73rd International Astronautical Congress (IAC) – Paris, France, 18-22 September 2022.

IAC-22-D.1.5x71520

A framework for collecting lessons learned for university CubeSat projects

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Abstract

In this paper, we present a framework for collecting, discussing, and implementing lessons learned from university CubeSat projects. The framework is demonstrated on the 6U CubeSat HYPSO-1 (Hyperspectral Small Satellite for Ocean Observation) which was launched in January 2022. HYPSO-1 is the first research CubeSat mission from the Norwegian University of Science and Technology (NTNU), and it carries a novel hyperspectral imager payload with a configurable on-board processing unit for oceanographic data collection. The payload was developed by NTNU, and NanoAvionics (LT) provided the satellite bus.

The HYPSO-1 project was started at the end of 2017, and almost 100 students have been involved since then. The project team is based on bachelor and master students with support from PhD and post-doctoral researchers. A challenge for the team has been the high turnover of students each semester, and how to successfully ensure knowledge management and transfer of responsibilities in the transitions. Furthermore, now that the first satellite has been launched, how to effectively ensure that the lessons learned from HYPSO-1 are carried over to future satellites to reduce risk and increase mission performance. The HYPSO-2 satellite is largely based on the HYPSO-1 design, but there is a need from the stakeholders to increase the performance and to add a second payload. At the same time, most of the researchers are graduating from their PhD, which leaves the HYPSO-2 at a risk from losing the inherent knowledge gained from these researchers during HYPSO-1.

We describe a framework for lessons learned for university CubeSat teams, based on best practices from the Project Management Institute (PMI). We also describe how to incorporate these lessons learned into the semesterly design reviews and agile framework used for software and hardware development of the HYPSO-X satellites.
Keywords: University, Project Management, CubeSat.

1. Introduction

There are technical and managerial lessons to be learned from any experience, and it is typical to conduct “lessons learned”-sessions at milestones or at the end of the project. For many organizations, the most challenging points of the lessons learned process are to (1) take the time to conduct a systematic lessons learned; and (2) retrieve and use the lessons learned moving forward [1].

The Norwegian University of Science and Technology (NTNU) SmallSat Lab are planning to regularly launching scientific CubeSats with different types of payloads, such as imaging and communication payloads [2]. The team at the NTNU SmallSat Lab consists of approximately 30 students (master and bachelor) and researchers (Ph.D. and Post-doctoral) at any time. There is a high turnover of personnel at the lab, where the students follow the natural graduation cycle (typically joining in September and leaving in June the following year). The SmallSat Lab is both a physical facility with office space and an electronics workshop, and a collection of knowledge and shared working platforms in different cloud services.

The HYPer-Spectral SmallSat for Ocean Observation (HYPSO)-1 CubeSat was launched on January 13th 2022. The CubeSat and the supporting in-house mission control center was developed and built by the SmallSat Lab at the NTNU. The satellite is a 6U CubeSat [3] with a HyperSpectral Imager (HSI) payload. The HYPSO-1 CubeSat main mission objective is to “To provide and support ocean color mapping through a Hyperspectral Imager (HSI) payload, autonomously processed data, and on-demand autonomous communications in a concert of robotic agents at the Norwegian coast [2].” The HYPSO-1 is the first scientific CubeSat built at the NTNU SmallSat Lab, and the project started in 2017, with no faculty or participants having worked on a scientific CubeSat mission before. However, there have been CubeSats built at the university in the beginning of the 2000s, but much of that information was not available when the HYPSO team started. The spacecraft bus and subsystems are procured from NanoAvionics (LT), while the payload (the

HSI instrument and processing unit (On-board Processing Unit (OPU))) is built from in-house machined parts and Commercial-Off-The-Shelf (COTS) components.

The NTNU SmallSat Lab has a goal of regularly developing and launching scientific CubeSats, and there is an organization where there is a high turnover, it is important to collect and retrieve lessons learned. There is a risk that knowledge is lost when there is a high turnover, and most of the new students who join the team have no prior knowledge with the development of CubeSats before they join. Many university CubeSat teams write papers, such as this one, on their lessons learned [4]. However, how to systematically conduct a lessons learned is not always described, except that it is recommended to collect items at important milestones or events.

This paper describes a framework used for collecting, discussing, and implementing lessons learned from University CubeSat projects. The following section outlines the framework and how it was applied to a HYPSO-1 lessons learned workshop. The next section provides the main lessons learned items from the workshop, with associated actions were applicable. The lessons learned are divided into three topics: Assembly, Integration and Test (AIT), Management and teamwork, Technical design. The final section discusses the framework and results, and highlights important findings moving forward for future CubeSat projects at NTNU and other universities.

