Individual System Design Report - Payload Engineer

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1 Introduction

This report investigates the payload subsystem of a project that aims to redesign TechDemoSat-1 (TDS-1). A technology demonstrator requires a platform consisting of adapters, allowing the payloads to essentially "plug in" to the satellite. This report is concerned with the design and development of the platform interface and what it can provide for the potential payload configurations, with an in-depth focus on power, mass and data storage budgets.

Based on market research [1][2], it is clear that the payloads with the largest market size for the timeframe of this mission and for the future are as follows:

Communications, Imaging, Navigation, Scientific, Testing, Earth Observation, Defence, Surveillance, Propulsion, Space Exploration, Energy & Environmental, Manufacturing.

After consideration of the user requirements for this mission, however, the list above was reduced and the final types of payloads that can be accommodated for by this satellite are as follows:

Communications, Imaging, Navigation, Scientific Monitoring, Testing (biological), Energy & Environmental.

This is the list of payload types that was considered initially due to market research and the meeting of user requirements. The rest of this report will consider different combinations of these payload types and will aim to demonstrate the feasibility of different configurations, as well as their effect on the overall performance of the payload interface.

2 Description of System Model Development

2.1 Power and Mass Budget

The Electrical Engineer for this project has allocated 61W of average power to the payload subsystem, based on their system model for power. For spacecraft in LEO with propulsion, 46% [3] of the total system power is allocated to the payload subsystem. High (20W $\leq$), medium (10-20W) or low ($\leq$ 5-10W) power will be supplied to the payloads through the interface using a power distribution unit (PDU), depending on the payload type. The Systems Engineer for this project has allocated 60kg of mass to the payload subsystem, based on their system model for mass. For spacecraft in LEO with propulsion, 31% [3] of the total spacecraft mass is allocated to the payload subsystem.

Table 1 gives an initial sizing [4] of the power and mass budgets for the six potential payloads listed in the introduction. This will allow several combinations of payload types to be developed as design alternatives for which the payload interface shall provide. The ranges were produced based on heritage for payloads that were sized in a similar way and also meet the user requirements for this mission.

Payload Type	**Power (W)**	**Mass (kg)**
Communications	10-20	5-10
Imaging	15-25	10-15
Navigation	5-15	2-5
Scientific Monitoring	10-20	2-5
Testing (biological)	10-15	5-10
Energy and Environment	5-10	5-10

Table 1: Power and Mass ranges for potential payload types

Table 2 is an example of a potential payload type configuration. It includes one of every type of payload listed in the introduction to demonstrate that the payload interface can provide sufficient power to all types, proving the system's flexibility in terms of ability to host a wide range of payload types. P_{nom} is the nominal power and P_{eff} is the effective power, once duty cycle is applied by the equation $P_{eff} = P_{nom} * DutyCycle$ [5]. From the ranges in Table 1, the highest values for power and mass were used in order to provide an idea of the "worst case scenario":

Payload Type	**Quantity**	**Duty cycle (%)**	P_{nom} **(W)**	P_{eff}**(W)**	**Mass (kg)**
Communications	1	40	20	8	10
Imaging	1	20	25	5	15
Navigation	1	90	15	13.5	5
Scientific Monitoring	1	70	20	14	5
Testing (biological)	1	30	15	4.5	10
Energy & Environmental	1	70	10	7	10
		Total	**105**	**52**	**55**

Table 2: Payload Configuration 1 (Power and Mass)

Payload Type	Quantity	Duty cycle (%)	P_{nom} (W)	P_{eff}(W)	Mass (kg)
Communications	0	-	-	-	-
Imaging	6	20	25	5	15
Navigation	0	-	-	-	-
Scientific Monitoring	0	-	-	-	-
Testing (biological)	0	-	-	-	-
Energy & Environmental	0	-	-	-	-
		Total	**150**	**30**	**90**

Table 3: Payload Configuration 2 (Power and Mass)

Configurations 2 and 3 show the worst case scenario for the mass and power budgets, respectively.

