How to Make It Easy to Use Satellites: Onboard Planner for Autonomous Spacecraft using Model-Based Systems Engineering

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ABSTRACT

The use of nano-satellites has exploded in recent years. The standardization of CubeSat has lowered the hurdle for the development of nano-satellites, but there is still a challenge to use them with ease. One of the issues with the increase in the number of satellites in orbit is the human and financial cost of their operation. Therefore, it is expected that the satellite will have an autonomous function to reduce the operation cost. In this study, we aimed to develop a model-based planner as an autonomous function for satellites. One of the challenges of the model-based planner is the construction and verification of domain models used for the planner. To solve this problem, Model-Based Systems Engineering (MBSE) was used to describe the spacecraft design information as graphical models, and a domain model was constructed from that model. Figure 1 shows the overview of this framework. By carrying out a simple experiment on a subject of 6U CubeSat called EQUULEUS [1], it was confirmed that the autonomous function worked as expected.

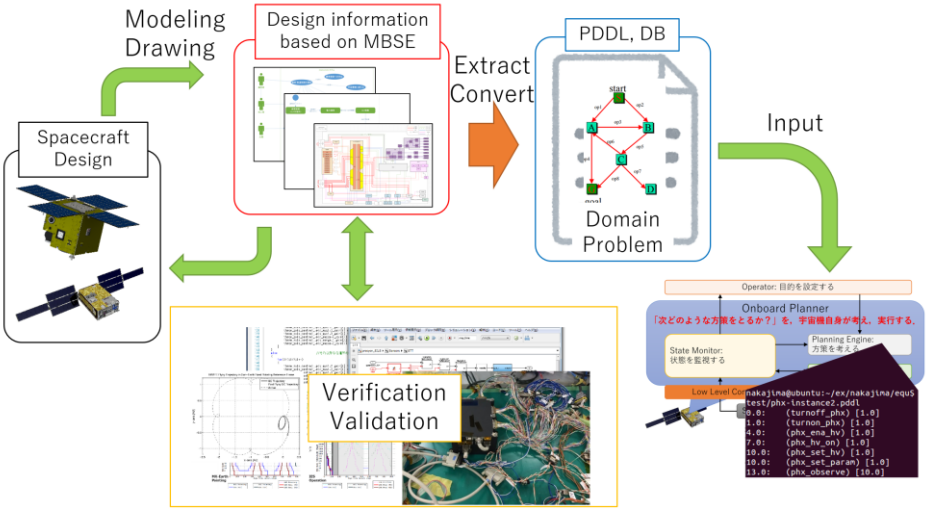

Figure 1 Overview of proposed framework for generating model-based satellite autonomy based on satellite design information

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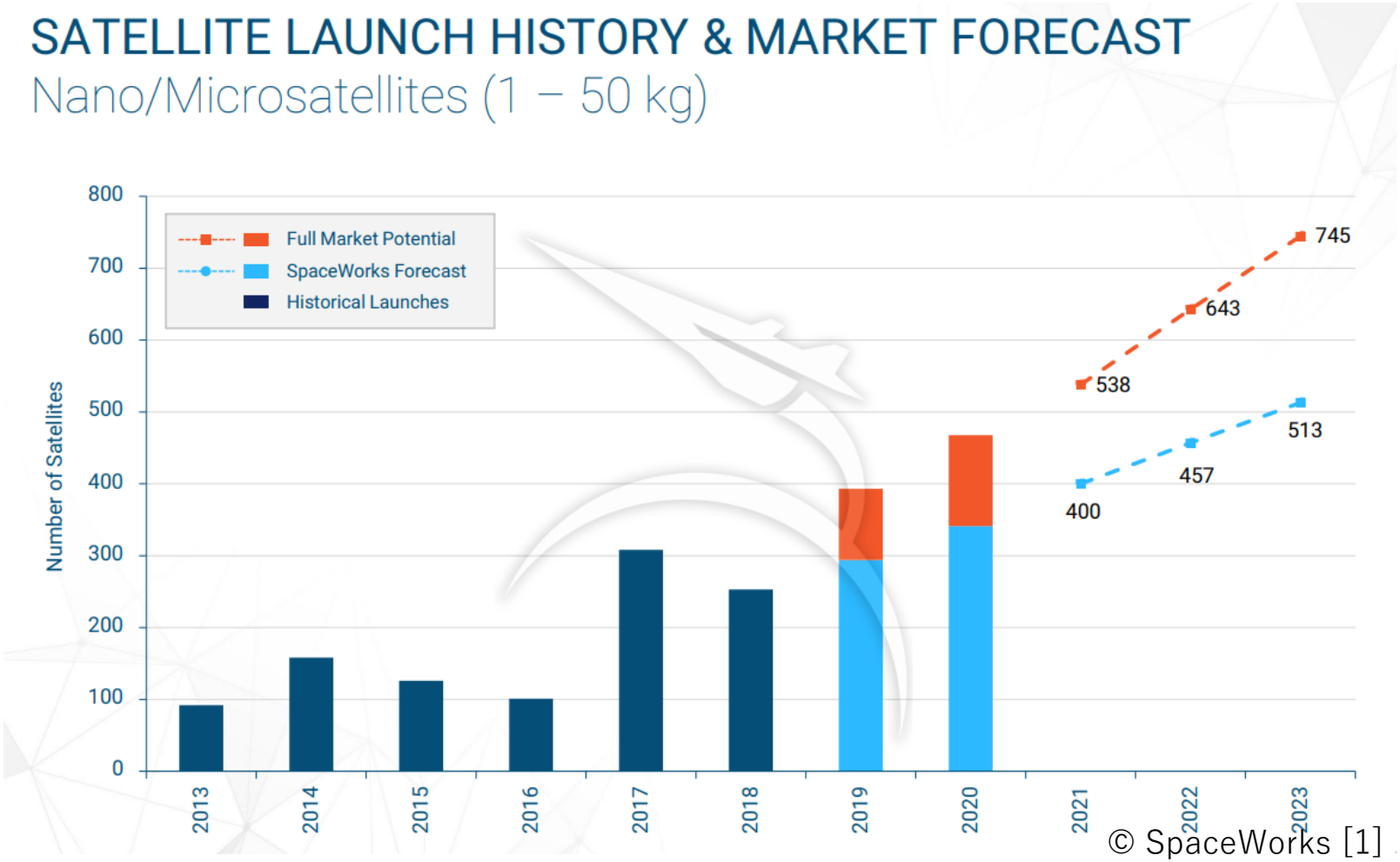
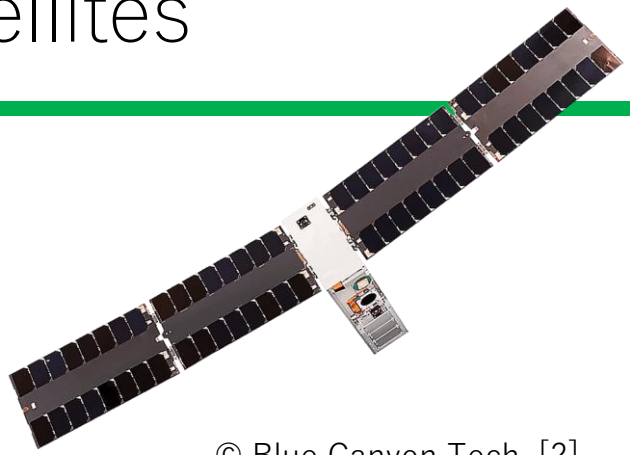
Forecast of nano/micro satellites



