SEMESTER 1 ASSESSMENT 2021/22

TITLE: **Spacecraft Systems Engineering and Design**

DURATION: 120 MINS (150 MINS if moved online)

This paper contains **FOUR** questions.

Answer All **FOUR** questions on this paper.

Your answer to each question attempted should commence on a new page and be appropriately numbered.

All Questions are worth 25 marks (total 100 marks). An outline marking scheme is shown in brackets to the right of each question. Note that marks will only be awarded when appropriate working is given.

The following will be provided on request:

1. An Engineering Data Book by Calvert and Farrar
2. Graph paper

**Note that The Astro Equation booklet is provided separately**

Only University approved calculators may be used.

A foreign language direct 'Word to Word' translation dictionary (paper version ONLY) is permitted, provided it contains no notes, additions or annotations.

**Q1.** An advanced hyperspectral instrument is being used for a remote sensing mission to monitor natural resources and atmospheric characteristics, including information on land cover and crop status, pollution quality of inland waters, soil mixture and carbon cycle. The satellite is in a Sun-synchronous circular orbit at an altitude of 615 km and inclination of 97.85°. The design of the advanced hyperspectral instrument is based on a pushbroom scanning approach providing hyperspectral imagery of 250 bands at a spatial resolution of 30 m on a swath width of 30 km. Data quantisation of multispectral images is 12-bits with a spatial sample rate of 20 $\mu m$.

Answer the following questions.

(i) Calculate the instantaneous field of view of the instrument in $\mu$rad.

**[3 marks]**

(ii) Calculate the focal length of the instrument in mm.

**[3 marks]**

(iii) Find the uncompressed data rate for which the in-track and cross-track spatial resolutions of the instrument are the same. Express your answer in Mbps.

**[10 marks]**

**Q1. Cont…**

 

**Q1. Cont…**

(iv) A second objective of this remote sensing mission is to provide centimetre-precision, sea surface height data. A radar altimeter can be used for this objective. Explain why a radar altimeter is better than a lidar system, and comment on the likely impacts on the power and attitude control sub-systems.

**[5 marks]**

(v) Explain how it is possible for a spacecraft to be compliant with all sub-system technical requirements when verified yet fail to meet mission objectives. Use clear systems engineering keywords and phrases.

**[4 marks]**

**[Total 25 marks]**

TURN OVER

**Q2.** Use the given information to answer questions (i) and (ii).

(i) A meteorological satellite in geostationary Earth orbit with zero eccentricity has a cross-sectional area of 40 $m^2$ and a dry mass of 3,000 kg. The solar radiation pressure coefficient of this communication satellite is 1.2. When it reaches the end of its life, it will be moved to a disposal orbit in compliance with the IADC space debris mitigation guidelines. It uses a mono-propellant hydrazine thruster for both station keeping and post-mission disposal, which provides a thrust about 20N at a specific impulse of 224 seconds.

a) Calculate the semi-major axis of the disposal orbit for this satellite assuming the final eccentricity is equal to the maximum value allowed in the guideline. Give your answer in km.

**[2 marks]**

b) Assume that this satellite uses approximately 25 kg of propellant annually for station keeping. This satellite has initially 250 kg of hydrazine for its mono-propellant hydrazine thruster. Estimate the maximum operational time of the satellite in compliance with the IADC space debris mitigation guidelines. Give your answer in years.

**[10 marks]**

**Q2. Cont…**

**Q2. Cont…**

(ii) ALPS (**ALI**-printed **P**ropulsion **S**ystem) is a variant of a vacuum arc thruster used for shortening a spacecraft's orbital lifetime or enable controlled re-entry and safe recovery of a 1U CubeSat. The total system mass of the ALPS is 200 g including 80 g of metallic propellants. It provides a thrust of about 10 μN at a specific impulse of 300 seconds. The drag coefficient of a 1U CubeSat is 2.2, and its maximum cross-sectional area is 100 cm$^2$. The remaining orbital lifetime in seconds of a CubeSat with mass $m$, cross-sectional area $A$ and drag coefficient $C_D$ on a circular low Earth orbit with semi-major axis *a* can be estimated using

$$t_L = \frac{H \cdot \tau \cdot B}{2000\pi a^2 \rho}$$

where *H* is the density scale height in m, $\tau$ is the orbit period (in seconds), $\rho$ is the atmospheric mass density, a is the semi-major axis in m, and $B$ is the satellite ballistic coefficient in kg/m$^2$. Use a density scale height of *H* = 266 km and an atmospheric mass density $\rho$ = 3.54×10$^{-16}$ kg/m$^3$. Assume the mass of 1U CubeSat (without ALPS) is 1.2 kg and ignore additional mass introduced by ALPS. Use the given information to answer the following questions.

a) Calculate the maximum altitude of 1U CubeSat without using ALPS while complying with the IADC space debris mitigation guidelines. Give your answer in km.

**[4 marks]**

b) Assume ALPS can apply $\Delta V$ instantaneously. Calculate the maximum altitude of a 1U CubeSat with using ALPS while complying with the IADC space debris mitigation guidelines. Give your answer in km.

