Combined Platform for Boost Guidance and Attitude Control for Sounding Rockets

Examensarbete utfört i Reglerteknik
vid Tekniska Högskolan i Linköping
av

Per Abrahmsson

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Kombinerad Plattform för Ban- och Attiydstyrning av Sondraketer

Combined Platform for Boost Guidance and Attitude Control for Sounding Rockets

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Sammanfattning
Abstract

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Nyckelord
Keyword

sounding rocket, attitude control, stabilization, boost guidance

Abstract

This report handles the preliminary design of a control system that includes both attitude control and boost control functionality for sounding rockets. This is done to reduce the weight and volume for the control system.
A sounding rocket is a small rocket compared to a satellite launcher. It is used to launch payloads into suborbital trajectories. The payload consists of scientific experiments, for example micro-gravity experiments and astronomic observations.
The boost guidance system controls the sounding rocket during the launch phase. This is done to minimize the impact dispersion. The attitude control system controls the payload during the experiment phase.
The system that is developed in this report is based on the DS19 boost guidance system from Saab Ericsson Space AB. The new system is designed by extending DS19 with software and hardware. The new system is therefore named DS19+.
Hardware wise a study of the mechanical and electrical interfaces and also of the system budgets for gas, mass and power for the system are done to determine the feasibility for the combined system.
Further a preliminary design of the control software is done. The design has been implemented as pseudo code in MATLAB for testing and simulations. A simulation model for the sounding rocket and its surroundings during the experiment phase has also been designed and implemented in MATLAB.
The tests and simulations that have been performed show that the code is suitable for implementation in the real system.

Keywords: sounding rocket, attitude control, stabilization, boost guidance

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Notation

Abbreviations

ACS	Attitude Control System.
BGS	Boost Guidance System.
CGS	Cold Gas System.
CPU	Central Processor Unit.
DAC	Digital to Analog Converter.
DMARS	Digital Minature Attitude Reference System.
DS19	A BGS built by Saab Ericsson Space AB.
DTG	Dynamically Tuned Gyro.
EGSE	Electrical Ground Support Equipment.
FOG	Fiber Optical Gyro.
GCS	Guidance and Control System, a BGS built by Saab Ericsson Space AB.
GPS	Global Positioning System.
G&C	Guidance and Control.
HGS	Hot Gas System.
H/W	Hardware.
IMS	Inertial Measurement System.
IMU	Inertial Measurement Unit.
NASA	National Aeronautics and Space Administration.
PID	Proportional, integration and derivation controller.
PDU	Power Distributing Unit.
RACS	Rate and Attitude Control System, an ACS built by Saab Ericsson Space AB.
RCS	Rate Control System.
SE	Saab Ericsson Space AB.
SPINRAC	SPINning Rocket Attitude Control, a BGS built by Saab Ericsson Space AB.
S/W	Software.
TM	Telemetry.
TVC	Thrust Vector Control.

Contents

Chapter 1

Introduction

A sounding rocket is controlled by two separate control system for attitude control and boost guidance. These system does not interchange any information, even though they use similar subsystems. This result in an increased weight and volume for the control system. Therefore is it desirable to merge these system into one system. The purpose of the report is to examine the possibility to merge the impact and attitude control functions for a sounding rocket to one system. Both hardware (H/W) and software (S/W) have to be analyzed to determine the possibility to design a merged system.
A preliminary design for a merged system is also done. The software for the design is given in detail.

1.1 Sounding Rockets

A sounding rocket is a small rocket, compared to a satellite launcher, that boosts up over the atmosphere to conduct experiments and then returns to the earth. This is a cost effective way to do space related science experiments. The sounding rocket flies in a suborbital trajectory up to an altitude of 200-700 km and then down again.
The sounding rocket consists of several subsystems, that are listed in table 1.1.
A typical sounding rocket mission is divided into three parts, boost phase, experiment phase and reentry phase.
During the boost phase the rocket is accelerates using the motors and the boost guidance system (BGS) controls the sounding rocket. The sounding rocket is boosted up to an altitude of approximative 100-700 km by the motor that can consist of one or more stages. In the end of this phase the motors is separated and the yo-yo mechanism reduces the roll rate of the payload.
An attitude control system (ACS) is used during the experiment phase to stabilize and control the payload in order to give the right conditions for performing the scientific experiments. In the reentry phase the payload reenters the atmosphere

Table 1.1. Subsystems in a sounding rocket.

Subsystem	Function
Motors	Generates the thrust for the sounding rocket. It can consist of one or more stages.
Payload	Experiments, control, recovery and service systems.
Boost Guidance System	Controls the rocket during the boost phase. The purpose of the system is to maintain constant attitude and/or control the trajectory. This is done in order to control the impact point for the rocket. See section 1.2.
Attitude Control System	Controls the payload attitude during the experiment phase. See section 1.3.

and deploys a parachute to soften the impact.

