Modeling a Lunar Surface Transportation System via SysML

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The south pole of the Moon is currently a target for expansion across the globe for its promise in mining, research, and diplomatic relations. Creating a framework for a sustainable lunar base will make it possible to achieve the goal of further exploration of Mars and resource collection on a greater scale. However, current models of a lunar base are too low-fidelity or too disparate to be broadly useful as decision-making tools. To model a functional, sustainable lunar base, a surface transportation system is a vital part of the architecture. Many aspects of a lunar base are dependent on reliable transportation, including infrastructure relocation, scientific missions, in-situ resource utilization, and exploration of permanently shadowed regions of the lunar surface. Three separate vehicles comprise this system: the Lunar Terrain Vehicle, the Pressurized Rover, and the Scientific Rover. This model is built around the framework of NASA's Artemis missions, synthesizing NASA requirements and data with previous work by the Aerospace Systems Design Laboratory at Georgia Institute of Technology. The sizing decisions made at the end of the preliminary design phase lead the direction of the entire project and the final system's capability. Minor future changes in these decisions would have outsized impacts on the cost and mission success. Thus, this is a complex problem involving consideration of cargo, missions, terrain, and all of the external systems that will interface with surface transportation. Modeling efforts utilize the MATLAB environment as well as SysML via the Dassault Systemes' software CATIA Magic. Within these models, inputs include the available power, power distribution method, rate of resource transportation, and number of vehicles. This is done by the use of parametric, requirement, and block definition diagrams in addition to MATLAB scripts. From these, the model estimates the range, mass, and cargo mass to size a lunar surface transportation system as part of a larger lunar base that meets the provided requirements. Some of the major challenges in this approach were collecting verification data to test the model and transferring data across different softwares. Despite these technical challenges, this tool will be a vital decision-making enabler when orchestrating future missions to the moon and beyond. The use of Dassault Systemes' tools enables this work to be easily integrated with future models of lunar bases, contributing to the eventual goal of a cohesive, high-fidelity model of a dynamic lunar ecosystem. 3DEXPERIENCE is a powerful tool, with capabilities that extend to high levels of detail. As this project matures and grows in complexity, it will be possible to link the highest level of system architecting to the most low-level product design.

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I. Introduction and Motivation

A. Motivation

The moon is a target of great interest for future scientific and economic prospects. Establishing a lunar base would make it possible to mine and process resources through in-space manufacturing on the surface of the Moon, which can then be used to allow further exploration of our solar system. In addition, a lunar base would have commercial benefits, such as tourism. In order to accomplish these prospects, a transportation system is a vital part of the infrastructure of a lunar base. However, as such a system contains many variables, each with a wide range of potential values, a systems engineering approach must be taken in the process of making decisions. Entities such as NASA are looking outward for aid in modeling these elements [1]. Therefore, there is a great need for a cis-lunar transportation decision-making tool designed with a systems engineering approach.

B. Challenges and Considerations

To model a surface transportation system to a satisfactory degree of fidelity, there are several things to take into account. First, the locations of points of interest must be noted. Indeed, not all areas on the lunar surface are equally useful candidates for resource mining or scientific study. For instance, permanently shadowed regions, often on the inner edge of craters, are more likely to contain volatiles such as ice [2]. This makes them excellent candidates for ISRU systems [3]. Similarly, there are locations of greater and lesser scientific interest in regards to ground composition and other experimental sites[4]. Additionally, rough terrain and variable slopes each affect the time and power it takes for a rover to traverse a given distance. Driving into a crater, for example, consumes significantly more resources than driving across a relatively flat region of the lunar surface. By considering these things, a model of greater reliability and accuracy will be possible. Other challenges encountered during this process were technical. The model for this study was first created in MATLAB with the intent to integrate it with CATIA Magic once it was functional. Unfortunately, this proved difficult and caused delays so the model was recreated in the new software.

