PRINT BRADLEY'S

PROBLEM ANALYSIS

METR4810

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1 TASK ANALYSIS

1.1 PROBLEM REQUIREMENTS

This problem requires the construction of a scale satellite and ground station. The satellite has some operational and construction requirements. The operational requirements are detailed in the first column below (see ***FIGURE*** for a summary of the system layers these occur on). The construction requirements are in column 2.

1. receive commands (calibrate, move to coordinate, etc.) from any human interface device, optionally using the freely permitted computer to enhance the experience;
2. transmit such commands from the ground station to the satellite via a wireless link, utilising the Deep Space Network (DSN);
3. receive and execute relevant commands (e.g. move to position and stabilise);
4. sense an image of a faraway information card;
5. encode the image in a suitable format;
6. transmit the image back to the base station;
7. store the image on the base station, and
8. display the image on the HDMI display for the human to interpret, optionally using the computer to produce the HDMI signal.

- a radiation-hardened management controller (MC) which can power cycle imaging, telemetry and orientation control systems;
- uplink commands must pass through the DSN (10 second delay, 1200 baud, 3.3V);
- a camera capable of imaging "small" text (to be defined later in the semester), and
- HDMI output data feed;
- a mass of less than 750g;
- $200 budget (free items to be costed at 50% market price);
- satellite centre of gravity and size requirements as defined in the project spec (approximately 100Øx175mm cylinder)
- <15kJ LiPo energy, other batteries unrestricted, and
- the whole system must fit into a 400x200x180mm mailing boxIf all the above requirements are satisfied, then the system can obtain full marks for the demonstration. The associated scope of these requirements is detailed below.

In Scope	***Out of Scope***
• operational considerations under space radiation (power cycle on command, rad-hardened mother MCU); • mass and size restrictions of a microsatellite (similar to cubesat); • stabilisation in a low-earth orbit environment (no atmosphere, no gravity, magnetic field still detectable); • imaging of a far target, and • image encoding.	• transmitting over space scale distances; • downlink time delays; • power harvesting; • momentum actuator desaturation in space environment; • ground-based imaging systems, and • thermal problems in space environment.

2 PROBLEM DECONSTRUCTION

The preceding operational analysis can be used to break down the problem into finite systems which when connected can solve the problem. The implementation of these systems must be done with respect to the constructional requirements. For simplicity, it makes sense to combine operational requirements 1, 7 and 8 into a unified "ground station device", and capabilities 2, 6 into a bi-directional link between the ground station and satellite. The finite hardware decisions are detailed below. The performance requirements of each system component are directly related to their function in the system.

Requirement Number(s)	***Design Choice***	***Requirements***
1, 7, 8	Ground station processing unit	Human interface devices (buttons, USB/keyboard) USART 3.3V output (for DSN)

		HDMI output (for displaying images) Persistent storage (for 20-50 photos@10MB[1] each, ~0.2-0.5GB) Interfacing with wireless link device (e.g. SPI/I2C/onboard)
2, 6	Bi-directional wireless protocol and physical layer specification	>10m range >5MBps throughput (e.g. 10MB image transmitted over 2 seconds) Not atmosphere dependent Easily interfaceable to ground station and satellite Simple and easy to interface with software tools Power efficiency
3	Satellite movement control system	Stable with minimal vibrations (to ensure best image) Power efficient Operable within the 90° cone field of view that targets will be in Simple to implement and construct
4	Imaging sensor and optics	Large sensor size for good low light performance Easily interface-able with satellite processing unit Optics to provide image of “small text” High enough resolution CALCULATION HERE
5	Image encoding processing unit	Must be able to process the image into a transmittable format Likely 32-bit to handle full images

3 CANDIDATE DESIGN

It is desirable to use off-the-shelf components when the specifications of such components match the application closely. The ground station processing unit, bi-direction wireless protocol, imaging sensor, and image encoding processing unit can be accomplished by a Raspberry Pi Zero and PiCameraV2. The Raspberry Pi has extensive support for the PiCamera. Wireless transmission can be achieved directly to a computer or directly to another Raspberry Pi Zero via WiFi. The PiCameraV2 has a 5MP sensor and 3.68x2.76mm sensor dimensions. This should give reasonable low-light performance. There are also multiple interfaces allowing design flexibility, USB and Bluetooth are alternatives for imaging and wireless communication if image quality or power usage become a problem.