1.2 Boost Guidance System

The BGS controls the rocket during the boost phase. The purpose of the control is to reduce the impact point dispersion for the rocket. The dispersion is minimized to keep the impact point within the borders of the missile range. This is done by controlling the trajectory and transverse attitude for the rocket.

The boost guidance is done during the duration of the motor burn.

There is mainly two means of controlling the rocket during the boost phase. Either with canards or with thrust vector control. These methods are described in the following sections.

The hardware for the BGS is listed in table 1.2.

1.2.1 Actuators

Aerodynamic control in the form of fins, so called canards, are used to control the sounding rocket during the boost phase. A typical system that uses this strategy is the Saab Ericsson Space AB (SE) DS19 seen in figure 1.1.

TVC controls the sounding rocket by altering the thrust vector of the motor. This results in a change of the movement for the rocket. A system that uses this type of control is the SE Guidance and Control System (GCS) seen in figure 1.2.

Table 1.2. BGS Hardware.

Components	Function
IMS	The Inertial Measurement System (IMS) is the sensor platform the system. It usually contains gyros and accelerometers.
Computer	The computer is used for calculating the control strategies.
Actuator	The set of actuators are the part of the system that provides the control forces on the body. This can be done with a servo system with canards or with a thrust vector control (TVC) that is used to control the direction of the motor thrust. See section 1.2.1.

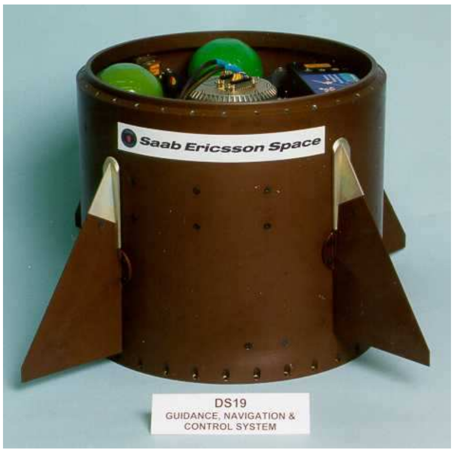

Figure 1.1. The DS19 module

1.3 Attitude Control System

The ACS is used to control the sounding rocket during the experiment phase. The main purpose for the control the payload during the experiments and reentry. The control during the experiments are done of several purposes, they are for example, minimize disturbances to achieve micro-gravity or control the pointing sequence to perform observations.
This is done with rate and/or attitude control for the system. The ACS usually uses a gas system as an actuator. A detailed description of the ACS can be found in chapter 2.

Figure 1.2. The GCS module

Chapter 2

Attitude Control System

In this chapter a more detailed description of the ACS will be presented including a description of the parts in it.

2.1 Missions

The purpose of an ACS is to control the payload during the ballistic phase. The control that is necessary is determined by the type of experiment that is conducted. There is some basic kinds of missions listed in table 2.1. The share of each type of missions compared to the total amount of sounding rocket missions flown by NASA is also listed. The figures are derived from [13].

Table 2.1. Basic mission control.

Mission type	Sensor	Accuracy	%
Zero gravity	Rate gyro	$0.2°/s$	10
Solar	Gyroplatform and sun sensor	1 arcsec	10
Coarse pointing	Gyro platform	$0.7°$	30
Fine pointing	Gyro platform and star sensor	60 arcsec	20
Magnetic field	Magnetometers	$2.0°$	5
Non controlled	No sensor	-	25

Zero Gravity Missions

Experiments that require a zero-gravity environment is normally only controlled in rate. The ACS used in this type of missions normally uses a gyro platform or magnetometers to measure the rate. Descriptions of these sensors can be seen in section 2.4.3 and section 2.4.4.

Solar Observation Missions

The sun is a target that often is studied during sounding rocket missions. Solar observation missions have requirements on the attitude and rate of the payload for the conduction of the experiments. These ACS uses sun sensors to determine the direction towards the sun. Sun sensors is described in section 2.4.1.

Coarse Pointing Missions

This control is similar to the solar observation control. The differences are the sensors used and the requirements on rate and attitude. The sensors used in these missions are for instance gyros or magnetometers. A description of these can be found in sections 2.4.3 and 2.4.4.

Fine Pointing Missions

The fine pointing control are similar to coarse pointing control but with higher requirements on accuracy for the attitude and rate. To achieve this a sensor platform supported by a star sensor is used. The star sensor is described in section 2.4.2.

Magnetic Field Missions

The missions that are flown to conduct experiments on the earths magnetic field usually use an ACS that uses magnetometers as sensors. These are described in section 2.4.4.

