A Design Guide for Attitude Determination and Control Systems for Picosatellites

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Abstract—**In this paper we present a design methodology for attitude determination and control systems for picosatellites. It is based on the ECSS documentations and shows through a practical example how the ECSS standard can be applied to a picosatellite project.**

Keywords- design, attitude, control, determination, methodology, picosatellite, CubeSat, functional specifications, design definition, verification, work packages

I. INTRODUCTION

A picosatellite is restricted to a mass between 0.1-1 kg, where the CubeSat is an example of a picosatellite which is $10x10x10cm^3$ and weighs 1kg.

The HiNCube is a student satellite program at Narvik University College in Norway. It was initiated in 2006 with the mission to build and launch a picosatellite capable of taking pictures of the Earth. Through this project, its members have obtained much experience with satellite design and manufacturing.

In general picosatellites are short term satellite projects that are intended only to require a few years of development time. The picosatellites are widespread in the educational community, which mean that the designer starts with little or no experience with satellite manufacturing. It is therefore imperative that the inexperienced designer has access to a guide.

A. Previous Work

In the European Cooperation of Space Standardization (ECSS) documents there is a detailed guide on designing and manufacturing systems for space applications. There is a guide to space projects in [1] which details how each of the different phases are executed and how the requirements are defined. In [2] there is documentation specially focused on control systems for space missions, which is applicable for robot arms, rovers, thermal control and attitude determination and control systems (ADCS).

B. Contribution

For the inexperienced the ECSS documentation can be a challenge to understand. Therefore we present a design methodology based on the ECSS documentation which shows through the HiNCube example how to design and build an ADCS system for picosatellites.

C. Attitude Determination and Control System

The ADCS system must be able to determine where its current location is as well as determine what its current attitude is. This is done through sensors which are used to measure physical quantities which then are used to determine its attitude and position.

The ADCS system must also be able to change the attitude to a new commanded attitude depending on operational mode, or keep the current attitude stable. This is done through the use of active actuators, which for picosatellites usually is done by using magnetic torquers or very small reaction wheels. There are also examples of passive attitude control devices such as the gravity boom and the magnetic torque rod [4] which are able to stabilize the attitude, but not to change it. In this paper we focus on active attitude control, which is the most challenging of the two control methods.

II. DESIGN METHODOLOGY

This design guide is divided into several chapters detailing different important tools for designing the ADCS system for a picosatellite. An overview of the different tasks that must be performed in the design of an ADCS system is shown in Figure 1.

First the mission objective is discussed and how it affects the ADCS regarding limitations and requirements for the system. From the mission objective, several different modes of operations can be extracted which details how the ADCS should operate in different situations. The mission objective is also the basis for defining the requirements of the picosatellite, which provide guidance for the rest of the design process as well as maintaining a system that is compatible with the rest of the satellite.

From the requirements, the functions that the ADCS shall perform are defined. These functions details how the ADCS will respond to a given situation and are the basis for the design definition of the system. The design definition details the hardware and software design of the ADCS system and is the result of the preceding work. The system is then tested and integrated together with the other subsystems that constitute the whole satellite, and the requirements are then validated as the system is proved to perform in accordance with the defined requirements.

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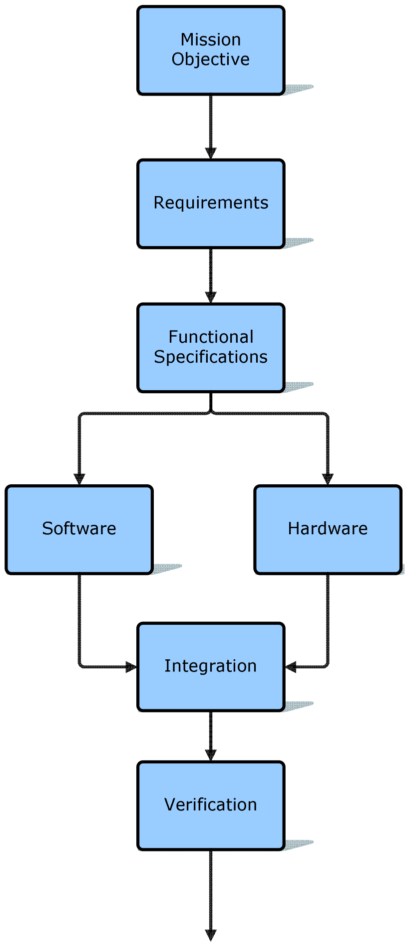

Figure 1 General Design Path

A. *Mission Objective*

In the HiNCube case, the mission objective was defined to be: "*Students of Narvik University College shall within two years (from 2006) build a picosatellite which will be deployed into low Earth orbit to take pictures of the Earth*".