**[9 marks]**

**[Total 25 marks]**

TURN OVER

 

**Q3.** Use the given information to answer questions (i) - (iii).

(i) Remote sensing of areas in the presence of harsh conditions, such as in deserts, requires high spatial and spectral resolutions. However, current instruments cannot provide these data due to the observational constraints. Image fusion is one of several useful approaches to tackle these challenges with current panchromatic and multi-spectral instruments. The main issue of using image fusion on remote sensing is that it has too many options and combinations of affecting factors in the fusion process. It therefore requires optimising some parameters such as the type of wavelet transformation, levels of decomposing imagery and methods of combining decomposed image components. Table Q3-ia shows the design parameters and their levels.

| **Design parameters** | **Description** | **Level 1** | **Level 2** | **Level 3** | **Level 4** | **Level 5** |
|---|---|---|---|---|---|---|
| A | Wavelet type | Db4 | Bior1.1 | Rbio1.1 | Coif1 | Sym2 |
| B | Decomposition level | 1 | 2 | 3 | 4 | 5 |
| C | Fusion method for approximation | Min | Max | Mean | Up-down | Down-up |
| D | Fusion method for the details | Min | Max | Mean | Up-down | Down-up |

***Table Q3-ia. design parameters and their levels.***

**Q3. Cont…**

**Q3. Cont…**

The signal-to-noise ($S/N$) values are given in Table Q3-ib.

| Level | A | B | C | D |
|---|---|---|---|---|
| 1 | -0.6507 | -2.8712 | -2.4692 | -1.8027 |
| 2 | -1.2350 | -2.6336 | -1.7322 | -2.0931 |
| 3 | -2.2776 | -1.8196 | -1.8640 | -1.7919 |
| 4 | -2.6090 | -0.9381 | -2.5610 | -3.0191 |
| 5 | -4.2546 | -2.7644 | -2.4005 | -2.3200 |

***Table Q3-ib signal-to-noise (S⁄N) values***

a) How many experiments would be required if a Design of Experiments approach was not used?

**[2 marks]**

b) Find the minimum number of experiments that must be conducted.

**[2 marks]**

c) Identify the optimum parameters for the image fusion approach on remote sensing.

**[4 marks]**

**Q3. Cont…**

TURN OVER

**Q3. Cont…**

(ii) A small satellite is providing images of the Earth from a dawn-dusk Sun-synchronous orbit at 1AU and with its long axis aligned with the local vertical. It uses body-mounted solar arrays mounted on the largest faces of the satellite to generate electrical power. The delivered power at the end of life can be estimated as:

$$P_{EOL} = S\eta\eta_p(1-D)A_n$$

where $S$ is the solar flux, $\eta$ is the solar cell efficiency, $\eta_p$ is the cell packing efficiency, $D$ is the degradation factor and $A_n$ is the effective surface area of the solar array. The properties of the solar array used in the satellite are listed as:

| | |
|---|---|
| Average solar cell efficiency | 25.5% |
| Degradation factor of a solar cell | 0.25 |
| Solar cell packing efficiency | 90% |

The effective surface area of the solar array is a function of both in-plane angle of the Sun and the out-of-plane angle as shown in the equation below:

$$A_n = ab\cos\theta\,(\cos\phi + \sin\phi)$$

where $a$ is the length of the longest side of the satellite, $b$ is the length of the shortest side, $\phi$ is the in-plane angle of the Sun, and $\theta$ is the out-of-plane angle.

Due to the baseline design of body-mounted solar arrays, the science-derived pointing requirement means that the solar panels will not always be normal to the Sun, causing a reduction in the performance proportional to the cosine of the angle between the solar array normal vector and the vector to the Sun.

**Q3. Cont…**

**Q3. Cont…**

a) Propose two design parameters and two noise factors.
**[4 marks]**

b) Identify one subsystem of this spacecraft, other than the power subsystem, that will have a strong influence on the choice of solar array configuration and justify your choice.
**[3 marks]**

c) Propose a suitable quality metric (i.e. the value that the engineers would like to minimise or maximise) and provide a justification for your answer.
**[4 marks]**

(iii) The propellant tank for a spacecraft is the focus of a robust design approach using the Taguchi method. The tank is being designed to burn up completely on re-entry, once the spacecraft has broken up due to the aerodynamic forces and heating, so that there is no risk to people or property on the ground. Engineers need to keep the capacity (volume) of the tank constant. In addition, it must also be ensured that the tank is destroyed even if the spacecraft breaks up at different altitudes.

a) Propose two design parameters and two noise factors.
**[4 marks]**

b) Propose two suitable quality characteristics.
**[2 marks]**

**[Total 25 marks]**

TURN OVER

 

**Q4.** Use the given information to answer questions (i) and (ii)

(i) A space-orientated service provider plans to operate a constellation of satellites to provide global internet services.

a) Assume that the coverage area of each satellite just touches the coverage area of the nearest Easterly or Westerly satellite at the Equator, the region to be served spans from 150° West to 140° East longitude, and the minimum acceptable elevation at the edge of coverage is 50°. Calculate the number of satellites in Geostationary orbits that are required to deliver 24-hour internet service.

**[7 marks]**

b) Assume the minimum acceptable elevation at the edge of coverage is 10°, and the orbital height of the constellation is 5400 km. Calculate the number of satellites in the constellation that are required to deliver complete (24-hour) global internet service.

**[6 marks]**

(ii) The company Space-Z plans to operate a constellation of small-satellites to provide future global data communication services for autonomous ships. The constellation of 42 satellites will be arranged in 6 circular orbital planes inclined at 89° and at an altitude of 750 km.

a) Calculate the in-plane spacing between the satellites and the node spacing

**[4 marks]**

**Q4. Cont…**

**Q4. Cont…**

b) Assume the ground-based antenna is at the edge of the coverage area**.** Calculate the latency for a four-way “hop” if the minimum acceptable elevation at the edge of coverage is 30°.

**[3 marks]**

c) Identify three key design drivers that might have led to the selection of the altitude for the constellation; rank them according to importance and justify your choice.

**[5 marks]**

**[Total 25 marks]**

**END OF PAPER**



 