Spreading of micro/nano satellites

- There are many companies selling components for CubeSats:
  - At Small Satellite Conference, over 200 companies have their booth.
  - Leading companies of CubeSats:
    - Pumpkin
    - AAC Clyde Space
    - Blue Canyon Technologies
    - MMA Design
    - Hyperion
    - …
  - Some companies sells 3U/6U Cubesat Bus System
    - BCT, Pumpkin, etc.



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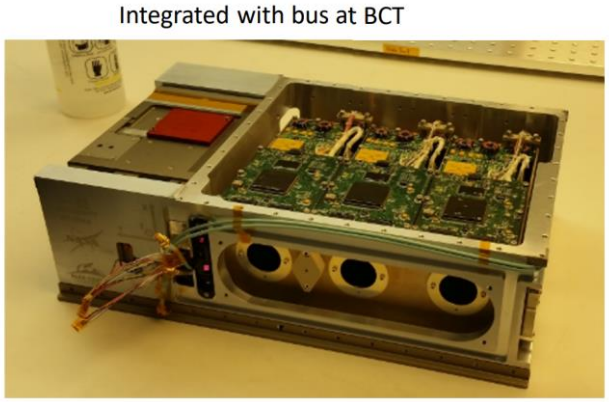

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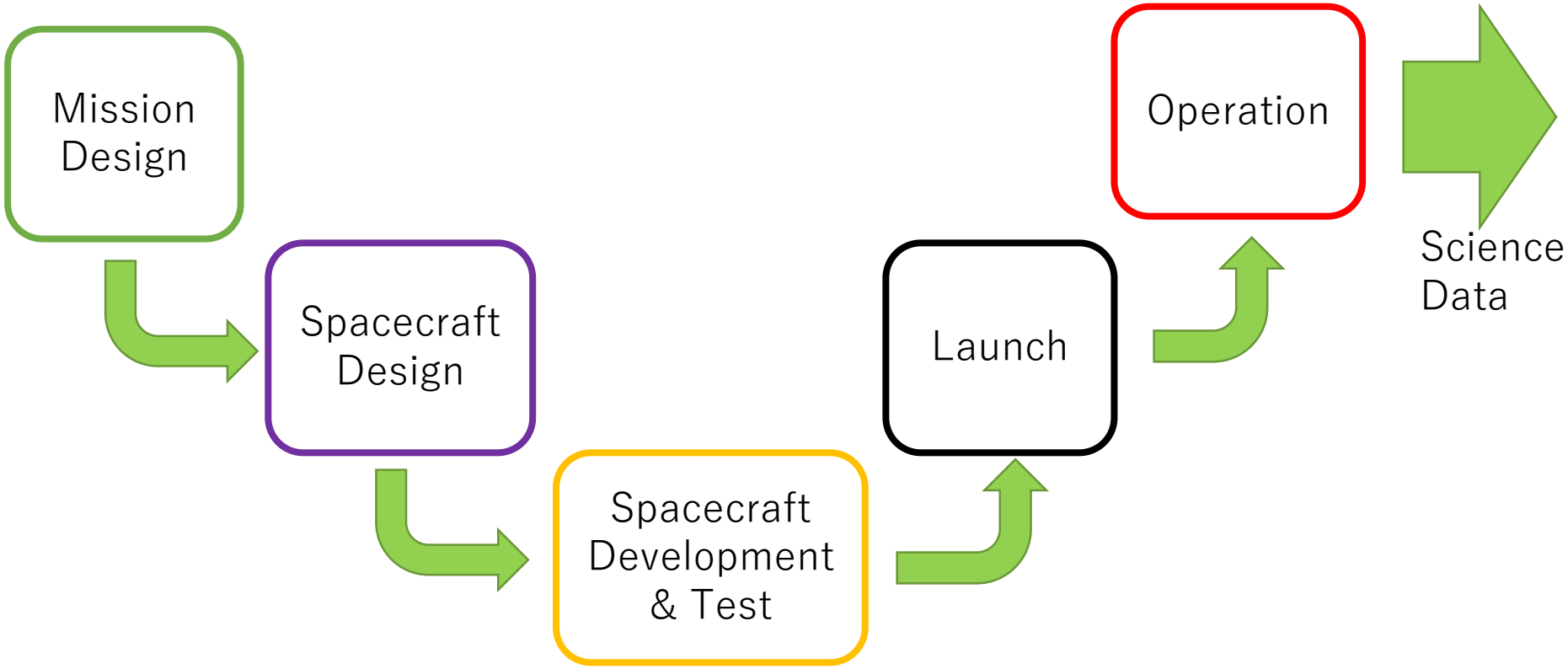
It becomes easy to use satellites … ?

