms

0.032 ms

0.32 ms. $32/10^5$.

4. 14-bit levels…

16,384

4096

65,536

14

16,384. 2^{14}.

Try this quiz again

How this helps save the planet

NASA lists Landsat 9 with 14-bit radiometric resolution, 11 spectral bands and more than 700 scenes a day, each 185 km by 180 km.

Fine radiometric steps let scientists see subtle changes in water quality and vegetation health, at the cost of more data for the avionics to store and send.

On Saving Planets: Earth Observation · Circuits

Sources: NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

Free learning resources

- MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/): Free MIT lectures.
- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook.

☐ **I finished this unit**

Navigation Sensors: IMUs, GNSS, Cameras and Lidar

Gyros and accelerometers, inertial navigation drift, satellite navigation ranging, and vision and lidar sensors for autonomy.

Learning objectives

By the end of this unit you can:

- Compute drift from an accelerometer bias.
- Relate timing error to range error.
- Compare sensor strengths.
- Explain why sensors are combined.

Key concepts

- An inertial measurement unit (IMU) measures rotation rates (gyros) and specific force (accelerometers).
- Integrating twice turns a small accelerometer bias into a position error that grows with t².
- Satellite navigation measures range from signal travel time; 1 µs of clock error is about 300 m of range.
- Cameras and lidar measure the surroundings directly, giving position and hazard information that does not drift.
- No single sensor is enough: IMUs are fast but drift; external sensors are slower but bounded.

Key equations

$$e = \tfrac{1}{2} b t^2$$

`e=12bt^2`

Position error from accelerometer bias

$$\rho = c\,\Delta t$$

`ρ=c Δ t`

Range from travel time

$$\theta_e = \omega_b t$$

`θ_e=ω_bt`

Heading error from gyro bias

$$b = 10^{-3} g$$

```
b=10^-3g
```

Sample bias of 1 milli-g

Worked examples, step by step

Example 6.1 An accelerometer bias of 1 milli-g (9.807×10^{-3} m/s²) runs uncorrected for 60 s. Position error?

1. $\tfrac{1}{2} \times 9.807 \times 10^{-3} \times 60^2$.

Answer: 17.7 m.

Example 6.2 After 600 s?

1. $\tfrac{1}{2} \times 9.807 \times 10^{-3} \times 600^2$.

Answer: 1765 m, 100 times worse for 10 times the time.

Example 6.3 A receiver clock is off by 1 μs. Range error?

1. $299{,}792{,}458 \times 10^{-6}$.

Answer: 300 m.

Practice problems

Work each on paper first, then check.

1. Error after 10 s with the same bias?

   0.49 m.

2. Gyro bias 0.01°/h for 10 h?

   0.1° of heading.

3. Why does Dragonfly need lidar at Titan?

   To measure terrain altitude and slope and spot hazards.

4. Clock error for 3 m of range?

   10 ns.

Common misconceptions

Myth: IMUs never need correction.

Actually: Their errors grow with time.

Myth: GNSS works everywhere.

Actually: Not indoors, underwater or at Titan.

Myth: Drift grows linearly.

Actually: Bias drift grows with t^2.

Flashcards

IMU

Gyros and accelerometers.

Dead reckoning

Navigation by integration.

GNSS

Satellite navigation.

Lidar

Laser ranging.

Bias

Constant sensor offset.

Pseudorange

Range including clock error.

Self-check quiz

1. Error at 60 s...

17.7 m

0.59 m

1765 m

35 m

17.7 m. ½bt².

2. Error at 600 s…

1765 m

177 m

17.7 km

600 m

1765 m. 100×.

3. 1 µs clock error…

300 m

3 m

30 km

0.3 m

300 m. c Δt.

4. Sensor that drifts…

IMU

lidar

camera map match

GNSS

IMU. Integration.

Try this quiz again

How this helps save the planet

NASA says Dragonfly's recent "first flight" test ran flight software and flight-like avionics with simulated data from its navigation cameras, inertial measurement units and lidar.

Lidar measures terrain altitude and slope and identifies hazards, letting the rotorcraft choose a safe landing site on Titan, where it is due to arrive in 2034.