Payload Type	Quantity	Duty cycle (%)	P_{nom} (W)	P_{eff}(W)	Mass (kg)
Communications	0	-	-	-	-
Imaging	0	-	-	-	-
Navigation	0	-	-	-	-
Scientific Monitoring	6	70	20	14	5
Testing (biological)	0	-	-	-	-
Energy & Environmental	0	-	-	-	-
		Total	**120**	**84**	**30**

Table 4: Payload Configuration 3 (Power and Mass)

Payload Type	Quantity	Duty cycle (%)	P_{nom} (W)	P_{eff}(W)	Mass (kg)
Communications	1	40	20	8	10
Imaging	2	20	25	5	15
Navigation	0	-	-	-	-
Scientific Monitoring	2	70	20	14	5
Testing (biological)	0	-	-	-	-
Energy & Environmental	1	70	10	7	10
		Total	**120**	**53**	**60**

Table 5: Payload Configuration 4 (Power and Mass)

Configuration 4 is a more realistic configuration for the satellite.

2.2 Data Budget

Figure 1 shows the system model used to calculate data storage for each payload type, where parallelograms are calculated values and ovals are variable inputs.

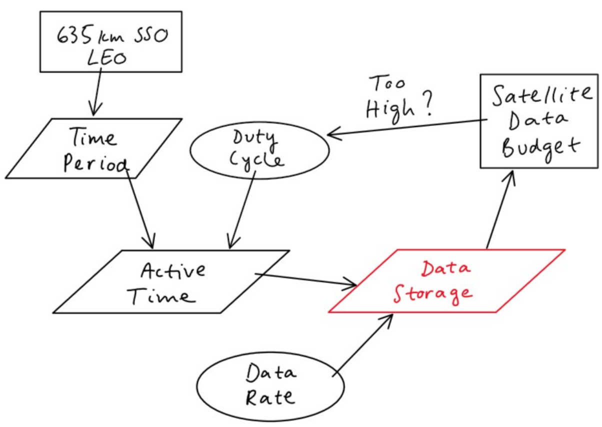

Figure 1: Data system model

The following equations were used for orbital time period [6], active time [7] and data storage [8], respectively:

$$T = 2\pi\sqrt{\frac{r^3}{\mu}}$$

$$ActiveTime = DutyCycle * T$$

$$DataStorage = ActiveTime * DataRate$$

Table 5 shows the values used for these

calculations for each payload type, with the same duty cycles used in the power system model. The data rates were derived from heritage for payloads that were sized in a similar way and also meet the user requirements for this mission.

Payload Type	**Duty Cycle (%)**	**Data Rate (Mbps)**
Communications [9]	40	100
Imaging [10]	20	250
Navigation [11]	90	15
Scientific Monitoring [12]	70	40
Testing (biological) [13]	30	7.5
Energy & Environmental [14]	70	20

Table 6: Values for data system model

This gave a final data storage output per orbit of 107.46 GB for configuration 1; 218.1949 GB for configuration 2; 122.189 GB for configuration 3 and 152.736 GB for configuration 4. The downlink capacity per orbit of this satellite is 184 GB and was found using the following equation, where T is the time period of the orbit:

$$DataStorageCapacity = \frac{(\sum DataTransferRates) * T}{8000}$$

3 Analysis of Design Alternatives, System Tradeoffs and Feasibility Analysis

3.1 Developed System Models

The configurations in section 2 consider six different payload types. Configurations 2 and 3 only consider one type of payload in order to demonstrate the effect on system performance of extreme power and mass budget constraints. Configurations 1 and 4 consider more than one type of payload and in order to develop the systems models further, the relationship between payload constraints will be defined. The main constraints other than the mass and power ones mentioned previously are the size of antenna used for the communications payload type and the pointing & positioning of the imaging payload type.

The type of antenna to use was decided in the first group report to be a phased array. The sizing of this antenna is as follows, assuming a peak gain of 30dB [15] and 8 $\times$ 10^9Hz for the X-band frequency:

$$\lambda = \frac{c}{f} = \frac{3\times10^8}{8\times10^9} = 0.0375m$$

$$PeakGain = 10\log\left(\frac{A}{\lambda^2}\right) + 8$$

The peak gain equation [3] was then rearranged to find A, the size of the phased array. This was found to be 0.223m. This is not a large value, relative to the size and volume capacity of the satellite and in turn the payload platform, therefore this does not pose major constraints on other payload types. Choosing a different antenna type would change this sizing method and therefore could affect the performance of the system.

The biggest constraint on the entire system imposed by an imaging payload type is its pointing and positioning requirements. The ADCS subsystem capability must conform with the imaging payload's angular accuracy requirement, sized as follows:

$GSD = \frac{pH}{f}$, where p is pixel pitch, H is orbit altitude and f is focal length [16]

$\theta_p = \frac{GSD}{H} = \frac{p}{f}$, where θ_p is pointing error in μrad [17]

Using assumptions for these variables, a pointing accuracy of 2.06 arcseconds was determined.