It is evident that this timeframe has been exceeded which is due to the complexity of designing and manufacturing a picosatellite.

The elements that are important from the ADCS perspective are the limitations created by this mission objective. It is apparent that the control system is limited to a picosatellite, which eliminates larger actuation and sensor systems such as thrusters and star trackers. Through a selection and justification process the suitable determination components and control components can be selected. This process must take into account the timeframe of the project weighed up against the complexity of the different kinds of sensors and actuation systems, as well as the demands of these systems on the satellite and project as a whole.

In the HiNCube case, magnetic torquers were selected as actuators, while sun sensors and magnetometer was selected as sensors. These systems are non-mechanical, and thus reduce the demands on the complexity of the mechanical design.

B. *Modes of Operation*

From the mission objective and the selection of actuator and sensors, it is possible to define modes of operation that the ADCS system must operate in. Note that these modes will be dependent on mission objective and which hardware that has been selected. For example if reaction wheels are selected as an actuator, it would require a momentum dumping mode.

For the HiNCube ADCS case, where the satellite is in low Earth orbit employing magnetic torquers for attitude control there are five different modes of interest:

1) *Detumble*

After the satellite is deployed into orbit, the satellite is required to wait 30 minutes before boot up [3]. After it has booted and performed a system check it enters the detumble mode. As the satellite is deployed into orbit, it will have an angular velocity which must be reduced towards zero.

2) *Attitude Stabilization*

During the attitude stabilization mode, the satellite shall maintain a defined attitude.

3) *Maintenance*

During the maintenance mode, ADCS software can be updated and the controller gains can be changed.

4) *Communication*

During the communication mode, the antenna onboard the satellite must be able to point in the direction of the ground station in order to minimize the misalignment loss.

5) *Camera*

During the camera mode, the satellite must be able to point at a target with high attitude accuracy. A target can be selected by longitude and latitude and a picture can be taken at a predefined time.

C. *Requirements*

From the mission objective and modes of operations, a list of requirements can be generated which acts as a total specification of how the ADCS will solve the mission objective as well as the different modes. The following requirement list is derived based on [1].

1) *Functional Requirements*

F_1. The ADCS shall be able to determine its attitude and position.

F_2. The ADCS shall on command change the satellite attitude and maintain that attitude.

2) *Mission Requirements*

M_1. The ADCS shall have a detumble mode where it reduces its angular velocity towards zero.

M_2. The ADCS shall have an attitude stabilization mode where it shall maintain a defined attitude.

M_3. The ADCS shall have a communication mode where it points the antenna towards the ground station at NUC.

M_4. The ADCS shall have a camera mode where it points the camera towards a target longitude and latitude.
M_5. The ADCS shall have a maintenance mode where new controller gains can be uploaded.
M_6. The ADCS shall have three axis control of the satellite using three orthogonal magnetic torquers.
M_7. Attitude determination shall be done by using six sun sensors and a three-axis magnetometer.
M_8. The ADCS shall have a real time clock to determine its current position.
M_9. The ADCS shall have a microcontroller able to perform measurements of the sensors, calculate the attitude and perform attitude changes using the magnetic torquers.
M_10. The microcontroller shall be able to perform the mathematical computations.
M_11. Each magnetic torquer shall have an H-bridge to enable magnetic moment in both directions.

3) *Internal Requirements*

I_1. The ADCS shall communicate with the other systems through a Serial Peripheral Interface (SPI) bus.
I_2. The ADCS circuits shall operate on a supply voltage of 3.3V.
I_3. The magnetic torquers shall operate on a supply voltage of 3.7V.

4) *Environmental*

E_1. The ADCS shall be able to obtain the vector towards the sun using six sun sensors.
E_2. The ADCS shall be able to obtain the magnetic field vector using a three axis magnetometer.
E_3. The ADCS shall be able to perform rotational motion by using the magnetic field for attitude control.

5) *Physical*

P_1. The ADCS module shall not weigh more than 0.15kg.
P_2. The ADCS circuitry shall not exceed the dimensions $90x96x15mm^3$.
P_3. The magnetic torquers shall be placed behind the solar panels on three orthogonal sides of the satellite.
P_4. One sun sensor shall be mounted on each of the six sides between the solar cells.