On Saving Planets: Flight Dynamics & Controls · Earth Observation

Sources: NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/)

Free learning resources

- NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/): NASA Dragonfly story.
- MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/): Free MIT lectures.

☐ **I finished this unit**

Sensor Fusion and the Kalman Filter

Combining noisy measurements, inverse-variance weighting, the scalar Kalman filter and its predict-update cycle.

Learning objectives

By the end of this unit you can:

- Fuse two measurements by variance.
- Compute a Kalman gain.
- Run one predict-update step.
- Explain why fusion beats either sensor.

Key concepts

- Two independent estimates are best combined by weighting each by the inverse of its variance.
- The fused variance is smaller than either input variance.
- The Kalman filter predicts the state forward, then corrects it with a measurement using gain K.
- K = P/(P + R): trust the measurement more when the prediction is uncertain (large P) and the sensor is good (small R).
- Navigation systems fuse fast IMU predictions with slower camera, lidar or GNSS updates.

Key equations

$$\sigma^2 = \frac{\sigma_1^2 \sigma_2^2}{\sigma_1^2 + \sigma_2^2}$$

Fused variance

$$K = \frac{P}{P + R}$$

K=(P)/(P+R)

Scalar Kalman gain

$$\hat{x}^+ = \hat{x}^- + K(z - \hat{x}^-)$$

x^+= x^-+K(z- x^-)

Update

$$P^+ = (1 - K)P$$

$P^+ = (1 - K)P$

Updated variance

Worked examples, step by step

Example 7.1 Sensors with σ = 4 m and 3 m are fused. Fused σ?

1. $\sigma^2 = 16 \times 9/25 = 5.76$.
2. $\sigma = \sqrt{5.76}$.

Answer: 2.4 m.

Example 7.2 Prediction variance P = 16 m², measurement R = 9 m². Gain?

1. 16/25.

Answer: 0.64.

Example 7.3 Prediction 100 m, measurement 105 m. Update and new variance?

1. $x = 100 + 0.64 \times 5 = 103.2$ m.
2. $P = 0.36 \times 16$.

Answer: 103.2 m with variance 5.76 m².

Practice problems

Work each on paper first, then check.

1. Fuse two equal sensors of σ = 2 m.

   σ = 1.41 m.

2. Gain if R = 0?

   1: trust the measurement fully.

3. Gain if R is huge?

   Near 0: keep the prediction.

4. What grows P between updates?

Process noise in the prediction.

Common misconceptions

Myth: Average sensors equally.

Actually: Weight by inverse variance.

Myth: Fusion can't beat the best sensor.

Actually: It beats both.

Myth: Kalman filters remove all error.

Actually: They minimize variance under assumptions.

Flashcards

Sensor fusion

Combining measurements.

Kalman gain

Weight on the measurement.

Covariance

Uncertainty of the estimate.

Predict

Propagate the state.

Update

Correct with a measurement.

Innovation

Measurement minus prediction.

Self-check quiz

1. Fused σ...

2.4 m

3.5 m

1 m

5 m

2.4 m. √5.76.

2. Kalman gain...

0.64

0.36

1.78

0.5

0.64. P/(P + R).

3. Updated estimate...

103.2 m

105 m

100 m

102.5 m

103.2 m. 100 + 0.64 × 5.

4. New variance...

5.76 m^2

16 m^2

9 m^2

25 m^2

5.76 m^2. (1 − K)P.

Try this quiz again

How this helps save the planet

NASA reports that Dragonfly's team added sensors and capabilities step by step, ending with lidar, the final piece needed to fully simulate what the rotorcraft will encounter on Titan.

A camera emulator rendered each simulated Titan scene in roughly the 20 to 70 millisecond exposure times the cameras will use, so fusion software saw realistic timing. Variances in this unit are sample values.

On Saving Planets: Flight Dynamics & Controls · Spacecraft Design

Sources: NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/)

Free learning resources

- MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/): Free MIT lectures.
- NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/): NASA Dragonfly story.

☐ **I finished this unit**

Communication and Surveillance: ADS-B

Aircraft radios, line-of-sight range, free-space path loss, ADS-B Out and In, and how surveillance supports air traffic control.