Although the other payload types inevitably have different constraints, none (other than the ones mentioned) are significant enough to interfere with the performance of other payloads or subsystems. Considering all developed systems models in this report, it is clear that configurations like number 2 will have much stricter constraints, since it combines only imaging payload types.

3.2 System Tradeoff

The following Pugh Decision Matrix provides a tradeoff between all four design configurations in terms of the payload interface's criteria. These criteria were derived from the system and payload subsystem requirements. Here, $+$ is good, $-$ is bad and n is negligible.

		Configuration			
Criteria	**Weighting**	**1**	**2**	**3**	**4**
Mass	3	+	-	+	+
Power	4	+	+	-	+
Data Storage	5	+	-	+	+
Pointing Constraint	3	n	-	+	n
Versatility	5	+	-	-	+
	Number of +	17	4	11	17
	Number of -	0	16	9	0
	Number of n	3	0	0	3

Table 7: Pugh Decision Matrix for design alternative tradeoff

Table 7 shows that configurations 1 and 4 meet the requirements better, compared to configurations 2 and 3. A Pugh analysis method was used to gain an initial idea of design alternative ranking quickly [18] and engineering judgement was used to decide how well each configuration met the requirements. The weightings showed how crucial and flexible the criteria were, relative to each other, also allowing us to see how well the designs meet the requirements. For example, mass was weighted a 3, relative to data storage at a 5. This is because a design with a mass higher than the current budget could still be feasible, despite requiring significant changes to other subsystems, whereas exceeding the data storage budget would mean that the payload interface would not meet the system requirements.

	Configuration					
Criteria	**1**	**2**	**3**	**4**	**V***	**V-**
Mass	4	1.5	5	4	5	1.5
Power	4	5	2	4	5	2
Data Storage	5	2	4	4	5	2
Pointing Constraint	2	1	5	2	5	1
Versatility	5	1	1	4.5	5	1
S*	3.3	7.3	5.1	3.5		
S-	6	3	5.7	5.2		
C*	0.645	0.291	0.528	0.598		

Table 8: TOPSIS analysis for design alternative tradeoff

A TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) [18] analysis method was then used to see how far each design alternative was from the worst solution (i.e. not meeting the system and payload subsystem requirements). As a result of this, the payload configurations were ranked from best to worst as follows: 1, 4, 3, 2. A TOPSIS analysis uses qualitative ideas to output quantitative tradeoff, which is ideal for this report. It considers the best and worst case scenario so that as well as a final ranking, there is an idea of exactly how good or bad each design alternative is, making it more thorough than a Pugh analysis.

3.3 Assumptions and Limitations

Throughout this report, many assumptions were made, namely the assumed list of 6 payload types for which the payload interface can provide. Although this was based on market forecasting of potential customers and expected research areas in the next 5 years, this list does not include all payload types. Because of this, the team is limited to sizing all subsystems based on only these six types, meaning the payload interface might not have an adapter required for a payload that does not fit into this list. The most holistic approach was adopted, given the constraints defined by the system requirements.

In the systems models in sections 2 and 3, several variables were assumed based on heritage for satellites that were sized in a similar way and that meet the user requirements for this system, including: power, mass, duty cycle, pixel pitch and focal length values. Duty cycle affects both effective power and effective data rate, however the values used for duty cycle in section 2 assumed the minimum percentage from the ranges sourced:

Payload Type	**Minimum Duty Cycle (%)**	**Maximum Duty Cycle (%)**
Communications [19]	40	50
Imaging [20]	20	30
Navigation [21]	90	100
Scientific Monitoring [22]	70	80
Testing (biological) [23]	30	40
Energy & Environmental [24]	70	80

Table 9: Ranges of duty cycles for different payload types from sources

Looking at using the maximum values of duty cycle would mean increasing the allowable active time for all payloads, resulting in the following effective power and effective data rate budgets for the proposed payload configurations:

Configuration	**Effective power (W)**	**Effective data rate (Mbps)**
1	62.5	191
2	45	450
3	96	192
4	63	280

Table 10: Effective power and data rate at maximum duty cycles

It can be seen from Table 10 that using maximum duty cycles results in only configuration 2 meeting the requirements for the power budget (61W). Configurations 1 and 4 only exceed this limit by 1.5W and 2W respectively, meaning they could still be feasible design alternatives as long as power margins are considered. In this case, configuration 3 would not be feasible due to its extremely high effective power, therefore other factors that affect scientific monitoring payloads would need to be changed drastically. This might impose limitations on the payload interface that could therefore cause this design alternative to not align with the system requirements of the mission. In terms of effective data rates provided in Table 10, configurations 2 and 4 exceed the required data transfer rate set by the Electrical Engineer (253Mbps), whereas configurations 1 and 3 still meet this requirement, despite the larger duty cycle values.