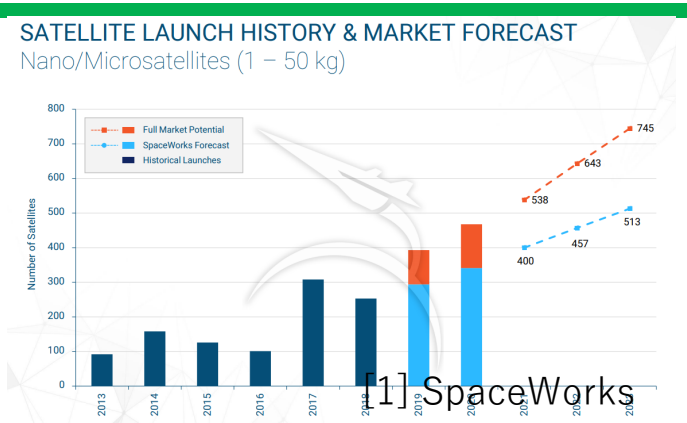
Flow to achieve science data



- To achieve science data, not only the development of satellites but also operation is necessary.

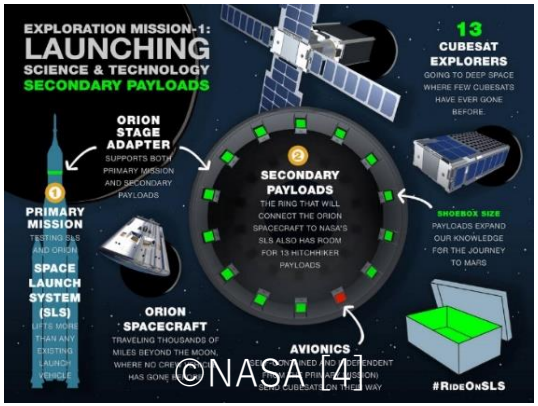
Future issues of micro satellites; operation

- Spread of micro-satellite use causes
  - Increasing missions using **constellations with hundreds of satellites**.
    - OneWeb, Planet, Axelspace, and so on.
  - Some missions using micro satellites **in deep space**.
    - 13 6U Cubesats will be launched on SLS EM-1.
- The number of satellites in orbit will increase explosively
  - **Costs for operation** will increase.
  - Especially in deep space, we should **share a small number of ground station** with larger spacecraft mission.
    - Limited operation time.



[1] SpaceWorks

To solve these issues, we aim to conduct an **onboard automatic operation.** This function is called **autonomy.**



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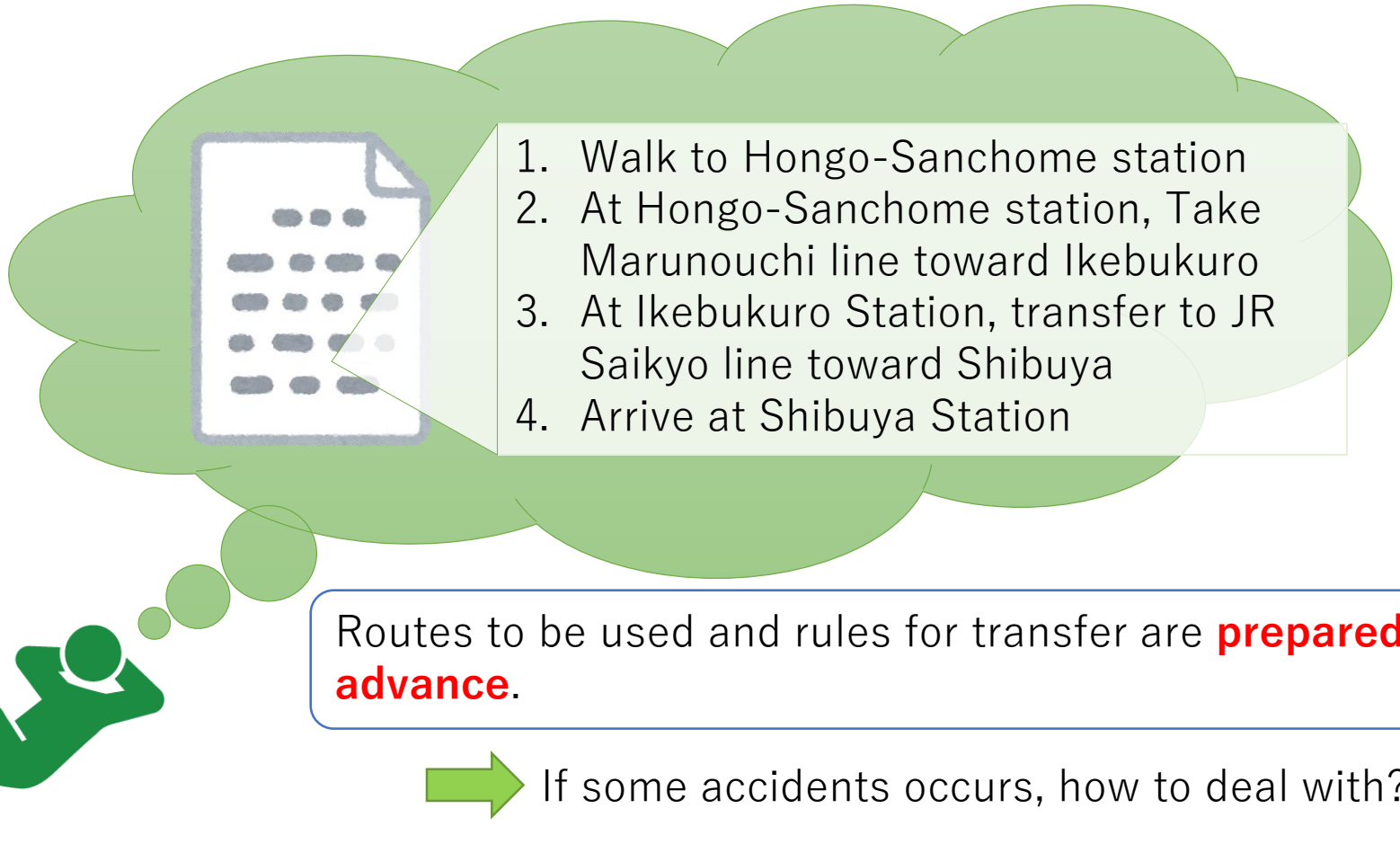
The type of autonomy #1: If-then Rule Based