Learning objectives

By the end of this unit you can:

- Compute radio horizon range.
- Compute free-space path loss.
- Explain ADS-B Out and In.
- Put FAA traffic numbers in scale.

Key concepts

- VHF and higher frequencies travel by line of sight, so range depends on antenna heights.
- Free-space path loss grows with distance and frequency, 20 $\log_{10}(4\pi d/\lambda)$.
- With ADS-B Out, an aircraft broadcasts its satellite-derived position; ADS-B In lets other aircraft and the ground receive it.
- The FAA calls real-time ADS-B the preferred method of surveillance for air traffic control in the National Airspace System.
- In the U.S., aircraft must carry ADS-B Out to fly in the airspace defined in 14 CFR 91.225.

Key equations

$$d \approx 4.12(\sqrt{h_1} + \sqrt{h_2}) \text{ km}$$

Radio horizon (h in m)

$$L = 20 \log_{10} \frac{4\pi d}{\lambda}$$

`L=20_10(4π d)/()`

Free-space path loss

$$\lambda = c/f$$

Wavelength

$$\bar{n} = N/24$$

`n=N/24`

Worked examples, step by step

Example 8.1 An aircraft at 10,000 m and a ground antenna at 10 m. Radio horizon?

1. 4.12(100 + 3.162).

Answer: 425 km.

Example 8.2 Path loss at 1090 MHz over 200 km.

1. $\lambda = 0.2750$ m.
2. $20 \log_{10}(4\pi \times 2 \times 10^{5}/0.2750)$.

Answer: 139.2 dB.

Example 8.3 The FAA serves more than 44,000 flights a day. Average per hour?

1. 44,000/24.

Answer: About 1833.

Practice problems

Work each on paper first, then check.

1. Double the distance: added path loss?

   6.02 dB.

2. Wavelength at 1090 MHz?

   0.275 m.

3. Passengers per flight from 3 million and 44,000?

   About 68.

4. What does ADS-B Out require on board?

   A transmitter broadcasting position.

Common misconceptions

Myth: Radio range is unlimited.

Actually: Line of sight limits it.

Myth: ADS-B uses radar.

Actually: Aircraft broadcast their own position.

Myth: Path loss is linear in distance.

Actually: It grows as $20 \log_{10} d$.

Flashcards

ADS-B

Automatic dependent surveillance-broadcast.

ADS-B Out

Broadcasts own position.

ADS-B In

Receives traffic and weather.

Path loss

Signal spreading loss.

Radio horizon

Line-of-sight limit.

NAS

National Airspace System.

Self-check quiz

1. Radio horizon...

425 km

42.5 km

4250 km

100 km

425 km. 4.12×103.2.

2. Path loss…

139.2 dB

119 dB

160 dB

13.9 dB

139.2 dB. 20 $\log_{10}(4\pi d/\lambda)$.

3. Flights per hour…

≈ 1833

≈ 440

≈ 44,000

≈ 183

≈ 1833. 44,000/24.

4. ADS-B Out does…

broadcast position

jam radar

track weather only

land the plane

broadcast position. FAA.

Try this quiz again

How this helps save the planet

The FAA says ADS-B improves safety and efficiency in the air and on runways, reduces costs, and lessens harmful effects on the environment.

The FAA's Air Traffic Organization serves more than 44,000 flights and more than 3 million airline passengers a day across more than 29 million square miles of airspace (FY24 figures), so small efficiency gains add up.

On Saving Planets: Aircraft Performance · Solutions

Sources: FAA: Automatic Dependent Surveillance-Broadcast (ADS-B) (https://www.faa.gov/air_traffic/technology/adsb) · FAA: Air Traffic By The Numbers (https://www.faa.gov/air_traffic/by_the_numbers)

Free learning resources

- FAA: Automatic Dependent Surveillance-Broadcast (ADS-B) (https://www.faa.gov/air_traffic/technology/adsb): FAA overview.
- FAA: Air Traffic By The Numbers (https://www.faa.gov/air_traffic/by_the_numbers): FAA facts.