6) *Operational*

O_1. The ADCS shall be able to detumble the satellite without interaction from the ground station.
O_2. The ADCS shall be able to change its attitude to a defined longitude so that pictures can be taken of a target when the satellite reaches the correct latitude.
O_3. The ADCS shall change the attitude on command from the On Board Data Handling module.
O_4. The ADCS shall perform sensor measurements on command from the On Board Data Handling Module.
O_5. The ADCS shall be able to detect errors with the magnetic torquers.

7) *Verification Requirements*

V_1. The controller algorithms shall be verified through simulations.
V_2. The attitude determination algorithm shall be verified through simulations and testing.
V_3. The sun sensors shall be verified through testing.
V_4. The magnetometer shall be verified through testing.
V_5. The microcontroller shall be verified through testing.
V_6. The magnetic torquers shall be verified through testing.
V_7. The H-bridge shall be verified through testing.
V_8. The internal communication shall be verified through testing.
V_9. The physical requirements shall be verified through metric measurements.
V_10. The ADCS module shall be verified through the Critical Design Review.

D. *Functional Specification*

With a list of requirements defining how the ADCS module shall perform and which limitations it has, it is possible to define the functional specification of the ADCS. The functional specification details all the functions that the ADCS module must do and how it is done. It presents an overview of the tasks that must be performed in the microcontroller (MCU) and their relations to the hardware and is shown in Figure 7.

E. *Design Definition*

After defining all the functions that the ADCS shall perform, the actual design can be created. The design definition can be divided into a hardware part and a software part.

1) *Hardware*

The hardware of the ADCS is defined to contain all the components outside the microcontroller that is shown in Figure 7 and the product diagram containing the components is shown in Figure 2.

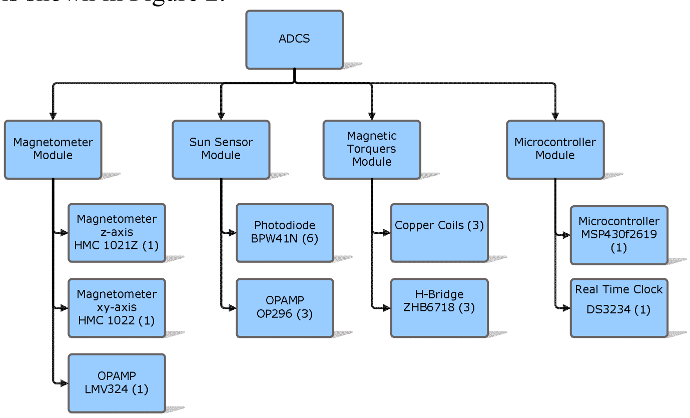

Figure 2 Product Diagram

a) *Magnetometer*

The magnetometer design is built around two magnetic sensors from Honeywell [5]. These sensors are built on an integrated circuit, where the first one is a 1-axis magnetic sensor, while the second is a 2-axis sensor. When combining these two components we get a complete 3-axis magnetic sensor system. In Figure 3 the design for the 1 axis is shown where the measurements from the magnetometer are amplified through an operational amplifier and then measured by the microcontroller.

b) Sun Sensors

In order to determine the sun vector, the ADCS employ six photodiodes, which produce current in reverse bias as they are illuminated by the sun. This reverse current is then amplified and measured by the microcontroller. A schematic is shown in Figure 4 and is duplicated for each of the six photodiodes enabling them to be used to determine the sun vector.

c) H-Bridge

The purpose of the H-bridge is to change the direction of the current that passes through the magnetic torquers producing magnetic moment. By changing the direction of the current, the direction of the magnetic moment is changed, and thus we are able to have control in two directions around each of the axes. The principle of an H-bridge is shown in Figure 5, where the MCU is able to choose the direction of the current through the coils by activating different transistors.

d) Magnetic Torquers

The magnetic torquers are copper coils that are located at three of the satellite sides as shown in Figure 6 where they enable three axis control. The magnetic torquers are mounted on the outside of the structure and are behind the solar panels (shown as brown lines in Figure 6).

e) Microcontroller (MCU)

The microcontroller controls all the functions that are defined in Figure 7. Regarding selection of a microcontroller for ADCS, it must be taken into account that it should be able to perform a high level of computations due to the mathematical algorithms implemented in this system. Dependent on the lifetime of the project the radiation resistance of the controller may also be needed to be factored into the selection process.

f) Real Time Clock

The real time clock is an important part of the ADCS system, as it is required to perform rotations between reference frames, determination of the magnetic field and to determine the sun vector. It is also required to determine the true anomaly of the orbit as well as to change attitude towards a target defined by longitude and latitude. In the HiNCube case, the real time clock is a commercial off the shelf product connected to the microcontroller.