- Problem: How to get to Shibuya station from University of Tokyo.

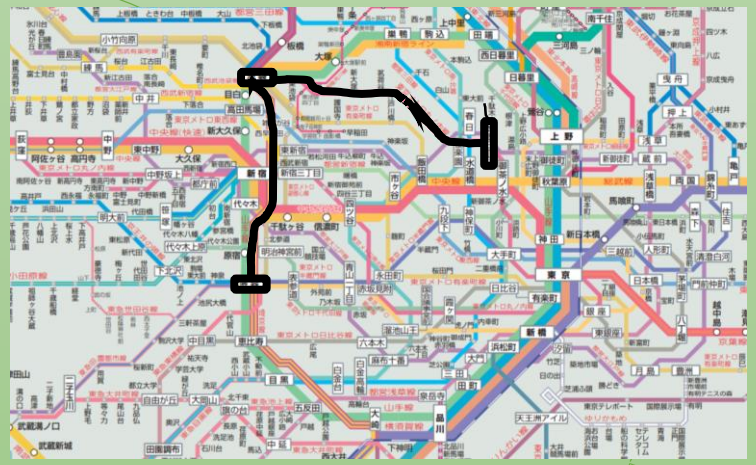


Routes to be used and rules for transfer are **prepared in advance**.

→ If some accidents occurs, how to deal with?

The type of autonomy #2: Model Based

- Problem: How to get to Shibuya station from University of Tokyo.



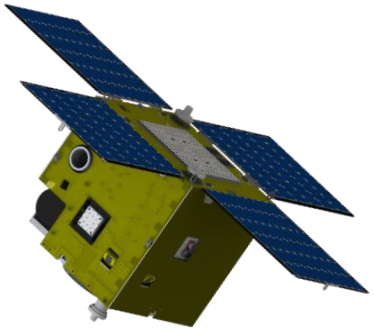
[5] http://www.chiri.com/railwaymap/pdf/syutoken_rosen_201003.pdf

Have **a model like a rail map**, and use the optimal route under that model.

Comparison of autonomy function

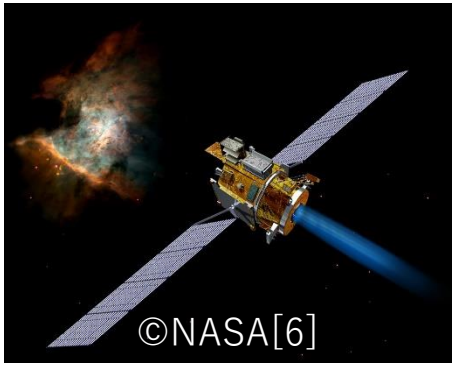
If-then Rule based

Pros: Behaviors are **predictable**, easy to **verify**
Cons: lack of **flexibility**



Model based

Pros: **Flexibility** to handle unknown situation
Cons: **hard to verify** (model & func.)



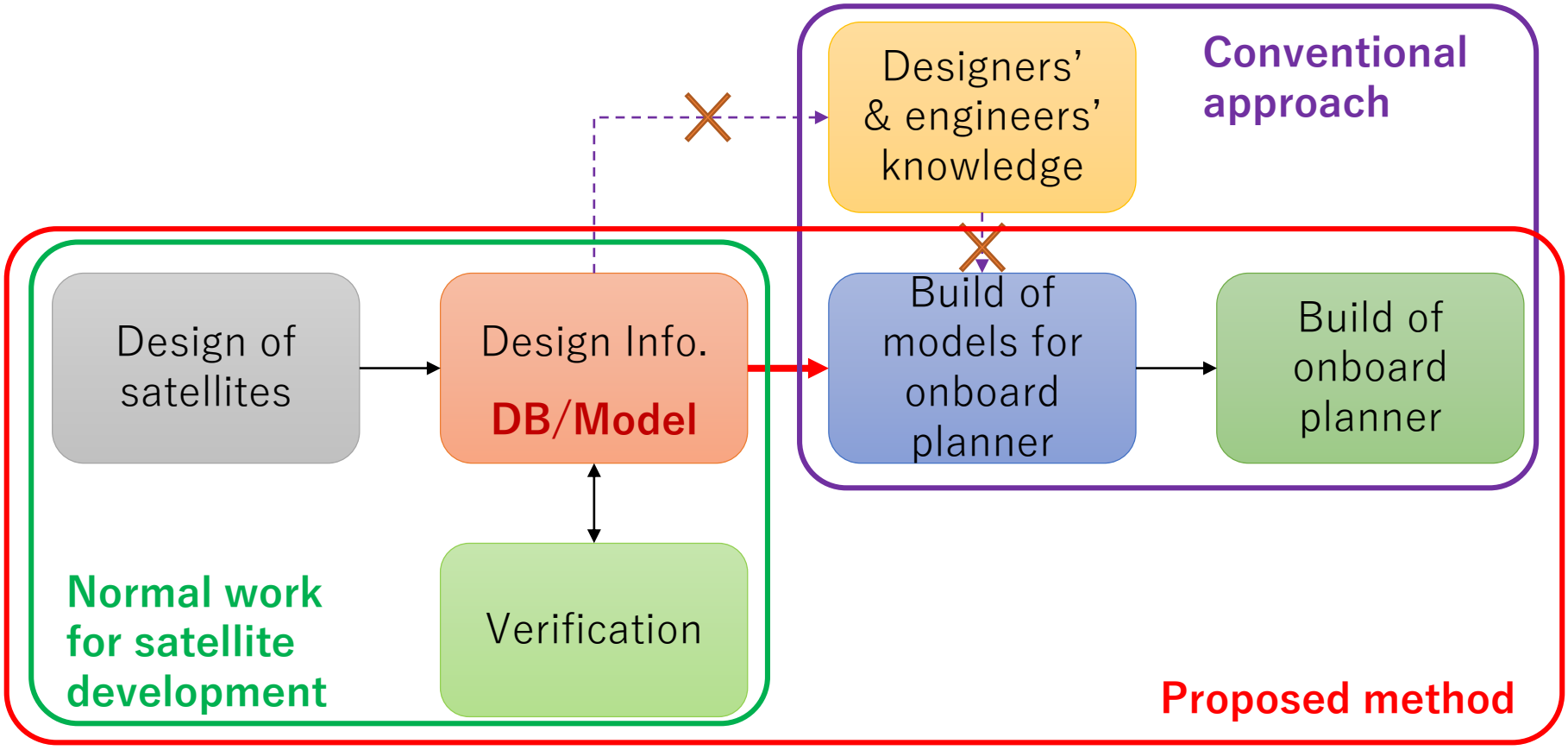
- From **the viewpoint of coverage** that can handle unknown situations, we want to build **a model-based onboard planner** that uses an automatic planning algorithm as an autonomous function.
  - We should overcome the problem of “How to build a model for on-board planner and its verification method.”