As for the movement control system, this can be achieved with a rad-hardened available ATMEGA128. It has enough GPIO pins to control power cycling critical systems, it has I2C interfaces for gyroscope and magnetometer communication, at has optional 16MHz clocking. The sensors chosen have a maximum output data rate of 1kHz, this means there are 16000 clock cycles between sensor readings which will be enough to calculate simple PID control values, as well as leaving some room for expansion. Sensing for the control system can be done using a gyroscope and magnetometer. The gyroscope provides high frequency and high precision angular rate information while the magnetometer provides absolute heading information.

Risk	***Mitigation Strategy***
Blurry images caused by large exposure times[2]	Change to USB webcam interface with larger sensor size (C920 for example), remove camera optical stage to increase aperture size.
Control loop processor not fast enough	Investigate use of STM32F0 series microcontrollers which have a higher clock rate. VA10820 is an example of a rad hardened ARM M0 MCU.
Control loop unstable	Early bench testing of solution, modelling of solution in MATLAB.
Premature saturation of reaction wheels	Reaction wheel size is configurable, calculations performed to ensure reaction wheel has adequate control authority.
WiFi high power consumption	Duty cycling of radio, alternate lower power Bluetooth protocol.

Task	***Resources***	***Time to complete***	***Milestone date***
Bench testing of single axis control system	Ben B, Josh, 3D printed prototype, motor, gyro, magnetometer	1-2 weeks	16/3
Feasibility testing of camera and optics	Howie, PiCam, PiZero, USB webcams	1 week	9/3

[1] Suppose 5MP image with 16-bit colour. 5 million pixels x 2 bytes = 10MB image. Possible to get lower with compression but raw is ideal.
[2] See Appendix C.

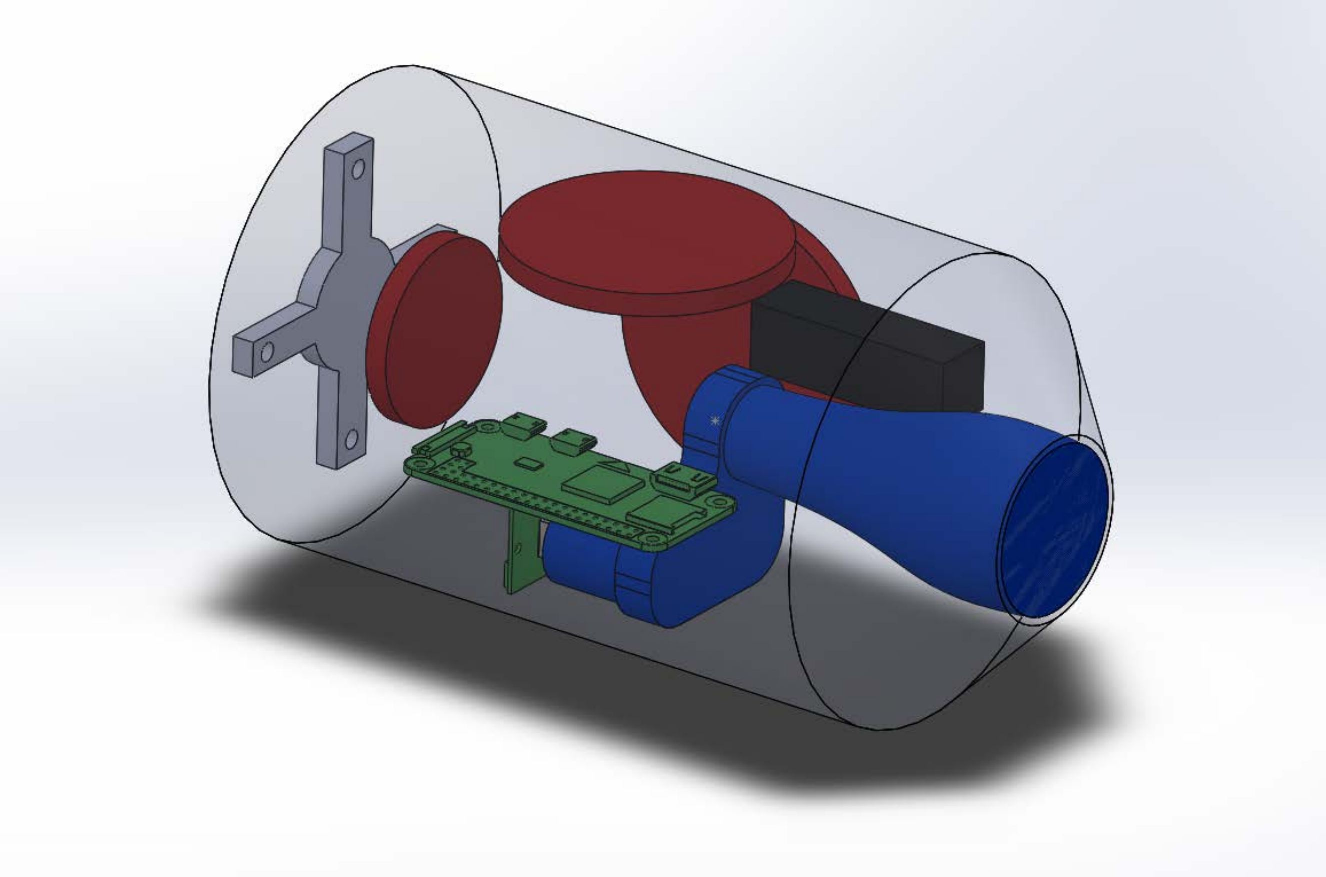
Sat CAD model (inc PCB)	Ben C, Creo/Inventor, Altium/Kicad	2-3 weeks	23/3
Manufacture parts (inc PCB)	Ben B, Josh, Howie, Ben C	2 weeks	
Craft Construction	Ben B, Josh, Howie, Ben C	2 weeks	
WiFi link software	Howie	2 weeks	
Testing/Design Iteration	Ben B, Josh, Howie, Ben C	3-4 weeks	