2. Framework for lessons learned workshop

The framework for conducting a lessons learned for university CubeSat projects should be straightforward to apply for inexperienced teams, and allow for a pragmatic integration into the team's information system. The Project Management Institute (PMI) Body of Knowledge (BoK) recommends a five-step approach as shown in Fig. 1 for conducting lessons learned.

In the **Identify** step, the team identifies what is useful to carry on to the next project or across projects or programs. In the framework, the participants are asked to consider the following questions when working with the identification of items:

1. What went right?
2. What went wrong?
3. What needs to be improved?

This is typically done continuously throughout the project lifecycle, and organizations have different approaches and methods for recording this information (**Document**). For step three, the findings should be **Analyze(d)** and organized (for example, according to lifecycle phases, with tags indicating topic. etc.) so that it is easier for others to apply the findings. The findings and analysis are **Store(d)** in the organization's information system. This could be as a document or in a database. The final, and arguably the most important step, is to **Retrieve** the lessons learned and findings for current projects and programs throughout and across organizations.

In the following subsections, the methods applied in the HYPSO-1 project lessons learned workshop are described, with emphasis on steps 1–3. For the HYPSO-1 team, some of the participants at the workshop had been a part of the team since the beginning, while most participants had joined 6 months before the workshop was held. The "Lessons Learned" workshop was conducted at the end of HYPSO-1 Launch and Early Operations Phase (LEOP), over two half-days (one evening half-day and one morning half-day), with some ice-breakers activities and a team dinner.

Each session of the workshop should start and end with a *check-in/check-out* where each participant states how they are feeling about the day and the task at hand, and reflects on their contribution. This approach is chosen to increase and foster team collaboration (by spending time together), and dividing it into two days instead of one full day to encourage some "maturing" of thoughts for the **Analyze** step of the process.

2.1 Step 1: Identify

To support the identifications of lessons learned, it is recommend to limit the scope by selecting specific topics or time periods. These should be selected based on the participants' knowledge, so that all participants can contribute. The HYPSO-1 project conducted a project lessons learned at the end of LEOP applying the framework. Three focus areas were chosen for the lessons learned sessions to limit the scope:

- Management and teamwork,
- Technical design,
- Assembly, Integration and Test (AIT).

In addition, the lessons learned participants should be diverse, meaning that they have different educational backgrounds, different project experiences (some that have been a part of the whole project, while others may be new, or peripheral), and if possible, include participants that have not been a part of the project, but e.g., in the review team or similar. A diverse team supports the generation of new insights and ideas. Depending on the number of participants, the group can be subdivided into several teams. For the HYPSO-1 team, a size is 3–5 people per team for the following part worked well.

The teams are asked to identify items for the lessons learned associated with the specific topics/time periods. The participants use post-it notes and a flipover or online post-it systems (such as collaborative boards) to identify

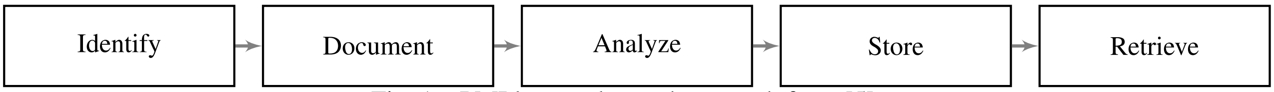

Fig. 1 PMI lessons learned approach from [5].

items and organize them in the grid from miro [6] shown in Fig. 2.

The participants get 5 minutes to generate post-it notes individually, and are encouraged to find at least 3 notes per square of the grid. Next, the participants share their items in their teams, and categorize according to the topics identified. For this part, the participants should take time explaining each of their post-it note to the other team members, so that there is a common understanding of what each note means. Explaining each note instead of "just" placing it on the grid also kickstarts the thinking process of what the item means and how it can be addressed moving forward.