- [ ] **I finished this unit**

Real-Time Flight Software

Tasks, periods and deadlines, CPU utilization, rate-monotonic scheduling, frame rates, watchdogs and fault protection.

Learning objectives

By the end of this unit you can:

- Compute CPU utilization.
- Apply the rate-monotonic bound.
- Relate frame rate and period.
- Describe fault protection.

Key concepts

- Flight software runs periodic tasks that must finish before their deadlines, not just quickly on average.
- Utilization is the sum of each task's run time divided by its period.
- Rate-monotonic scheduling gives higher priority to shorter periods; it is guaranteed when U ≤ n(2^(1/n) − 1).
- Watchdog timers reset a processor that stops responding; fault protection puts a spacecraft in a safe mode.
- Autonomy matters when ground help is far away; NASA says Dragonfly must fly without real-time help from Earth.

Key equations

$$U = \sum \frac{C_i}{T_i}$$

`U=(C_i)/(T_i)`

Utilization

$$U \leq n(2^{1/n} - 1)$$

Rate-monotonic bound

$$f = 1/T$$

`f=1/T`

Frame rate

$$\text{slack} = 1 - U$$

`slack=1-U`

Spare capacity

Worked examples, step by step

Example 9.1 Tasks take 2, 3 and 5 ms with periods 10, 20 and 50 ms. Utilization?

1. 0.2 + 0.15 + 0.1.

Answer: 0.45.

Example 9.2 Rate-monotonic bound for three tasks?

1. 3(2^(1/3) − 1).

Answer: 0.780, so 0.45 is guaranteed schedulable.

Example 9.3 Dragonfly’s camera exposures run about 20 to 70 ms. Matching frame rates?

1. 1/0.07 and 1/0.02.

Answer: About 14.3 to 50 Hz.

Practice problems

Work each on paper first, then check.

1. Bound for n = 2?

   0.828.

2. Bound for n = 4?

   0.757.

3. Slack with U = 0.45?

   0.55.

4. Why safe mode?

To keep the vehicle stable and wait for help or a fix.

Common misconceptions

Myth: Fast on average is enough.

Actually: Every deadline matters.

Myth: U ≤ 1 always means schedulable under RMS.

Actually: Only the bound guarantees it.

Myth: Safe mode means failure.

Actually: It protects the mission.

Flashcards

Deadline

Latest finish time.

Utilization

CPU fraction used.

Rate-monotonic

Shorter period, higher priority.

Watchdog

Reset timer.

Safe mode

Protective configuration.

Autonomy

Acting without ground help.

Self-check quiz

1. Utilization...

0.45

0.10

1.0

0.78

0.45. Sum C/T.

2. RM bound n = 3...

0.780

0.693

0.828

1

0.780. n(2^(1/n) − 1).

3. 70 ms frame...

14.3 Hz

70 Hz

7 Hz

50 Hz

14.3 Hz. 1/0.07.

4. Watchdog does...

resets a hung processor

counts bits

measures gyros

cools boxes

resets a hung processor. Timer.

Try this quiz again

How this helps save the planet

NASA reports Hubble entered safe mode several times when a gyro gave faulty readings, suspending science while the telescope awaited instructions; fault protection kept it safe.

NASA says Dragonfly engineers will deliberately introduce faults in tests so the rotorcraft can respond autonomously, because everything it does on Titan must happen without real-time help from Earth.

On Saving Planets: Intro to Programming · Flight Dynamics & Controls

Sources: NASA Science: NASA to change how it points Hubble Space Telescope (https://science.nasa.gov/missions/hubble/nasa-to-change-how-it-points-hubble-space-telescope/) · NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/)

Free learning resources

- MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/): Free MIT lectures.
- NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/): NASA Dragonfly story.

☐ **I finished this unit**

Integration, Verification and Operations

Incremental integration, verification methods, hardware-in-the-loop testing, fault injection, commissioning and life extension.

Learning objectives

By the end of this unit you can:

- Name the four verification methods.
- Plan incremental integration.
- Explain hardware-in-the-loop testing.
- Connect operations to mission life.