C. Project Scope and Definition

Several projects to build a lunar base are currently in the works, one of which is NASA's Artemis program. This program was taken as a basis for the study. The Artemis program is partitioned into stages which eventually culminate in a long-term, sustainable lunar presence. As that final stage is far in the future and lacking in specificity, this project focuses on the early stages of a lunar base and more specifically on surface transportation, ie. rovers. Primarily, two main functions of the surface transportation system can be identified: payload transportation and human transportation. These both also contain sub-objectives. One objective of payload transportation is resupply missions; cis-lunar transportation between a lander and the central base makes it possible to bring cargo such as food, water, and construction materials from Earth to a lunar base. A second objective within this category regards in-situ resource transportation, which is necessary to facilitate in-situ resource utilization and other payload movement outside of resupply. For ISRU, this transportation would be seen in moving refined resources to the lunar base. Other transportation movement includes the broader category of scientific exploration and sample gathering. While not impossible without surface transportation, these objectives are enhanced with rover capability. These objectives can also be connected to human transportation as astronauts go to different sites of interest to carry out tasks such as moving equipment, performing scientific experiments, and checking on different systems of the base. These main functions form the core missions of the model. Figure 1 shows a flow chart of the different resources and cargo that will interact with the surface transportation system and how they do so.

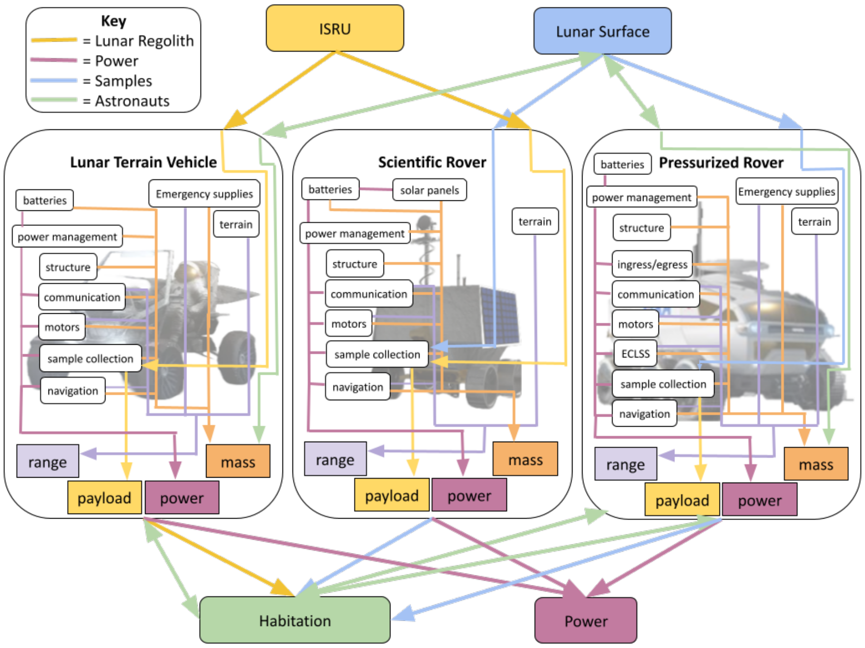

Fig. 1 OV-1 of the Model
[5] [6][7]

II. Framework

A. Overall Approach

A systems engineering approach is necessary for this type of problem because the subdivision of the problem allows for a more efficient implementation of a solution. To elaborate, this approach begins by analyzing the requirements that need to be fulfilled and the constraints that need to be considered. After defining these requirements, it is possible to divide the system first by type of vehicle, then by mission, and finally into subdivisions of the mission. More specific requirements are needed to allow for higher fidelity simulations. Once the model is built, the second stage of this approach focuses on testing it by varying inputs to the simulations and finding the limits of mission success and failure, which can then be used for subsequent findings. Several assumptions are made in this stage, particularly while a lower-fidelity model is built as a proof of concept prior to constructing a higher-fidelity model. With every iteration of the model, more levels of nuance and fidelity are added to create a more complete simulation. The purpose of these steps is to develop a model that can analyze a given mission profile and indicate whether it will be successful, the power and mass requirements to achieve the mission, and the resulting mass of the system and payload it can transport. This will enable faster optimization for the user.

B. Modeling Enablers

MATLAB is a programming language that is matrix-based and is thus particularly useful for analyzing data and creating models. The language is primarily used for numerical computing and thus useful for calculating specific data requirements and analyzing them. SysML, otherwise known as the Systems Modeling Language, is a modeling language that uses a variety of diagrams to support the analysis, design, verification, and validation of a system when following the systems engineering approach. The diagrams offer visual representations to support the information they provide and can be integrated into other analysis models, which allows the software to be used more efficiently and effectively [8][9][10]. CATIA Magic Systems of Systems Architect, more commonly known as CATIA Magic, is a Model-Based Systems Engineering (MBSE) tool that is useful in visualizing complex system specifications. As CATIA Magic fully supports SysML, it is useful for creating diagrams, easily connecting them, and running simulations. The support given by CATIA Magic to SysML ensures that a given system can be accurately represented and analyzed. Furthermore, CATIA Magic makes it easier to track requirements and ensure that they are satisfied by modeling efforts [11][12].