2.2 Step 2: Document, and Step 3: Analyze

The **Document** and **Analyze** steps are grouped together because they happened with the same mechanism for the HYPSO team for the items collected during the workshop. After the participants identify, present, and categorize the items in their teams, they are now asked to analyze and prepare a presentation to share with the rest of the group. For each item, the team should list:

- **Topic:** *Either:* AIT, Management and teamwork, or Technical design,
- **Category:** *Either:* Liked, Learned, Lacked, or Longed for,
- **Description of lessons learned:** *Short description of the item (from the post-it)*,
- **Suggested action(s):** *List of actions for the short and long term to address the item,*
- **Responsible role:** *Identification of responsible role.*

The teams get 30 minutes to make these presentations per topic, and then they present in the larger group (total 30 minutes). Everyone is encouraged to discuss and asked questions during the presentations, and the presentation slidedecks are updated based on the discussions (for example, identifying new actions). For the HYPSO workshop, this would then take 3 hours in total because there are 3 topics, plus breaks between each topic.

2.3 Step 4: Store

Storing the lessons learned items is necessary so that the information can be disseminated and retrieved later. For example, using a database with keywords and incorporating it into the information system of the organization. Many organization have processes where they store the information as documents that can be accessed across projects, and some also publish the information so it is available for others.

The HYPSO team stored the lessons learned slidedecks in their information system, and have started making a SharePoint page with the different lessons learned. The SharePoint site is better for getting an overview, and also easily searchable, compared to e.g., the post-it notes.

2.4 Step 5: Retrieve

Arguably the most critical step in the process is to retrieve the information when appropriate. Retrieval of information is closely linked to how the information is stored, and what processes the project has for revisiting lessons learned. For example, if the project is in the AIT phase, the team can review the lessons learned from previous projects that are categorized under AIT at test readiness reviews or Ground Support Equipment (GSE) design reviews. The lessons learned can also be incorporated as a part of checklists, if the project uses these as a part of the process.

3. Results

The framework for lessons learned workshop was conducted over two half-days at the end of LEOP. There were five teams in total, where one of the teams was online and used Miro as a collaborative whiteboard space. Some students from another university CubeSat team (who had not yet finished their first CubeSat) joined the lessons learned workshop as well. The workshop participants were divided into teams as a part of an icebreaker game (icebreaker question ranking game), so that the teams consisted of more and less experienced members. In addition to the lessons learned workshop steps, a more focused brainstorming session on how to improve operations and operations training based on the lessons learned from LEOP was conducted.

The individual brainstorming generated many post-it notes in some of the teams, while in others the participants took more time. Therefore, the number of items to continue working with differed across the teams. An example of post-it generation from the miro board is shown in Fig. 3. The categorization and presenting of post-it notes within each team helped eliminate/merge some of the items because multiple team members had described the same issues. In step 2, not all teams were able to finish the write-up of each item because of the

LIKED What was good?	LEARNED What did the team learn?
LACKED What did the team lack?	LONGED FOR What did the team long for?

Fig. 2 4Ls framework from miro [6].

time limits and having too many items. All items were documented though, so the project team can revisit them at a later time to perform the analysis.

Some of lessons learned items generated from the workshop are given in the following separate sections per topic.

3.1 Management and Teamwork

- **Meetings:** Liked having regular small and big meetings —- especially during the home office time during the Covid-19 pandemic. Weekly meetings were good to follow progress. Having project reviews was good as deadlines.
- **Following the standards:** Liked having the work divided into phases, so that we understand where we are in the process. Tailoring the European Cooperation for Space Standardization (ECSS) standards. Having a Systems engineering approach, including the Work Breakdown Structure (WBS).
- **How to do agile software development using GitHub and agile methods.** Liked the agile workflow to get better transparency between individual team members, and supported integration and testing activities.
- **More people/technical experts:** Lacked enough people. We need redundancy for each position because when the people working are leaving there is no one left to take over. Also, more technical experts in optics, AIT, communications and operations. (Not only students, but phd/postdoc + professors + engineers). This affected the schedule, especially when students graduated and knowledge was lost.
  Responsible role: Management — recruiter.
  Actions:
  1. Better and more systematic recruiting,
  2. Promote the SmallSat Lab in the first year courses,
  3. Add pull-up posters over campus,
  4. Try to recruit permanent positions (operator, mechanics engineer, manager)
- **Organized documentation:** Lacked organized documentation. We have lots of documentation, but it is hard to find it. It is difficult to keep consistency in the documentation, know latest version.
  Responsible role: Project/payload manager.
  Actions:
  1. Overview pages/documents, with one main overview page? SharePoint page?
  2. Guidelines (date and time, name of person) on name of files/folder to put it in.
- **Cross team communication and team coordination:** Longed for better communication across teams. Requires some effort of team members to think about and mention aspects of their work that is relevant to the other teams.
  Responsible role: Project manager/team lead.
  Actions:
  1. Common standup once a week,
  2. Re-introduce monthly cross team A3 presentations [7],
  3. More team leads and split up the software team,
  4. Use "huddles" on Slack more,
  5. Regular workshops days where everyone gathers in the lab
  6. Make a data processing team.
- **Systematic onboarding process:** Longed for a better and systematic onboarding process with a set of reference documents.
  Responsible role: Project manager/team leads.
  Actions:
  1. Present (theory about) model philosophy (according to our tailoring of ECSS),
  2. Present our implementation of this (breadboards [dev.kits, FlatSat/LidSat], Engineering Model (EM), Qualification Model (QM), Flight Model (FM)),
  3. Project overview and team overview,