APPENDIX A: SATTELITE MOCKUP

Satellite mockup. Intended to see the maximum size available for reaction wheels.

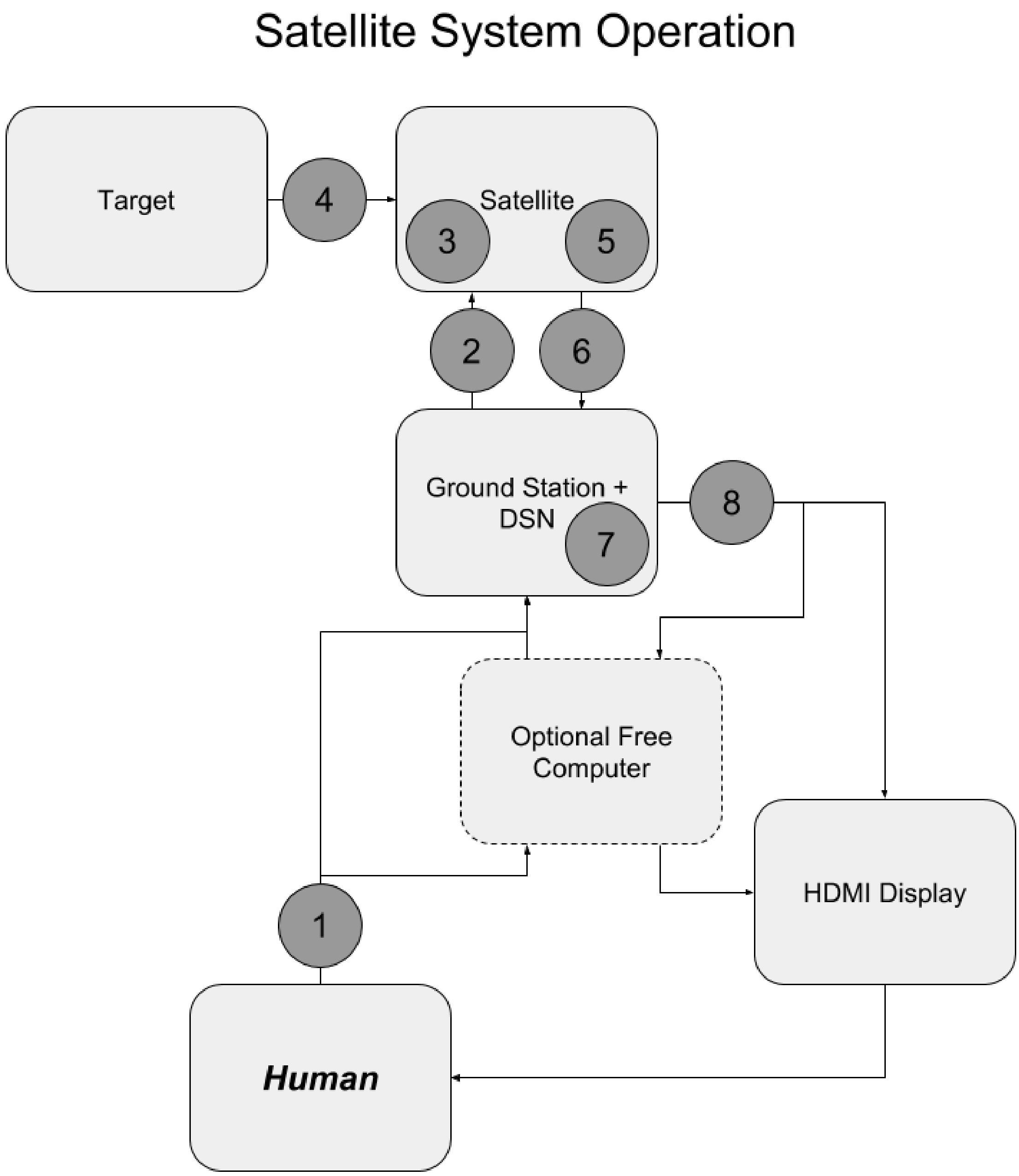
Blue	optics
Red	movement control system
Green	imaging
Black	power