Objectives of model-based planner

- Obj.1: When a operational goal is given, spacecraft can search a plan to achieve the goal, and can execute that plan.
  - Ex. If the spacecraft receive a goal “observation of the moon”, the spacecraft plan the flow to observe, such as “change attitude, power on the telescope, observe” .
- Obj.2: If some faults / anomalies occurs during the plan, spacecraft can deal with the events and try to achieve the goal.
  - Ex. If the mission data processor stops, the spacecraft try to power off and power on the processor.
- The model for this onboard planner should include information of spacecraft functions and activities.

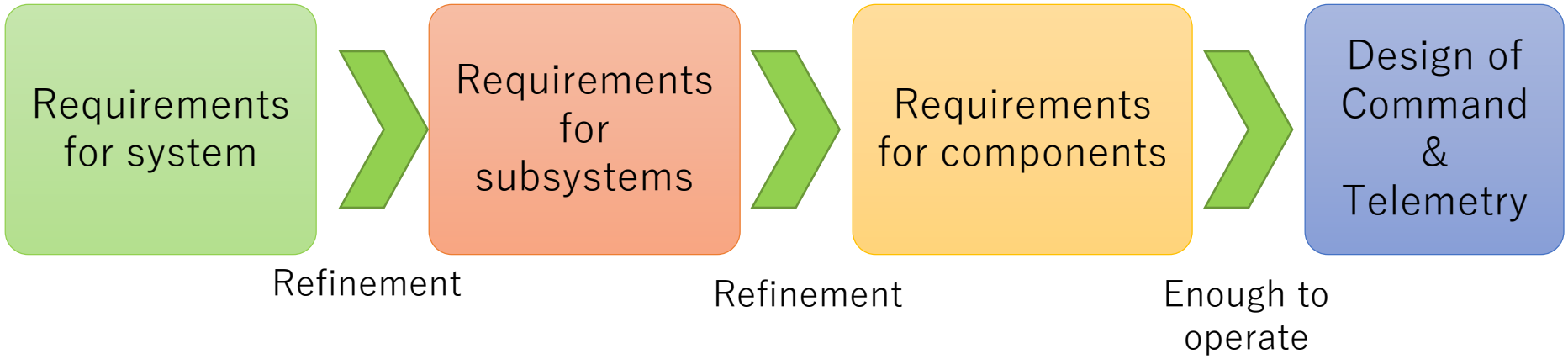
The main idea of my research

- Is it possible to build a model for onboard planners based on satellite design information?



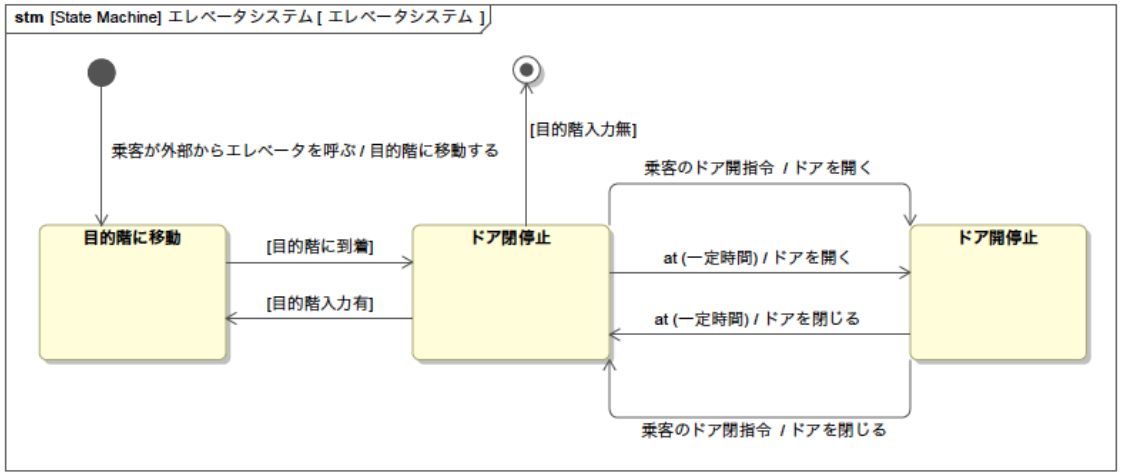
How to “correctly” design commands & telemetries of components?