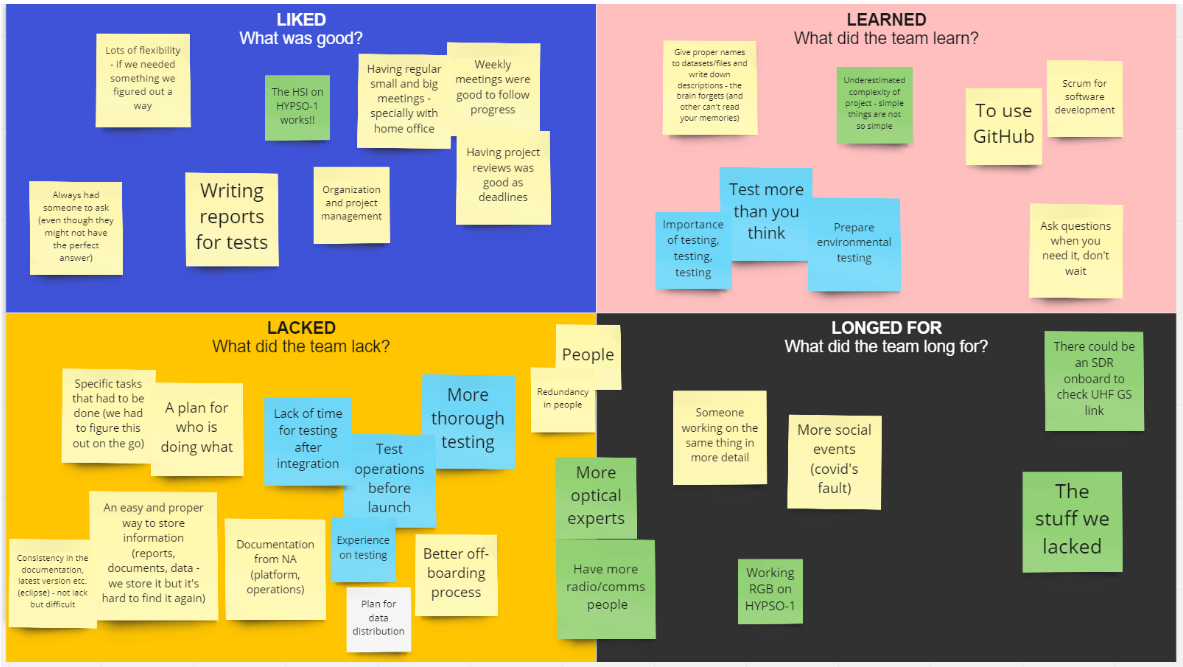

Fig. 3 Post-it session from online whiteboard.

4. Tools used in project,
5. Schedule and milestones,
6. Use a combination of workshops, lectures, presentations, videos,
7. Assign person responsible for keeping reference documentation updated.

3.2 *Technical Design*

- **The main instrument on HYPSO-1 works better than expected:** Learned that the prioritization of resources focused on early testing of target hardware in various environments, which gave good results.
- **Underestimated complexity of project - simple things are not so simple:** Learned that things took more time than expected like: environmental testing, manufacturing time, assumed simple instruments (RGB), getting the ground station fully integrated with mission operations, model philosophy (consistency between models).
  Responsible role: Project lead/team lead.
  Actions:
  1. Asking experts and listen to their tips,
  2. Online courses for new members — simple videos explaining concepts and equipment,
  3. Identify tasks, input and output, what is expected, who is responsible.
- **More precise requirements:** Lacked precise requirements. The requirements have been a work in progress, it would have been easier working with the design if the requirements were set in stone (but at the same time not as some requirements would be too strict).
  Responsible role: System engineer (and team leads/experts).
  Actions:
  1. Spend more time on the requirements,
  2. More requirement reviews with experts,
  3. Make sure we have requirements for all subsystems and instruments (RGB).
- **Optical model (for simulation), Structural Thermal Model (STM), characterization for different temperatures:** Lacked good optical models. Makes it more difficult to know what data is expected, what have been changed pre-launch to post-launch.
- **The GitHub workflow for Software is great and we need one for hardware too:** Liked the GitHub workflow. Learned that it is important to document ALL choices made — e.g., This one screw is 0.15mm offset. Why? The other one is offset 0.10mm?.
  Responsible role: Team lead.
  Actions:
  1. "git flow" methods also in mechanical design workflow.