Key concepts

- Requirements are verified by test, analysis, inspection or demonstration.
- Integration goes step by step so a problem can be traced to the last thing added.
- Hardware-in-the-loop and flight-like testbeds run real flight software against simulated sensors.
- Fault-injection tests prove the system responds correctly when something breaks.
- Good operations, spares and consumables can stretch a mission well past its design life.

Key equations

$$t_{arr} = t_{launch} + t_{cruise}$$

`t_arr=t_launch+t_cruise`

Arrival year

$$L_{ext} = \frac{L_{actual}}{L_{design}}$$

`L_ext=_actualL_design`

Life extension ratio

$$A = \frac{MTBF}{MTBF + MTTR}$$

`A=(MTBF)/(MTBF+MTTR)`

Availability

$$V = \{T, A, I, D\}$$

`V=,A,I,D\`

Verification methods

Worked examples, step by step

Example 10.1 NASA says Dragonfly launches no earlier than 2028 on a six-year voyage. Earliest arrival?

1. 2028 + 6.

Answer: 2034, matching NASA.

Example 10.2 Landsat 9 consumables last at least 10 years against a 5-year design life. Extension ratio?

1. 10/5.

Answer: 2.

Example 10.3 Dragonfly will spend three years flying at Titan. Mission end at the earliest?

1. 2034 + 3.

Answer: 2037 (computed).

Practice problems

Work each on paper first, then check.

1. Name the four verification methods.

   Test, analysis, inspection, demonstration.

2. Why integrate incrementally?

   To trace problems to the last change.

3. Hubble launched in 1990; its 34th anniversary was in which year?

   2024.

4. What is fault injection?

Deliberately causing faults in test.

Common misconceptions

Myth: Test everything at the end.

Actually: Integrate and test in steps.

Myth: Analysis is weaker than test.

Actually: Each method fits different requirements.

Myth: Design life is the end.

Actually: Missions often run longer.

Flashcards

Verification by test

Measure it.

Analysis

Prove by calculation.

Inspection

Look at it.

Demonstration

Show it works.

HIL

Hardware-in-the-loop.

Commissioning

Checkout after launch.

Self-check quiz

1. Dragonfly arrival...

2034

2028

2030

2040

2034. 2028 + 6.

2. Landsat 9 ratio...

2

0.5

5

10

2. 10/5.

3. Methods count...

4

2

3

6

4. T, A, I, D.

4. Testbed with real software...

hardware-in-the-loop

FMEA

N^2 diagram

trade study

hardware-in-the-loop. HIL.

Try this quiz again

How this helps save the planet

NASA says Dragonfly's team built flight capabilities incrementally, from spinning a single rotor to a full simulated first flight, and plans to repeat it on the actual flight system.

NASA notes Landsat 9's onboard calibration and redundancy keep its data accurate and reliable for the mission's life, extending the longest record of Earth observation.

On Saving Planets: Earth Observation · Spacecraft Design

Sources: NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/) · NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

Free learning resources

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook, Section 5.
- MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/): Free MIT lectures.

☐ **I finished this unit**

Problem Sets

These practice problems live inside each unit. Work on paper first, then open the answer.

1. The Systems Engineering Life Cycle and Requirements
   4 problems
2. Architecture, Interfaces and Integration
   4 problems
3. Reliability and Redundancy
   4 problems
4. Safety Analysis: FMEA and Fault Trees
   4 problems
5. Digital Avionics and Data Buses
   4 problems
6. Navigation Sensors: IMUs, GNSS, Cameras and Lidar
   4 problems
7. Sensor Fusion and the Kalman Filter
   4 problems
8. Communication and Surveillance: ADS-B
   4 problems
9. Real-Time Flight Software
   4 problems
10. Integration, Verification and Operations
    4 problems

The lab (Avionics and systems lab)

The lab is the hands-on part of the course. Here it is free and for practice only, with no credit.

Every lab runs in a free simulation or a spreadsheet, so there are no electrical hazards. Do not open or modify real aircraft, drone or vehicle electronics for this course. Take screen breaks, sit with good posture, and keep cables out of walkways.