Large flywheels: 60mm dia, 5mm thickness
Small flywheels: 30mm dia, 5mm thickness

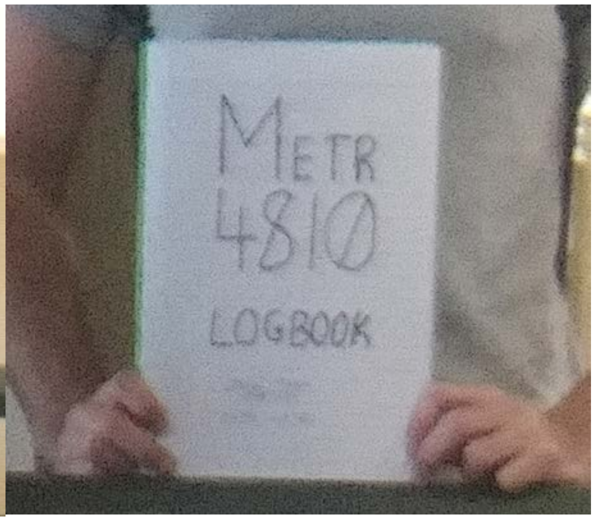


APPENDIX B: SATTELITE SYSTEM OPERATION

An operational overview of the whole system with numbers referenced in section 1.



APPENDIX C: CAMERA TESTS



“M” height is 53mm tall, 85pixels on image. 85/5.3=15.5 pixels per cm.

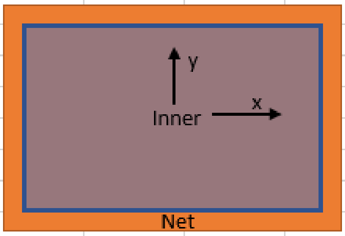
This was taken with a 15MP phone camera.

Even with a mid-range phone camera it is clear that there is significant noise in the image. This is due to a high ISO setting as a result of the low light detected by the camera. To decrease this noise, the camera can be stabilised or more light can enter the camera.