2. Let external partners review design, e.g., NanoAvionics, or the mechanical workshop at relevant departments.

- **There could be a Software Defined Radio (SDR) onboard to measure the quality of the UHF link:** Longed for an SDR based radio because the UHF link does not work as well as expected and it is difficult to troubleshoot due to lack of data.
  Responsible role: Team leads.
  Actions:
  1. With an SDR onboard we could have investigated the problem,
  2. The SDR could have used the UHF-band for other experiments.

3.3 Assembly, Integration and Test

- **More testing:** Longed for more testing. We should test more than we think. Prepare well before testing, including testing checklists (for environmental testing write all cables, connectors, adapters,...), write reports and analyze results.
  Responsible role: Project manager/AIT manager.
  Actions:
  1. Verification matrix,
  2. Split so that someone else are testing the thing you did (separate development from testing) - some people developing and some people testing,
  3. Perform internal test first, then when things are "finished" perform external test (we need people, money and time).
- **Regular testing using target hardware:** Lack of adherance to only using target hardware. Failure to notice lack of IR filter on RGB and too wide aperture on the lens (only performed tests inside the lab).
  Responsible role: AIT manager.
  Actions:
  1. Regularly used FlatSat with flight configuration as early as possible to notice bugs/failures earlier,
  2. Make the setup as true to life as possible (point camera in open air, not through the window or just onto the wall),
  3. Set up QM and EM in a rack for easier maintainability.

3.4 Incorporating into the workflow

The final step of the lessons learned, **Retrieve**, is arguably the most critical step. The participants at a lessons learned will most likely remember some of the lessons, and apply the actions unconsciously. In addition, the retrieval of lessons learned can be incorporated into the project or organization workflow.

The HYPSO team uses an agile approach to managing work, as described in previously published papers [8, 9]. Although obvious, incorporating the actions suggested from the workshop is a low-hanging fruit. Depending on the action, they can be single issues, or epics/stories. For example, "Set up QM and EM in a rack for easier maintainability" could be a single issue, while "Perform internal test first, then when things are 'finished', perform external test" could be associated to a development epic with multiple issues and dependencies (so that the external test is not performed until the design is finished). For onboarding, there could be a set of issues that all new members must complete, such as "Online courses for new members — simple videos explaining concepts and equipment", and "Project overview and team overview", introduction to "Tools used in the project", etc..

Many of the lessons learned items from the HYPSO-1 workshop were "larger" items. Therefore, it may be challenging to reduce them to issues or stories that can be handled in an agile workflow. Rather, the workflow might need to be reviewed, for example "Re-introduce monthly cross team A3", "Common standup once a week", "Regular workshops".

To incorporate the lessons learned into design reviews, there needs to be a responsible person who takes the time to review the items with respect to the design review objective. Future work could look at methods to automate this process, but a good first step is to incorporate the review of lessons learned items prior to releasing models and documents for design review. To facilitate this process, it is important that the lessons learned items are easily **Retrievable**, which depends on how they are **Stored**.

4. Discussion and Conclusion

This paper describes the framework and the experiences from a workshop done after the LEOP of HYPSO-1 at NTNU. The lessons learned workflow framework presented is based on the PMI process, and is suitable for offline, online, and hybrid teams. While this paper addresses university CubeSat projects, it can also be suitable for other university projects such as Formula Student or DNV Fuel Fighter.

During the writing of the paper, another university CubeSat team has applied the framework in a shortened format, and the initial feedback is that it was a structured, pragmatic and efficient approach to collecting lessons learned.

For academic CubeSat projects, it would be beneficial if the lessons learned systems were collaborative and cloud-based, since many of the challenges are similar across teams. Many academic CubeSat teams publish papers on their lessons learned from different projects, which are available for other university teams. However, the pertinent information (such as recommended actions) may not be as easily retrieved in the papers as they would in a database. Furthermore, the papers are not categorized, which means that you would need to read all the papers to see if they are relevant to the problem you are working with or the project phase you are in.

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