Safety reference: OSHA: Walking-working surfaces (slip, trip and fall hazards) (https://www.osha.gov/walking-working-surfaces)

Lab A: Interface growth and an N² diagram

WEEK 2

Goal: Build an N² diagram for a small avionics suite and see how potential interfaces grow with the number of boxes.

$$I = n(n-1)/2$$

`I=n(n-1)/2`

Potential interfaces

Procedure

1. List boxes: flight computer, IMU, GNSS receiver, radio, display, power unit, air data, autopilot.
2. Draw an 8 × 8 grid with boxes on the diagonal and mark which pairs exchange data.
3. Compute n(n − 1)/2 for n = 4, 8 and 12.
4. Count your marked cells and compare with the maximum.

Data table

Boxes n	Potential interfaces
4	6
8	28
12	66

Computed values.

Sample calculation

1. 8 × 7/2 = 28.
2. 12 × 11/2 = 66.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/)

Planet link: NASA: its handbook update includes Model-Based Systems Engineering. NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/)

- [ ] **I completed this lab (wet or virtual)**

Lab B: Reliability of single, dual and triple units

WEEK 4

Goal: Compare a single unit, a parallel pair and 2-of-3 voting over time in a spreadsheet.

$$R_{2/3} = 3R^2 - 2R^3$$

R_2/3=3R^2-2R^3

Two-of-three voting

Procedure

1. Enter λ = 10^{-5} per hour.
2. Compute R = e^(−λt) for t = 1000, 10,000 and 50,000 h.
3. Compute the parallel pair and 2-of-3 voting.
4. Find where 2-of-3 drops below a single unit (R = 0.5).

Data table

t (h)	Single	Dual	2-of-3
1000	0.990	0.9999	0.9997
10,000	0.905	0.991	0.975
50,000	0.607	0.845	0.657

Computed sample values.

Sample calculation

1. R(50,000) = e^(−0.5) = 0.607.
2. 2-of-3 = $3(0.607)^2 - 2(0.607)^3$ = 0.657.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/)

Planet link: NASA: Hubble can make science observations with only one working gyro. NASA Science: NASA to change how it points Hubble Space Telescope (https://science.nasa.gov/missions/hubble/na

sa-to-change-how-it-points-hubble-space-telescope/)

- [ ] **I completed this lab (wet or virtual)**

Lab C: Redundant circuits

WEEK 5

Goal: Use PhET Circuit Construction Kit: DC to compare series and parallel bulbs when one fails.

$$R_p = \frac{R_1 R_2}{R_1 + R_2}$$

`R_p=(R_1R_2)/(R_1+R_2)`

Parallel resistance

Procedure

1. Build two 10 Ω bulbs in series on a 12 V battery, then break one wire.
2. Rebuild them in parallel and break one branch.
3. Measure current before and after each failure.
4. Relate the result to series and parallel reliability.

Data table

Circuit	Resistance (Ω)	Current at 12 V (A)
Parallel, both good	5	2.4
Parallel, one failed	10	1.2
Series, both good	20	0.6

Computed sample values.

Sample calculation

1. 10 × 10/20 = 5 Ω.
2. 12/5 = 2.4 A.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Runs in a browser.

PhET: Circuit Construction Kit: DC (https://phet.colorado.edu/en/simulations/circuit-construction-kit-dc)

Planet link: NASA: Landsat 9's onboard redundancy keeps its data reliable. NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

- [ ] **I completed this lab (wet or virtual)**

Lab D: ADC resolution and data volume

WEEK 7

Goal: Compute step size and SNR for several converter resolutions.

$$\Delta V = V_{FS}/2^N$$

`Δ V=V_FS/2^N`

ADC step

Procedure

1. Enter a 10 V full scale.
2. Compute step and SNR for 8, 12 and 16 bits.
3. Compute word time for 32 bits at 100 kbit/s and 1 Mbit/s.
4. Discuss why Landsat 9 uses 14 bits.

Data table

Bits	Step (mV)	SNR (dB)
8	39.06	49.9
12	2.441	74.0
16	0.1526	98.1

Computed values.