III. Architecture

A. Structure

Transportation systems are vital to planetary exploration including scientific missions, ISRU functionality, and payload movement. The main goal of these systems is to support safety, mobility, and efficiency. The specific requirements for each of the main three rovers: scientific, LTV, and unpressurized, are outlined in Table 1, based on NASA's Moon to Mars Architecture and other sources.

Mission	Description	Rovers Involved
Resupply	The surface transportation system shall carry 1 Unit Loading Device from the landing site to the base every 30 days	LTV, Pressurized Rover
ISRU	The surface transportation system shall transport all the refined products of the ISRU system to the central base.	LTV, Pressurized Rover
Scientific Missions	The surface transportation system shall gather samples from and explore points of scientific interest.	LTV, Pressurized Rover, Scientific Rover
General Functions	The surface transportation system shall be able to reach a speed of 10 km/hr, travel 100 km without refueling, and carry 500 kg of payload	LTV, Pressurized Rover, Scientific Rover

Table 1 Requirements of the Surface Transportation System

[13][14][15][16]

B. Assumptions and Additional Considerations

In order to build a viable model, it was necessary to make certain assumptions. First, regarding terrain, the model assumes an average angle over the course of any full trip that is hard-coded into the inputs. This angle is dependent on whether the rover is traversing relatively flat areas, entering craters, or scaling slopes. Second, the model assumes that the rover's path is a straight line between the base and its target. In a true mission, the rover would need to dodge around boulders, steep slopes, and other obstacles, but for the sake of feasibility, a high factor of safety was added to account for these detours. Third, the rover power requirements are based on a constant rate, rather than a variable one dependent on temperature and activity. This assumption was made because modeling the surface temperature as the rover goes about its mission is a degree of fidelity significantly beyond the otherwise high level that this model is at. Since this model was designed to integrate with a larger simulation of a full lunar base, it needed to take into account how other systems in the lunar environment would affect it. Primarily, the transportation system varies as a result of payload mass and the distance to travel. Therefore, the model accounts for the distance to the landing site from the lunar base, the distance to the ISRU, and the distance to scientific points of interest, and how all of these distances would have variability. The model also takes into account that the payload mass of these systems will not be a fixed value across all simulations. More crew and longer missions, for example, will both require more resources to support a lunar base, so these systems will produce more for the transportation system to carry. These changes will, in turn, affect the range and power requirements of the system. To effectively simulate a lunar base, the model must then take all of these factors into account. Once run, the simulation will output the range, mass, payload mass, and power required for the system. Table 2 provides further detail on the individual inputs and outputs of the model.

Input	Variable Name		Output	Variable Name
Distance to Landing Site (km)	dist_resupply		Mass of Surface Transportation System (kg)	m_STS
Mass of Resupply Payload (kg)	m_resupply		Range of Surface Transportation System (km)	r_STS
Frequency of ISRU Trips	freq_ISRU		Payload Mass of Surface Transportation System (kg)	m_p_STS
Distance to ISRU (km)	dist_ISRU		Power Required for Surface Transportation System (kW)	P_STS
Mass of ISRU Payload per trip (kg)	m_ISRU			
Frequency of Scientific Trips	freq_p			
Distance to Points of Interest (km)	dist_p			
Mass of Scientific Cargo per trip (kg)	m_p			
Length of Mission (days)	t_dur_mission			
Number of Crew	num_crew			
Number of LTVs	num_ltv			
Number of Pressurized Rovers	num_pr			

Table 2 Inputs and Outputs of the Surface Transportation System

IV. Modeling

A. Preliminary Modeling

To obtain preliminary sizing values for the lunar surface transportation, MATLAB was used to rapidly test and iterate on the model based on changing requirements and information. As stated in the previous section, there are simplifying assumptions made that keep the model at a high level and allow for the rapid prototyping that was necessary. The model takes the number and types of rovers, basic statistics (mass, maximum speed, maximum power consumption, and crew member mass), a mission profile, the number of crew, and a factor of safety. The mission profile consists of the type of mission, the maximum allowed duration, the distance to the point of interest, the mass of what is being transported, and the slope of the terrain, estimated from a slope map [17]. This point of interest could be the ISRU system, the landing site, or any of a variety of areas for scientific study. The model outputs the total mass of the system, the range required, the maximum payload capability required, and the total power required, as well as a verification that the mission is possible. The mass, range, payload mass, and required power amounts for each rover are combined into a total statistic for each output of the surface transportation system. Equations 1-4 relate the inputs of the model to the outputs.