- Command and telemetry are design information which is related to spacecraft’s behavior.



- **Model-based Systems Engineering (MBSE)** is a method that allows the design of each subsystem and component while showing the requirements for the system and **keeping traceability of the requirements using drawings**.

Relationships between drawings by MBSE and domain model



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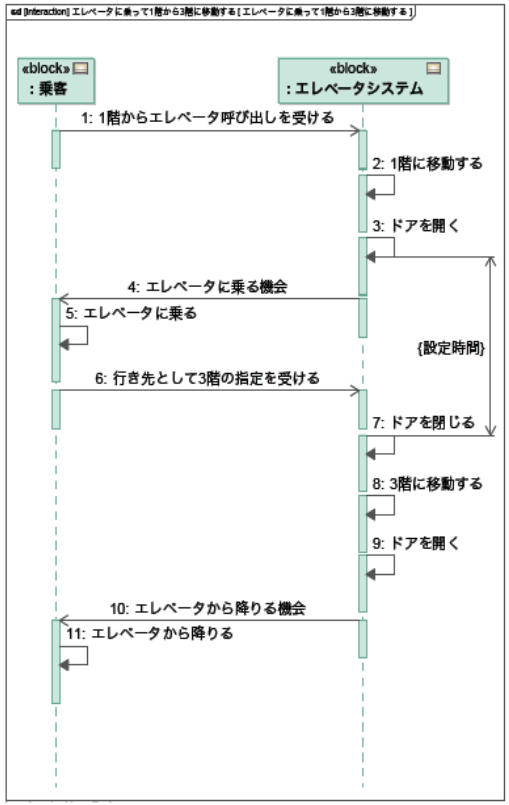

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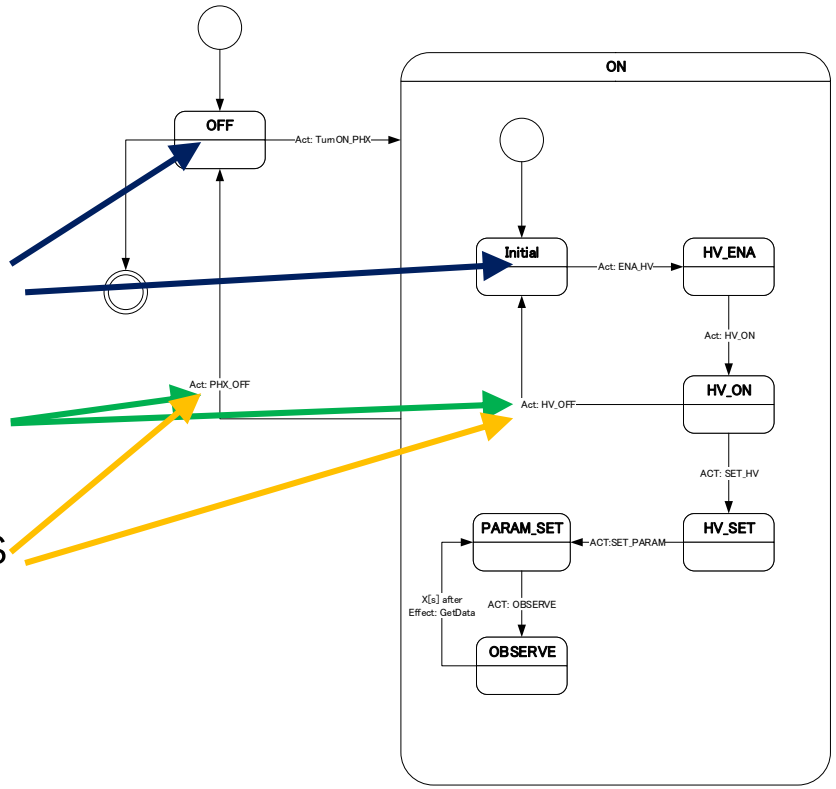
- During the MBSE process, system sequence diagrams and state transition diagrams will be drawn. **These describe the operation of each system and sub-system**, and if a similar diagram is drawn on a spacecraft, it can be inferred that **these diagrams are closely related to the domain model in the spacecraft.**