Sample calculation

1. 10/256 = 39.06 mV.
2. 6.02 × 16 + 1.76 = 98.1 dB.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

Planet link: NASA: Landsat 9 has 14-bit radiometric resolution. NASA Science: Landsat 9 (https://landsat.gsfc.nasa.gov/satellites/landsat-9/landsat-9-overview/)

- [ ] **I completed this lab (wet or virtual)**

Lab E: Inertial drift and sensor fusion

WEEK 9

Goal: Model position drift from an accelerometer bias, then fuse two position sensors.

$$e = \tfrac{1}{2} b t^2$$

e=12bt^2

Bias drift

Procedure

1. Enter b = 9.807 × 10⁻³ m/s² (1 milli-g).
2. Compute error at 10, 60 and 600 s.
3. Fuse σ = 4 m and 3 m sensors and compute the Kalman gain for P = 16, R = 9.
4. Add noise with a random-number column and watch the filter.

Data table

t (s)	Error (m)
10	0.49
60	17.65
600	1765

Computed sample values.

Sample calculation

1. ½ × 9.807 × 10⁻³ × 100 = 0.49 m.
2. Fused σ = √5.76 = 2.4 m.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/)

Planet link: NASA: Dragonfly's test used simulated camera, IMU and lidar data. NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/)

- [ ] **I completed this lab (wet or virtual)**

Lab F: Rate-monotonic schedulability

WEEK 12

Goal: Compute utilization bounds and test task sets in a spreadsheet.

$$U \le n(2^{1/n} - 1)$$

Rate-monotonic bound

Procedure

1. Compute the bound for n = 1 to 4.
2. Enter Unit 9's task set and compute U.
3. Add a task until U exceeds the bound.
4. Discuss what to do when the bound fails.

Data table

n	Bound
1	1.000
2	0.828
3	0.780
4	0.757

Computed values.

Sample calculation

1. 2(√2 − 1) = 0.828.
2. 4(2^(1/4) − 1) = 0.757.

> **Safety**
>
> - Computer only.

Home or virtual alternative

- Any spreadsheet works.

MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/)

Planet link: NASA: Dragonfly must fly autonomously, without real-time help from Earth. NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/)

☐ **I completed this lab (wet or virtual)**

Exam prep practice sets

Time yourself: about 10 minutes per problem. Then compare with the full solutions.

Midterm practice set (Units 1–5)

1. Potential interfaces for 10 boxes?
    1. 10 × 9/2.

    Answer: 45.

2. Parallel pair, $\lambda = 2 \times 10^{-5}$ /h over 5000 h?
    1. R = e^(−0.1) = 0.905.
    2. $1 - 0.095^2$.

    Answer: 0.991.

3. RPN for S = 6, O = 3, D = 7?
    1. 6 × 3 × 7.

    Answer: 126.

4. Step of a 10-bit ADC over 5 V?
    1. 5/1024.

    Answer: 4.88 mV.

5. Ideal SNR for 10 bits?
    1. 6.02 × 10 + 1.76.

    Answer: 62.0 dB.

Final practice set (Units 1–10)

1. Drift after 30 s with a 2 milli-g bias?
    1. ½ × 0.01961 × 900.

Answer: 8.83 m.

2. Fuse two sensors of σ = 5 m.

    1. σ² = 12.5.

    Answer: 3.54 m.

3. Kalman gain for P = 4, R = 1?

    1. 4/5.

    Answer: 0.8.

4. Radio horizon from 1000 m to a 10 m antenna?

    1. 4.12(31.62 + 3.162).

    Answer: 143.3 km.

5. Utilization for tasks 1/5, 2/10, 3/30 ms?

    1. 0.2 + 0.2 + 0.1.

    Answer: 0.5.

6. Availability, MTBF 500 h, MTTR 5 h?

    1. 500/505.

    Answer: 0.990.