$$R = 2df \tag{1}$$

$$m_p = \Sigma v(m_s + m_c * n_c) \tag{2}$$

$$m = m_r n_r \tag{3}$$

$$P = P_r n_r d/s \tag{4}$$

Equation (1) relates system range R to the distance to the farthest point of interest d and factor of safety f. A high factor of safety was used to account for simplifications made during the modeling process. Equation (2) connects the total required payload mass m_p to the frequency of trips v, the mass of the sample m_s, the mass of a crew member m_c, and the number of crew members n_c. The rovers can visit multiple points of interest in a mission, each of which has different values of m_s, so Eq. (2) accounts for this by summing the payload masses for each point of interest. Equation (3) scales the mass of the system with the mass of one rover m_r and the number of rovers n_r. Equation (4) calculates the total power requirements for the system P from the power consumption of a single rover P_r and the number of rovers n_r, the distance, and the max speed of the rover s. s is halved based on the value of the slope. The inputs and outputs for these equations were loosely based on previous works[18][19][20][21]. This MATLAB model provided an efficient method for verifying the overall model and its outputs and enabled a rapid transition to CATIA Magic.

B. SysML Modeling

The block definition diagram in Figure 6 highlights the major components of the transportation system, their relations to one another, and what variables will be necessary to model them. The top-down approach is useful for seeing what components are shared among systems. Furthermore, this outline is necessary in order to create and integrate the parametric diagrams that follow.

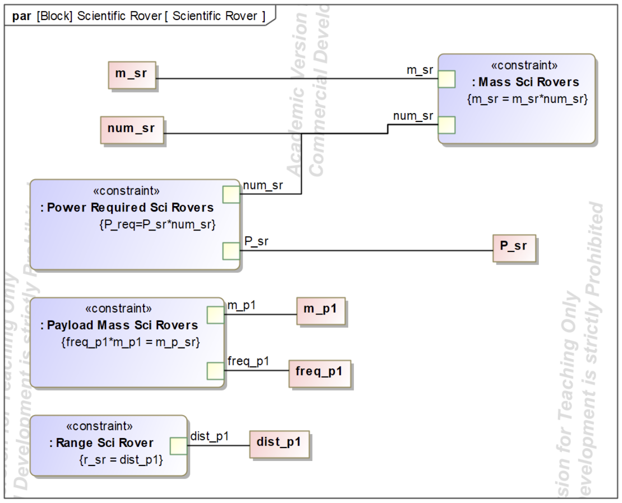

Fig. 2 Parametric Diagram of the Scientific Rover

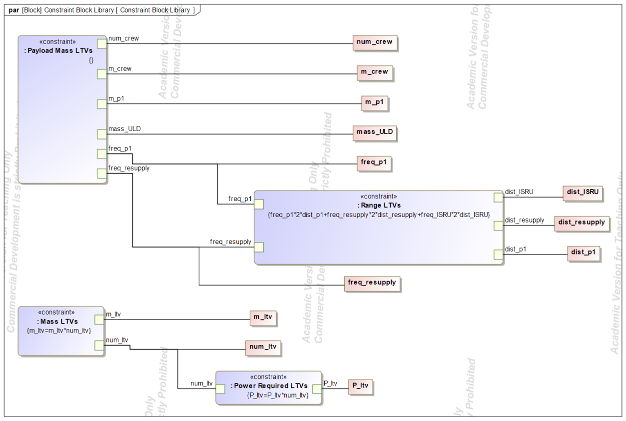

Fig. 3 Parametric Diagram of the Lunar Terrain Vehicle (LTV)

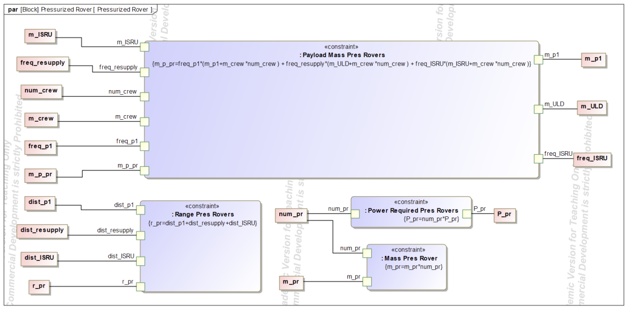

Fig. 4 Parametric Diagram of the Pressurized Rover

The parametric diagrams in Figures 2, 3, and 4 outline the different equations that are used for modeling the LTVs, pressurized rovers, and scientific rovers, respectively. After these blocks are integrated with the block definition diagram to create a parametric diagram, simulations can be run directly in CATIA Magic and used to verify requirements. If the mission is not successful, i.e., the system cannot complete all missions with the provided number of vehicles and mission duration, the model will return a failure.