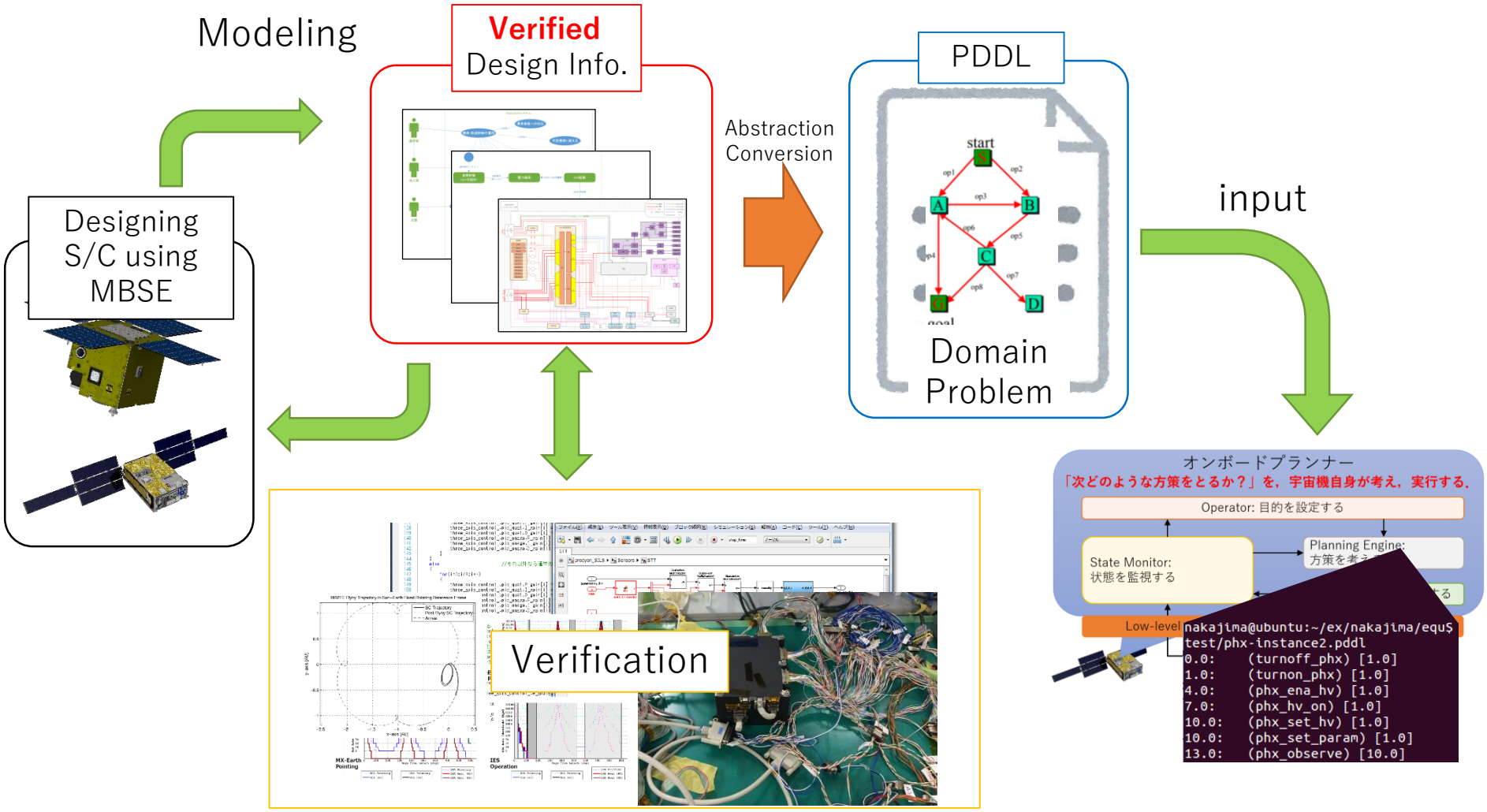
Relationships between drawings by MBSE and model for autonomous planner

- Necessary information for domain model:
  - states that each component/subsystem can take
  - Action with additional information
- States are described as squares in this drawing.
- Actions are describes as arrows in this drawing.
- Additional information of actions can be described as additional information for arrows.
  - This is not defined in the process of MBSE, but can be added.

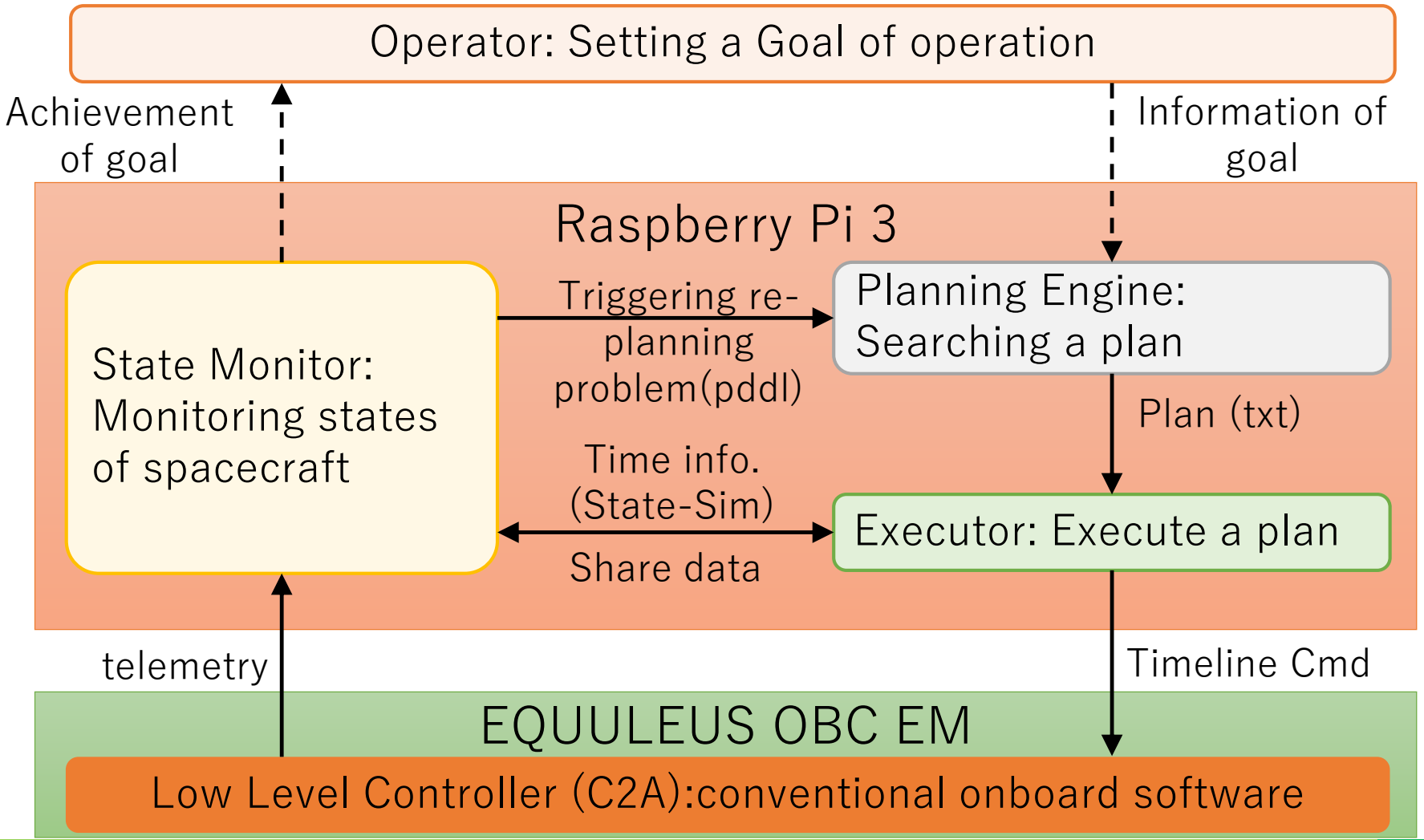


By adding information for action to this diagram, information necessary for domain model can be described in this drawing.