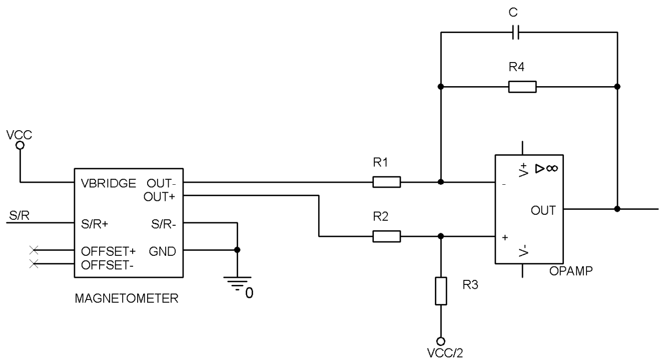

Figure 3 Magnetometer Circuit

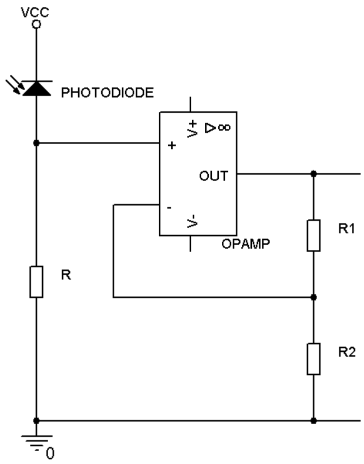

Figure 4 Sun Sensor Circuit

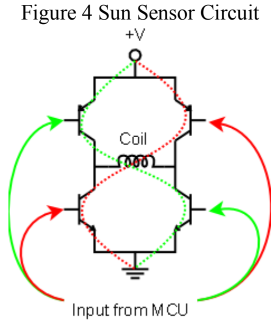

Figure 5 H-Bridge

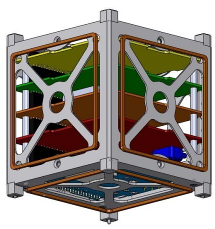

Figure 6 Magnetic Torquers

2) Software

The purpose of the software is to solve the functional specifications using the available hardware and ensuring that the ADCS is able to meet the functional requirements. An introduction to software design for space engineering can be found in [10]

a) Attitude Determination

There are several methods of performing attitude determination using sensors and models. Kalman filter, Extended Kalman Filter, the Triad algorithm [7] and the QUEST algorithm can be used to determine the attitude. In [5] and [6] the QUEST algorithm is presented which implements vectors from different reference frames and is the method which will be used in HiNCube. It is then able to obtain the rotation matrix between these reference frames, and is thus able to determine the attitude of the satellite. The sensor measurements onboard the satellite will be referenced in one reference frame, while the mathematical models will be in another. It is therefore possible to use the measurements together with the models of the magnetic field and sun vector to obtain the attitude of the satellite.

b) Attitude Control

Different satellite missions use different controllers. For the HiNCube mission, a nonlinear controller as presented in [8] will be used for attitude maneuvers, while the B-dot controller presented in [9] will be used in the detumbling mode.

F. Integration

After both the hardware prototype and the software are finished it must be integrated together. Throughout the design process it is recommended that there is a continuous dialogue between the people responsible for the hardware and software as the systems are developed. In the HiNCube case, the design managed to pass through the preliminary design review without a real time clock, a major discrepancy which was discovered late in phase C as the focus had been on hardware development.

The system must also be integrated with other systems in the satellite which must be taken into account throughout the project.

G. Verification

After the systems have been integrated together and is operational, the requirements must be verified and validated. For each of the requirements, they must be traceable and detectable and be proven through testing, analysis, metric measurements or simulations. Since the HiNCube satellite employs magnetometers as a sensor, its function can be validated by measuring the magnetic field and compare the resulting vector with a compass. The sun sensors should be able to determine the angle towards the sun, which can be done through testing with direct sun contact, and check to see if the sun sensors are able to determine the sun vector. The magnetic torquers can be tested as actuators using the magnetometer to measure the generated magnetic moment. Alternatively it is possible to create a test environment where the torquers would be able to perform attitude maneuvers and detumbling.