Non Controlled Missions

There are some missions that do not need any kind of control during the ballistic phase and no ACS is used at all.

2.2 ACS Hardware

The components in the ACS are listed in table 2.2.

2.3 Actuators

An ACS normally uses a pressurized gas system as an actuator. The force acting on the body is then generated when the gas is let out of nozzles.
The most commonly used system is the Cold Gas System (CGS). The CGS consists of a pressure vessel containing the gas, regulators, nozzles and valves to control the outlet of the gas. This system is based on a cold gas that generates the thrust. There is also an other system, Hot Gas System (HGS). In this system the gas is heated before it is used. The HGS consists of the same parts as the CGS and also a device to heat the gas before it is let out the nozzles. More thrust can be generated

Table 2.2. ACS Hardware.

Components	Function
Sensors	The system can have several sensors mounted on it. These sensors are used to determine the attitude of the payload during the flight. See section 2.4.
Computer	The computer is used for calculating the control strategies for the ACS.
Actuators	The actuators is the part of the system that produces the force that is used to control the payload. These actuators normally consist of a gas system of some kind. See section 2.3.

this way with the same amount of gas compared to a CGS. The drawback for the system is that the system itself has a higher weight and volume. Due to the small amount of thrust needed for a sounding rocket the weight increase for the HGS is greater then the decrease in weight for the gas. Therefore is the CGS most commonly used.
The gas used in the CGS is nitrogen in most applications. There are also alternatives to this gas. Argon is also a commonly used gas. Argon and Nitrogen generates approximately the the same thrust for the same amount of gas. The drawback with Argon is that is has a lower outlet temperature then Nitrogen therefore larger nozzles and valves has to be used according to [4]. Therefore is Nitrogen used in this application.
A CGS can be built in it is own self-contained module as long as it has an interface to the main module for receiving and sending control signals.

2.4 Sensors

In this part various sensors that can be used by the ACS will be described.

2.4.1 Sun Sensors

The sun sensor is the most commonly used sensor type. It is used in almost every satellite and also in a number of sounding rockets. For satellites this is because of the fact that almost all satellites rely on the sun as a power source. In sounding rocket applications this type of sensor is used to determine the attitude and also the direction to the sun in the case where the sun is the object that will be studied. This according to the sensor chapter in [16]. A drawback for the sensor is that the attitude only can be determined in two axis.
There exist a variety of sun sensors on the market. They have somewhat different functionality.

2.4.2 Star Sensors

Star sensors use the stars to determine the attitude. A star sensor consists of a star detector and a star map. To determine the attitude the sensor takes a picture of the stars. Then it tries to match the three to five brightest stars against an on board star map, to determine in which direction it is facing. After this, the attitude of the sounding rocket can be calculated. This sensor determines the absolute attitude in all three axes unlike the previous. A drawback with this sensor is that it often has a longer response time than the other sensors. The sensor is also heavier and has a higher power consumption than the other sensors. This is also a more expensive sensor then the other.

2.4.3 Rate Gyros

Gyros are used to determine the rate of the spacecraft. The principle of attitude determination with gyros is integration of the angular rates measured by the gyros and a known starting position. A benefit with gyros is the high sampling rate that can be achieved. There are several types of gyros on the market, some of these are listed in table 2.3. The most commonly used gyros in space applications today are the FOG and DTG gyros. Silicon gyros are a relatively new kind of gyros. Because of this they have not had enough time to prove their efficiency.

2.4.4 Magnetometer

Magnetometers use the earth magnetic field to determine the attitude. This type of sensor have many advantages. They are small, light, have no moving parts and they are tolerant to external conditions. However, there exist a disadvantage which is that the magnetic field is not completely known and the models that exist for prediction of the field have errors, according to [16]. Despite of this, the sensors are commonly used, especially for experiments concerning the magnetic field.

2.4.5 Accelerometers

The only difference between commonly used accelerometers and the ones used in spacecrafts is that the later has a smaller bias. This is because the spacecraft needs extremely accurate information about the acceleration to be able to determine the position. The accelerometer uses a mass that is attached to springs to determine the acceleration. This is done by measuring the displacement of the mass.

2.4.6 GPS Receiver

The GPS receiver is used for low altitude spacecrafts to get information about their position. This system is mostly used as an extra sensor for tracking of the rocket. The GPS receiver provides information about the position and velocity for the spacecraft. This information is normally not used by the ACS or BGS. But it is common that the information is sent down to the ground control with the other

Table 2.3. Rate Gyros.