V. Results

Table 3 outlines a use case of the Pressurized Rover doing a resupply mission, the Scientific Rover performing a scientific study of permanently shadowed regions, and two LTVs supporting the ISRU system. This use case assumes that the ISRU system is producing all the water for the crew and no other resources.

Input Variable	Value	Output Variable	Value
dist_resupply	10 km	m_STS	2574 kg
m_resupply	997 kg	r_STS	36 km
freq_ISRU	30	m_p_STS	1316.46 kg
dist_ISRU	7.02 km	P_STS	602.4 kWh
m_ISRU	26.46 kg		
freq_p	1		
dist_p	58.37 km		
m_p	20		
num_ltv	2		

Table 3 Use Case 1

Figure 5 illustrates the range of the given use case. The red points are points of interest; they have been deemed important to base functionality, whether for ISRU operations, scientific experiments, or payload retrieval. The transparent yellow circle represents the current range capability of the rovers, while the solid yellow circle represents the base the rover will be traveling to and from.

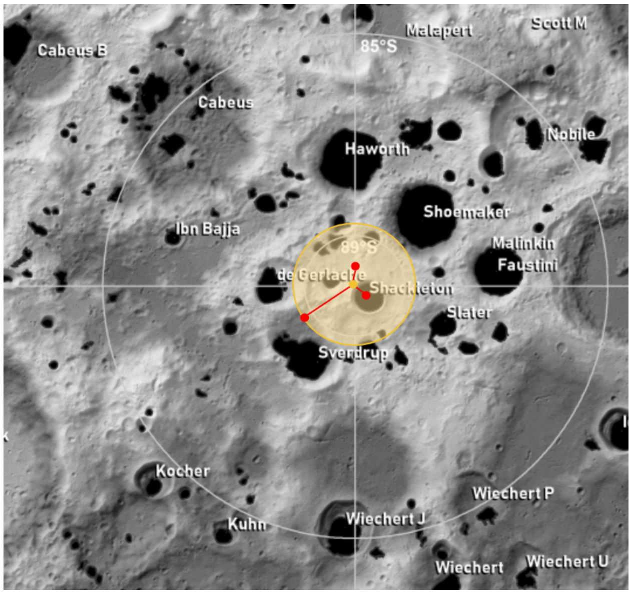

Fig. 5 Range of Given Use Case

[22]

A. Analysis

The outputs in Table 3 are representative of the high-level requirements a lunar surface transportation system would have to adhere to given the previously stated mission profile. They provide guidelines on how the transportation system and other, facilitating systems must be constructed to complete said mission. The power system must be capable of providing at least 604.2 kWh to the various rovers over its lifetime, and the Earth-to-Moon transportation system must have 2574 kg of cargo space allotted [3]. Over the duration of lunar habitation, the rovers will have to carry a total of 1313.46 kg over a maximum round trip distance of 72 km without encountering any failures [3]. These results comprise of a basic sizing for the transportation system, and can be refined when more detail is added to the model.

B. Next Steps

While the data collected thus far is useful in sizing the transportation system for a lunar base, additional detail can be added to construct a higher-fidelity model that will be of more use as a decision-making tool. The first area that comes under scrutiny is the terrain surrounding the base, particularly in the path from the base to locations of interest. Based on data on lunar terrain, MATLAB codes can be used to determine the terrain's effect on the power required to perform these missions and the time it will take to get there, including any detours due to obstacles. Integrating MATLAB with the CATIA Magic model will likely pose technical challenges, however, once the codes are integrated with CATIA Magic, it will be possible to plan routes in MATLAB and, using those, calculate the relevant outputs with CATIA Magic. As this project is a component of a project at the Aerospace College of Georgia Institute of Technology, transportation inputs and outputs will eventually be integrated with a user interface to be represented in a final dashboard alongside other systems. In addition, the model created in this project will interface with other relevant systems, such as power and ISRU. The power system of the lunar base manages the power production and its distribution. It will then provide the power for the rovers to run and thus will take the power output of the transportation simulation as an input to size power generation systems. The ISRU system makes use of the surface transportation system to carry processed resources to the central base, and so can provide the mass, frequency, and distance inputs regarding ISRU. Other systems will likely be integrated as it becomes necessary.