Analysing feasibility of a design alternative solely based on effective power or effective data rate is not realistic, as many factors (e.g. mass or data storage requirements in GB) will affect the feasibility and adherence to requirements of the system. However, the impact of duty cycle assumptions shown in Table 10 suggest which design alternatives would and would not need to resize other subsystem models in order to aim to satisfy the criteria set.

4 Sensitivity Analysis, Uncertainty and Risk

1	22	22	23	23	24	24	24	25	25	26	26	27	27	27	28	28	29	29	30	30	31	31	31	32	32	33	33	34	34	34	35	35	36	36	37	37	38	38	38	39	39	40	40	41	41	41	42	42	43	43	44
2	44	45	45	46	47	48	49	50	51	51	52	53	54	55	56	57	58	58	59	60	61	62	63	64	65	65	66	67	68	69	70	71	72	72	73	74	75	76	77	78	79	79	80	81	82	83	84	85	86	86	87
3	65	67	68	69	71	72	73	75	76	77	79	80	81	82	84	85	86	88	89	90	92	93	94	96	97	98	99	101	102	103	105	106	107	109	110	111	113	114	115	117	118	119	120	122	123	124	126	127	128	130	131
4	87	89	91	93	94	96	98	99	101	103	105	106	108	110	112	113	115	117	119	120	122	124	126	127	129	131	133	134	136	138	140	141	143	145	147	148	150	152	154	155	157	159	161	162	164	166	168	169	171	173	175
5	109	111	113	116	118	120	122	124	127	129	131	133	135	137	140	142	144	146	148	151	153	155	157	159	161	164	166	168	170	172	175	177	179	181	183	185	188	190	192	194	196	199	201	203	205	207	209	212	214	216	218
6	131	134	136	139	141	144	147	149	152	154	157	160	162	165	168	170	173	175	178	181	183	186	189	191	194	196	199	202	204	207	209	212	215	217	220	223	225	228	230	233	236	238	241	244	246	249	251	254	257	259	262
	150	153	156	159	162	165	168	171	174	177	180	183	186	189	192	195	198	201	204	207	210	213	216	219	222	225	228	231	234	237	240	243	246	249	252	255	258	261	264	267	270	273	276	279	282	285	288	291	294	297	300

Figure 2: Sensitivity analysis on imaging payload configurations vs data rates

Figure 2 is a sensitivity analysis with the following inputs: the y axis is the number of imaging payloads in each configuration and the x axis are the raw data rates (Mbps) of this payload type. The value that was chosen in Table 6 for the raw data rate required for an imaging payload type was within the range of 150-300 Mbps. 250 Mbps was chosen because if there is to be an imaging payload in the final design, the aim is for the payload interface to be able to provide for a high quality type, therefore meeting the versatility requirement of this subsystem. The numbers 1 to 6 come from the fact that each configuration has a maximum of six payloads.

The output here is the total data storage (GB) requirement for that configuration. As mentioned in the data system model in section 2, the maximum data storage capacity of the satellite is 184 GB, therefore any value above this is marked in dark red, corresponding to an infeasible design choice. The values in dark green mean that the design choice to only have one imaging payload with a low data rate would leave more than enough data storage to be flexible with the design choices for the other payload types used. This does not necessarily mean that configuration 1 is ideal because customers wanting to integrate an imaging payload to this interface might require a higher data rate than 153 Mbps. Values in light red show an achievable design alternative in terms of number of imaging payload types, however these would put large constraints on the other payload types used because there would not be much data storage budget left for them, therefore negatively impacting system performance. Along with the sensitivity analysis results, it is important to trade off between leaving enough data storage budget for other payloads and having several high quality imaging payloads.

4.1 Uncertainty

Many uncertainties in the final concept selection will stem from the Pugh and TOPSIS analyses in section 3. For the Pugh matrix, although decisions on weighting values were based on system and payload subsystem requirements, engineering judgements are still subjective and the values were decided by only the Payload Engineer rather than a consensus. This matrix also does not consider the relationships between the criteria. Uncertainties for the TOPSIS matrix [18] are similar in that the weightings are subjective and it assumes the criteria are independent. As well as this, the ideal negative solution might not always represent a feasible design alternative, which could cause a misunderstanding of the final rankings in terms of the comparison, since it does not take into account the effects of anomalies.