H. Work Packages

From the design presented in this paper, an overview of the work packages has been developed. The work packages are required in the beginning of the project, and have been divided into three main parts, simulator, hardware and software. The overview of the work packages is shown in Figure 8.

III. Conclusion

In this paper we have presented a design guide based on the ECSS documentation which shows how the HiNCube picosatellite has developed the ADCS system. It is intended to serve as an introduction for new educational institutions that intends to build ADCS systems for picosatellites, and can give a rough overview of the main elements that is required from the ECSS documentation.

References

[1] ECSS-E10-1B *Space Engineering – System Engineering Part 1: Requirements and process*, 2004.

[2] ECSS-E-60A *Space Engineering – Control Engineering*, 2004.

[3] Lee, S., Hutputanasin, A., Toorian, A., Lan, W. and Munakata, R., *"CubeSat Design Specifications"*, California Polytechnic State University, 2008.

[4] Sidi, M.J., *Spacecraft Dynamics & Control*, Cambridge University Press, 1997.

[5] Fossen, T.I, *Marine Control Systems*, Marine Cybernetics, 2002.

[6] Anderson, D., Sellers, J.J. and Hashida, Y., *Attitude Determination and Control System Simulation and Analysis for Low-Cost Micro-satellites*, 2004.

[7] Wertz, J.R., *Spacecraft Attitude Determination and Control*, Kluwer Academic Publishers, 1978.

[8] Schlanbusch, R., Reiten, K., Kristiansen, R. and Nicklasson, P.J., *Passivity-Based Attitude control of the SSETI ESMO Satellite*, International Lunar Conference, 2007.

[9] Wisniewski, R., *Satellite Attitude Control Using Only Electromagnetic Actuation*, Phd thesis, Aalborg University 1996.

[10] ECSS-E40-1B *Space Engineering – Software – Part 1: Principles and Requirements*, 2003.