VI. Conclusions and Findings

Through the use of SysML, CATIA Magic, and MATLAB, it was possible to create a high-level model of a lunar surface transportation system. This model is viable as a modular component of a full lunar base system of systems model: it accepts information that other systems may produce, such as the mass of ISRU resources, and uses it to create a dynamic and responsive simulation of how a transportation system would function. It is also able to produce information that other systems will take as their inputs. In addition, the model accounts for how terrain and payload weight, among other inputs, will affect the system's performance. All of these considerations create a powerful tool that can be used to effectively make decisions about future lunar missions, such as those in the Artemis program. Additionally, as this project matures further, the use of the tool CATIA Magic, as part of the 3DEXPERIENCE set of tools, allows for simulations of highly detailed situations to be seamlessly linked back to the higher-level model created at this point. This will make it possible to iteratively add fidelity to this model without needing to rebuild it entirely for each successive iteration.

Further work in this area could examine details that were abstracted out during the creation of this model. A more exact simulation of how terrain would affect performance, for instance, would greatly improve the accuracy and usefulness of this model. In addition, a more dynamic model that could suggest multiple solutions to provided mission requirements would enable greater flexibility in decision-making.

Appendix

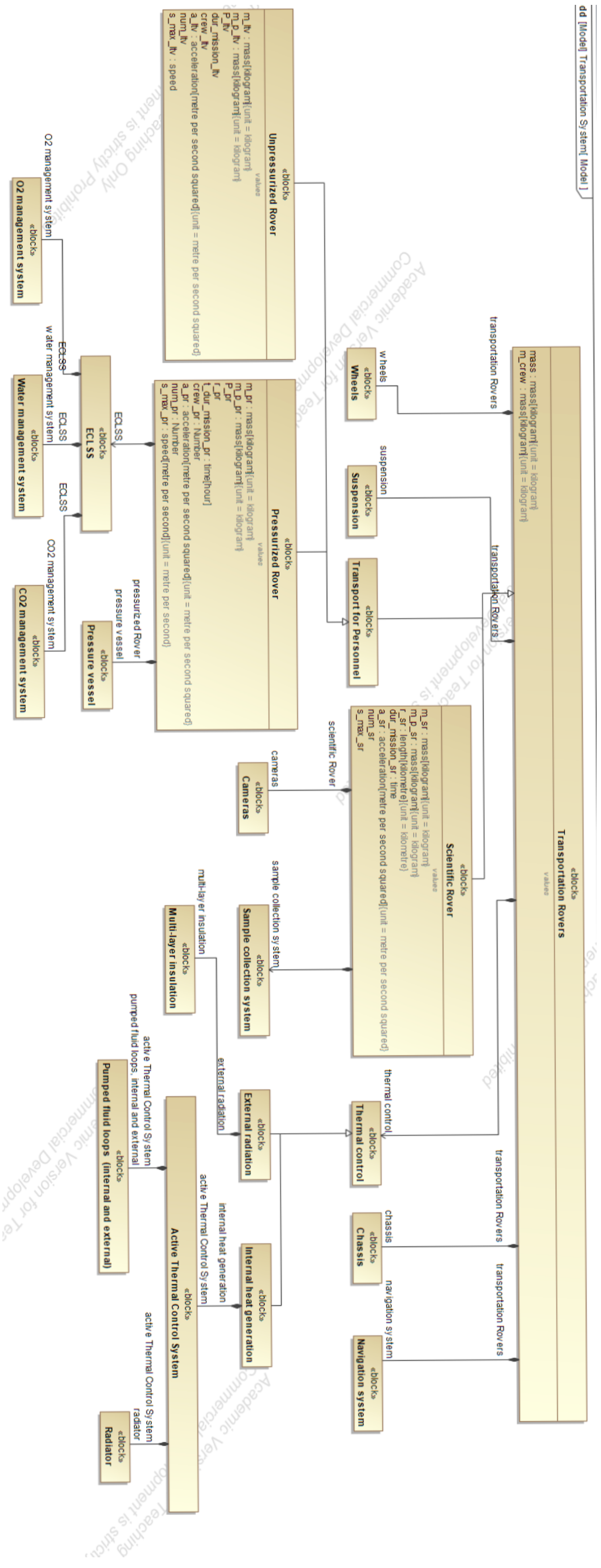

Fig. 6 Block Definition Diagram

Acknowledgments

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