It can be said that there are uncertainties in all of the values that were used in the systems models, mainly due to the fact that for this report, specific payloads are not defined. Only the *types* of payloads that could be potentially used are defined in order to meet the requirements of the payload interface and what the overall platform is able to provide. Because of this, adopting margins for these values is necessary in order to ensure design for good performance.

The payload interface for this mission can be considered to be in the category of a new design or a design that requires major modification. Because of this, the ESA [25] recommended margin for power, mass and data processing rate budgets in this case is at least 20% for all. For values used in this report like duty cycle, pixel pitch and focal length, a reasonable value for margin would be 25% [3]. Adopting these margins would result in the following system model budgets as an absolute maximum:

Value	Sized Value	Margined Value
Power (W)	52	62.4
Mass (kg)	55	66
Data rate (Mbps)	253	316.25

Table 11: Effect of margins on power, mass and data rate budgets

4.2 Risk Analysis

1. New technology implementation
    - Explanation: If new technologies are used, there is a possibility that they do not comply with older technologies that are now obsolete.
    - Likelihood/impact: Since the entire system is being redesigned, this should not be an issue.
    - Mitigation: Use technologies and systems for the payload interface that are not obsolete and that do not have significant constraints on design choices.
2. Human error
    - Explanation: During the integration of payloads onto the hardware mounts for the adapters on the payload interface, due to human error, damage to payloads might occur.
    - Likelihood/impact: This integration process will only occur once, reducing the chance of this risk impacting the mission. However, the consequence of human error in this situation could be catastrophic, as payloads could get damaged.
    - Mitigation: Make the interface easy to use and try to incorporate automation for crucial operations in the interface assembly phase.
3. Safety
    - Explanation: The end of life phase of the concept of operations could result in space debris produced by the satellite.
    - Likelihood/impact: This is inevitable, since the satellite cannot maintain its orbit forever and it could cause damage to other systems in its environment, as well as not complying with regulations [26].
    - Mitigation: Based on this project's system requirements, the satellite shall deploy a drag sail to de-orbit and then burn up before reaching Earth.
4. Reliability

- Explanation: If any system fails unexpectedly, loss of communication to and from the payloads may occur.
- Likelihood/impact: There is always a small chance of dealing with unpredictable risks and any failure like this would result in an immediate decrease in overall system performance and could potentially make the mission unsuccessful.
- Mitigation: Use redundant systems [27], for example ensure the CDH system is able to redistribute power in case of a sudden outage and make the communication links to all payloads in parallel so that the loss of one does not affect others.

5. Testing environment
    - Explanation: Payload types like imaging or biological testing require highly constrained environments and any small changes in environment might affect the data retrieved from these payloads.
    - Likelihood/impact: Depending on the payload types used, this could be a significant risk, as it could jeopardise the success of the users of that payload.
    - Mitigation: Ensure regular downlinking to ground stations in order to receive real-time data updates [28] from the payloads. Size systems like ADCS according to those specific payload requirements.
6. Payload interference
    - Explanation: Communications or scientific monitoring payload types could have interfering signals if they operate in the same frequency bands [29].
    - Likelihood/impact: If these payload types are used, then this risk could also be detrimental to the results achieved during the overall mission.
    - Mitigation: Structurally, ensure that these payloads are shielded from each other with the correct materials.
7. Budget management
    - Explanation: Providing a service for six payloads could lead to difficulties with power, mass, data storage and other budget allocation between all payloads.
    - Likelihood/impact: This is a significant risk to consider because it is crucial that the user and system requirements are met for each payload.
    - Mitigation: Use a reliable PDU to allocate the previously budgeted power and use a CDH system that operates on prioritised data transmission [30]. Use system models and sensitivity analyses to evaluate the feasibility of the design concept.

Based on the above risks and the other analysis methods provided in this report, the final concept was selected to be configuration 1. Although the Pugh, TOPSIS and sensitivity analyses suggested that both configurations 1 and 4 were the more feasible design alternatives (compared to configurations 2 and 3), the risk analysis highlighted that issues with payload interference and budget management would result in more design constraints and considerations for configuration 4. Configuration 1 will make it easier for the interface to meet the system and payload subsystem requirements, whilst providing a service for a wider range of users.

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