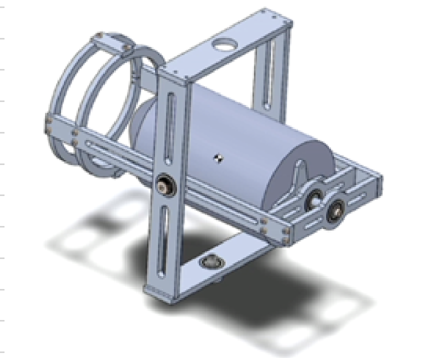
APPENDIX D: ANGULAR MOMENTUM

Sattelite Moments (assuming 750g mass and homogeneous solid cylinder distribution)			
Ix	2383	kgmm^2	yaw
Iy	2383	kgmm^2	pitch
Iz	937	kgmm^2	roll

Gimbal Moments (frames are approximated as a rectangular ring, caluclated by subtracting inner rectangle from outer)								
Dimensions				m_outer	2.808	kg		
40	mm	z		m_inner	2.4624	kg		
130	mm	x			x	y	z	
200	mm	y		I_outer	3954.6	9360	13314.6	kgmm^2
5	mm	thickness		I_inner	3467.88	8208	11675.88	kgmm^2
				I_net	486.72	1152	1638.72	kgmm^2
Aluminium density								
2.7	kmcm^3							



Net Moments (assuming gimbal is in the configuration as below with XYZ corresponding to RPY of the sattelite)			
I_x_max	4508.44	kgmm^2	rotating sattelite (x axis) and internal gimbal (z axis) and external frame (x axis)
I_y_max	3535	kgmm^2	rotating sattelite (y axis) and internal gimbal (y axis)
I_z_max	937	kgmm^2	rotating sattelite (z axis) only



Using the set flywheel size (appendix E) and above moments of inertia, the flywheel RPM for a 10 degree per second satellite slew can be calculated. 100RPM is reasonable and can be achieved by small scale hobby motors.

$$H = I_{sat}\omega_{sat} + I_{flywheel}\omega_{flywheel\_net} = 0$$

$$\omega_{flywheel\_net} = \omega_{flywheel} + \omega_{sat}$$

$$I_{sat}\omega_{sat} + I_{flywheel}\left(\omega_{flywheel} + \omega_{sat}\right) = 0$$
$$I_{sat}\omega_{sat} + I_{flywheel}\omega_{flywheel} + I_{flywheel}\omega_{sat} = 0$$
$$\omega_{sat} = \frac{I_{flywheel}}{I_{flywheel} + I_{sat}}\ \omega_{flywheel}$$

$$\omega_{sat} = 10°/s = 0.17rad/s$$
$$I_{flywheel} = 45kgmm^2$$
$$I_{sat} = 2383kgmm^2$$

$$\omega_{flywheel} = 9.172\,rad/s = 100RPM$$

APPENDIX E: MASS, COST AND POWER BREAKDOWN

Clearly the mass of the craft is feasible. Flywheels and mounting/structures are the two most uncertain quantities. They have generous estimates assigned based on the remaining mass after critical components.

Part	*Mass*	*Quantity*	*Line Total*
Lenses	66	1	66
Pi Zero	9.3	1	9.3
Pi Camera	3.4	1	3.4
Battery	51	1	51
Motor	20	3	60
ESCs	15	3	45
PCB + components	25	1	25
Flywheels	75	3	225
Mounting/Structure	250	1	250
		Total:	734.7g

The cost of all parts is known apart from the flywheels, PCBs and mounting equipment. The remaining budget of $45 is a feasible amount to purchase these unknown items.

Part	*Price*	*Quantity*	*Line Total*
PiZeroW	$ 14.96	2	$ 29.92
PiCamV2	$ 36.30	1	$ 36.30
Battery (500mAh@7.4V)	$ 8.73	1	$ 8.73
Microcontroller	$ 8.02	1	$ 8.02
Gyroscope	$ 6.91	1	$ 6.91
Magnetometer	$ 2.74	1	$ 2.74
Motor	$ 11.26	3	$ 33.78
ESCs	$ 10.01	3	$ 30.03
Flywheels		0	$ -
PCBs		0	$ -
Mounting Equipment		0	$ -
		Total	$ 156.43

A lipo battery is chosen because of its high energy density and low mass. This gives a 1.2A average current over the whole test which is reasonable considering

15kJ → 4.16Wh → 560mAh@7.4V

500mAh $500mAh \times 80\%\ efficiency \times \frac{60}{20}\frac{1}{hour} = 1.2A\ \ average$