Formula sheet

$$\text{Margin} = (C - N)/N,\ m_{alloc} = m_{est}(1 + M) \qquad I = n(n-1)/2,\ U_{bus} = B/B_{max}$$

$$R = e^{-\lambda t},\ R_p = 1 - \prod (1 - R_i),\ R_{2/3} = 3R^2 - 2R \qquad RPN = SOD,\ P_{OR} = 1 - \prod (1 - p_i),\ P_{AND} = \prod$$

$$\Delta V = V_{FS}/2^N,\ SNR = 6.02N + 1.76 \qquad e = \tfrac{1}{2} b t^2,\ \rho = c\Delta t$$

$$\sigma^2 = \sigma_1^2 \sigma_2^2/(\sigma_1^2 + \sigma_2^2),\ K = P/(P + R) \qquad d = 4.12(\sqrt{h_1} + \sqrt{h_2}),\ L = 20\log_{10}(4\pi d/\lambda)$$

$$U = \sum C_i/T_i \le n(2^{1/n} - 1) \qquad A = MTBF/(MTBF + MTTR)$$

Constants

Constant	Value
Speed of light	c = 299,792,458 m/s (exact)
Standard gravity	g = 9.80665 m/s²
ADS-B frequency (textbook value)	1090 MHz
ARINC 429 high speed (textbook value)	100 kbit/s
MIL-STD-1553 (textbook value)	1 Mbit/s
Hours per year	8760 h

Source: NIST: CODATA value, speed of light in vacuum (https://physics.nist.gov/cgi-bin/cuu/Value?c)

Free texts and simulations

Use these free texts, lectures and simulations alongside the course.

- NASA Systems Engineering Handbook (https://www.nasa.gov/reference/systems-engineering-handbook/): Free NASA handbook.
- MIT OpenCourseWare 16.842 Fundamentals of Systems Engineering (Fall 2015) (https://ocw.mit.edu/courses/16-842-fundamentals-of-systems-engineering-fall-2015/): Free MIT lectures.
- FAA: Automatic Dependent Surveillance-Broadcast (ADS-B) (https://www.faa.gov/air_traffic/technology/adsb): FAA overview.
- PhET: Circuit Construction Kit: DC (https://phet.colorado.edu/en/simulations/circuit-construction-kit-dc): Circuits and redundancy.
- NASA Science: Dragonfly completes first simulated flight (Oct. 23, 2026) (https://science.nasa.gov/blogs/dragonfly/2026/10/23/nasas-dragonfly-completes-first-simulated-flight/): Avionics testing story.
- NASA Science: NASA to change how it points Hubble Space Telescope (https://science.nasa.gov/missions/hubble/nasa-to-change-how-it-points-hubble-space-telescope/): Redundancy in practice.

Glossary

ADS-B
Automatic dependent surveillance-broadcast.

ARINC 429
One-way avionics data bus.

Availability
Fraction of time a system works.

FMEA
Failure modes and effects analysis.

Fault tree
Top-down failure logic.

Hardware-in-the-loop
Real software and hardware with simulated inputs.

IMU
Inertial measurement unit.

Interface control document
Agreement on an interface.

Kalman filter
Optimal recursive estimator.

Lidar
Laser ranging.

MBSE
Model-based systems engineering.

MIL-STD-1553
Command/response data bus.

MTBF
Mean time between failures.

N² diagram
Interface matrix.

Rate-monotonic scheduling
Shorter period gets higher priority.

Redundancy
Extra units for backup.

Requirement
Verifiable statement of need.

Safe mode
Protective spacecraft configuration.

V-model
Decompose then integrate and verify.

Watchdog timer
Resets a hung processor.

Self-assessment rubric

No grade or credit is given. Use this to judge honestly where you are in each unit.

Level	What it looks like
4 · Mastery	Traces every design choice to a requirement, checks interfaces and failure cases, keeps units and probabilities consistent, and explains trades in plain words.
3 · Proficient	Solves the practice and exam sets with minor slips and checks units.
2 · Developing	Follows worked examples but mixes up series and parallel reliability or OR and AND gates.
1 · Beginning	Computes without a requirement or block diagram; needs to revisit the unit.

Suggested weighting if you want a score

Part	Weight
Practice problems	20%
Labs	25%
Midterm practice set	25%
Final practice set	30%

Aim for level 3 or better in every unit before moving to the next course.

Related courses

- Heat Transfer AERO 440
- Capstone (aircraft or CubeSat) AERO 490
- Propulsion AERO 410
- All courses