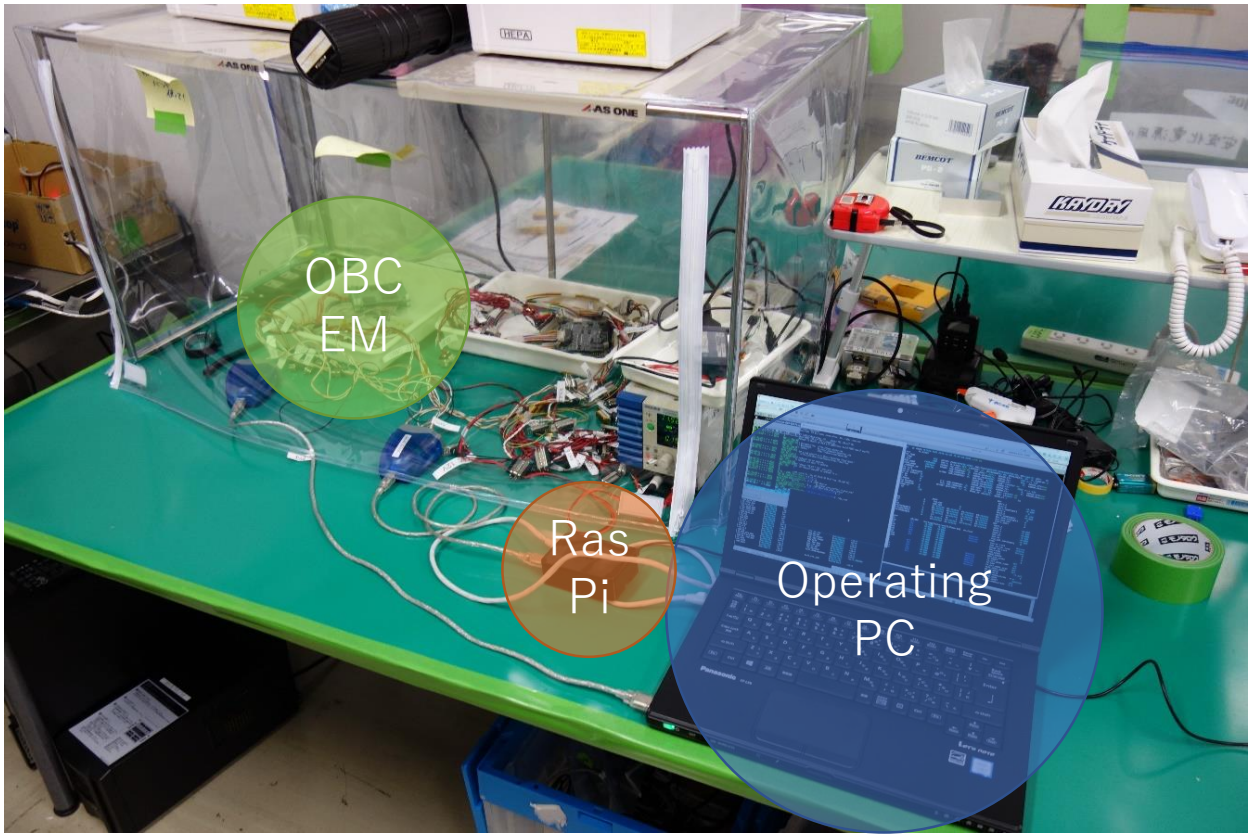
Overview of proposed method



Overview of onboard planner for EQUULEUS



Test configuration using OBC EM



Automated planning test #1: Observation using telescope (PHX)

- Planning the observation using PHX based on the domain model including information of multiple subsystem.
  - Initial state: all components are powered off
  - Goal: get a observation data of PHX

This plan is close to an time-efficient plan that humans think.

Conduct attitude control, which is time-consuming, and set parameters for observation in parallel.

Summary of test result using Raspberry Pi & EQUULEUS EM OBC

- Given the objective (goal) of "acquisition of observation data with PHX", **the operational procedure** was able to be **searched onboard by Planning Engine.**
  - This procedure is **close to an time-efficient plan**: “1. attitude control; 2. solar cell rotation; 3. observation parameter setting; 4. observation".
- OBC was able to **execute the operation procedure**, thanks to translation by Executor.
- The execution results of the procedure were monitored sequentially and **abnormalities were detected**.
- This onboard planner can search onboard for **procedures that can handle the abnormalities.**

Autonomous function based on satellite design information worked as intended.

The result of this work

- This study shows a framework that can build an autonomous planner naturally/automatically by constructing design information using Model-based Systems Engineering.
  - This framework made it easy to use model based autonomous functions.

Making satellite use closer and easier!
Helping to realize advanced missions!

- This framework can be applied to other systems.
  - Satellite-specific procedures are few.

Helping to realize model based autonomy easier.

Summary

- In model based autonomous functions that can cope with unexpected situations, the construction and verification of models is a challenge.
- In this study, **a method for seamlessly conducting spacecraft design to construction of autonomous onboard planner** is proposed.
  - In this method, spacecraft is designed and developed throughout model-based systems engineering (MBSE), then verified design information is built. Based on this information, domain models for Planning Engine are constructed.
- The proposed method was applied to 6U CubeSat EQUULEUS.
  - Autonomous function based on satellite design information worked as intended.

This method shows the possibility of standardized method for building model based autonomy.

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