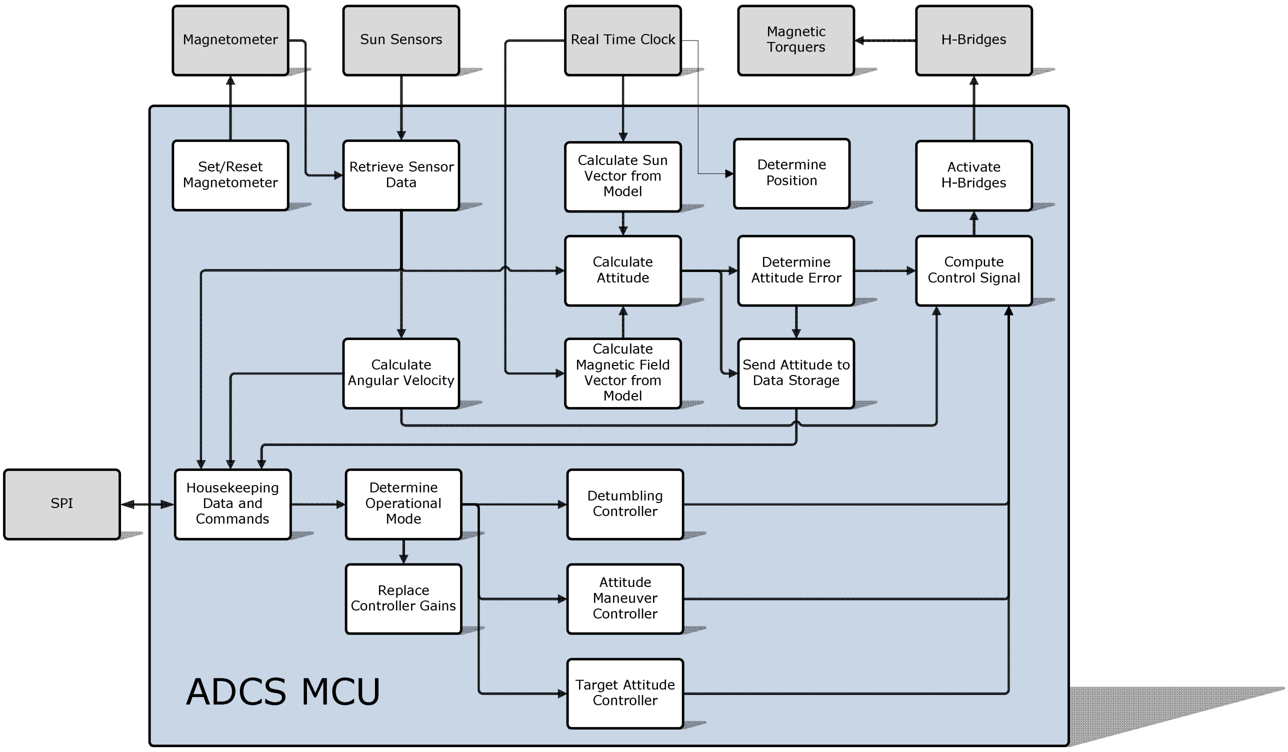

Figure 7 Functional Specifications

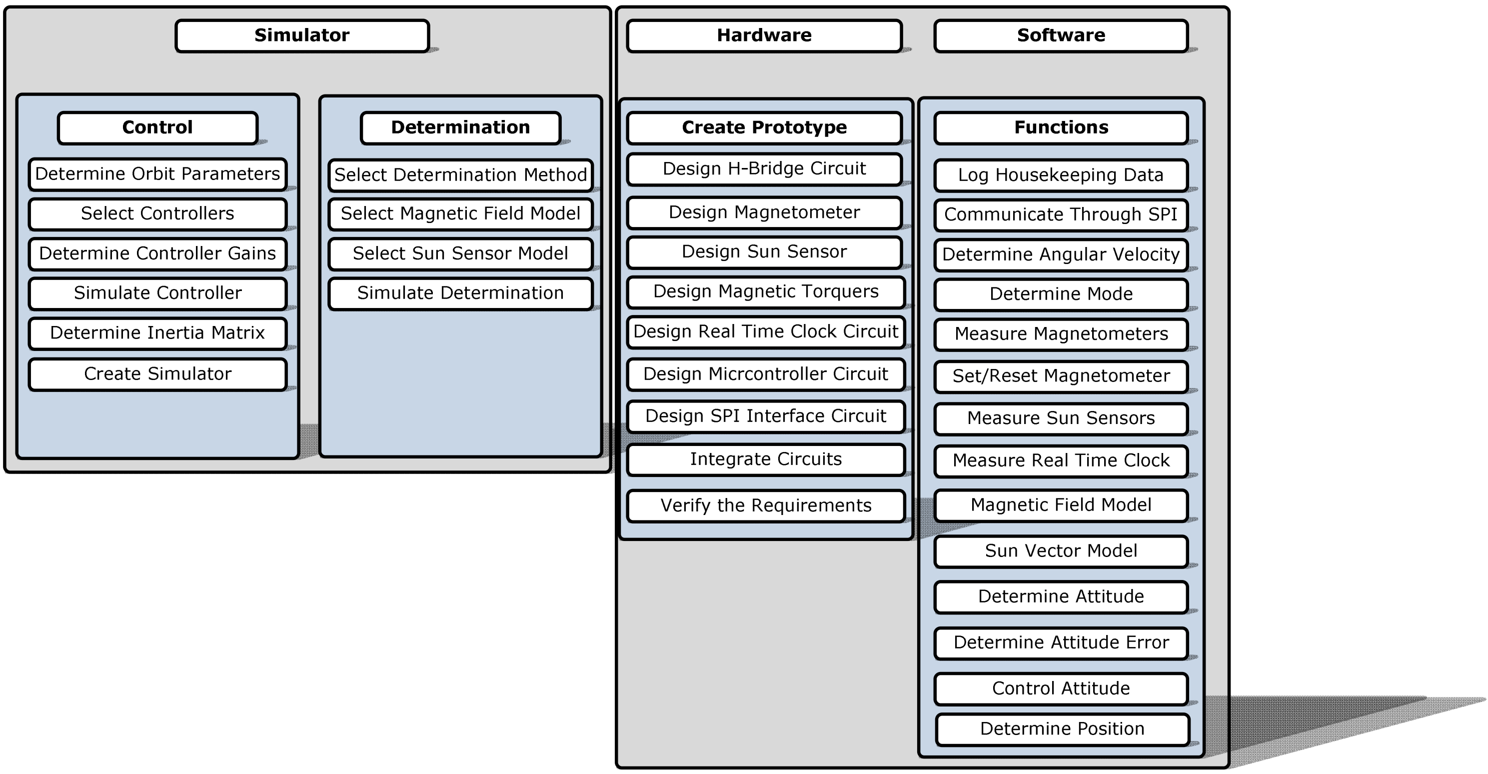

Figure 8 Work Packages