Type	Description
Mechanical gyro	This is the standard type of gyros that consist of a spinning disk that is mounted so that it can rotate around one axis. The rate in the different axis is measured by the deviation angel from the ground position that the gyro gets. This type of gyro is heavy and large. They are not as accurate as other gyros.
Standard laser gyro	These gyros consist of a platform where several mirrors are mounted. The rate is measured by the interference that occurs when the platform is spinning. These gyros is fairly large and heavy. The accuracy is better then for the mechanical gyro.
FOG	The Fiber Optical Gyro (FOG) is a laser gyro that instead of mirrors uses fiber optics. This makes the gyro both lighter and smaller then the standard laser gyro. These gyros is both accurate and small which makes them usable in space applications.
DTG	The Dynamically Tuned gyro (DTG) consist of a spinning disk, that spins at a tuned frequency that makes it dynamically decoupled from the sounding rocket. The bending of the disk is then measured and compensated for with a coil. This design makes the gyro efficient, light and small. This gyro has a very god accuracy.
Wine glass gyro	These type of gyros vibrates and then the position of the nodes is measured to determine the rate. This gyro is extremely accurate but also sensitive to environmental constrains.
Silicon gyros	These gyros are small and lightweight. They also have a fairly good accuracy.

attitude and position information. The GPS receivers are normally used in pairs to introduce redundancy in the system.

2.5 Existing Attitude Control Systems

A list of the ACS used by NASA is displayed in table 2.4.

Table 2.4. Existing ACS.

Type	**System**	**Accuracy**	**Sensors**	**Manufacturer**
Course Attitude Control	**Rate Control**	$< 0.2°/s$	3-axis rate sensor	Space Vector
	Magnetic ACS	$< 2.0°$	Tree axis magnetometer single axis rate gyro	Space Vector
	Inertial ACS	$< 2.0°$	MIDAS platform	Space Vector
Fine Attitude Control	**MARK VI-MARI platform**	$< 3.0°$	Inertial gyro	Aerojet
	MARK VI-Stellar Update	$<$ 120 arcsec	Inertial gyro Star Tracker	Aerojet
	MARK VI-Stellar Pointer	$<$ 60 arcsec	Inertial gyro Star Tracker	Aerojet
	MARK VI D-Stellar Update	$<$ 60 arcsec	Inertial gyro Star Tracker	Aerojet
	SPARCS VI	$<$ 1 arcsec in Pitch & Yaw $< 5°$ in Roll	Course/Fine sun sensors	NSROC
	SPARCS VII	$<$ 1 arcmin in Pitch & Yaw $< 5°$ in Roll	Course/Fine sun sensors Magnetometer or rate gyro	NSROC

Chapter 3

Problem Formulation

This section contains an overview of how the control systems work today and the purpose of the report. There will also be a description of the requirements on the new system and how these are derived.

3.1 Purpose of the Report

The systems flown in present missions consist of two separate control systems for attitude and trajectory control. These systems have no exchange of information between them. Both of them use their own computer, actuators and sensor platform.
The purpose of this report is to study the feasibility of merging the two systems into a single system.

3.2 DS19+

The system, called DS19+, that is designed is a combined ACS and BGS that uses a DS19 module as the main structure. The DS19 module should be used with as few changes as possible.

3.3 Requirements on the DS19+

The requirements on the system are that the boost control should remain the same as for DS19. The requirements for DS19 can be found in [14].
The total pointing accuracy for DS19+ where no extra sensors are used should be better than $0.7°$, 3-σ. This requirement is derived from [3]. The first acquisition maneuver, the maneuver to a new reference frame, should have a duration that is less then 35 s.

The components in DS19+ shall follow the requirements on similar components in DS19. If no mayor changes are done to the DS19 module these requirements will automatically fulfilled. New components in DS19+ shall follow the requirements in [3].

Chapter 4

DS19+ Heritage

This chapter discuss the use of present systems to design DS19+.
In the design of DS19+ knowhow and technical solutions from other SE control systems is used, mostly from DS19 and RACS but also from SPINRAC these system are described in section 4.1. The heritage tree for DS19+ can be seen in figure 4.1. In section 4.2 the basic types of attitude control is described, the changes that are needed in DS19 to achieve this functionality is also described.

4.1 Present Control Systems

These sections describe the systems that DS19+ is based on.

4.1.1 DS19

The DS19 system is a digital BGS. DS19 uses a gyro platform named DMARS as a measurement instrument. The information from the gyro platform is computed and a control signal is sent to the canards. This system can only function within the atmosphere, because of the use of aerodynamic forces by the canards.

4.1.2 SPINRAC

SPINning Rocket Attitude Control system (SPINRAC) is a boost guidance system that is used to minimize the impact dispersion by controlling the attitude of the sounding rocket before the third stage of a large sounding rocket is ignited. This is done with the use of an IMS controlled CGS system. A CGS is used instead of canards because the control is done above the atmosphere.

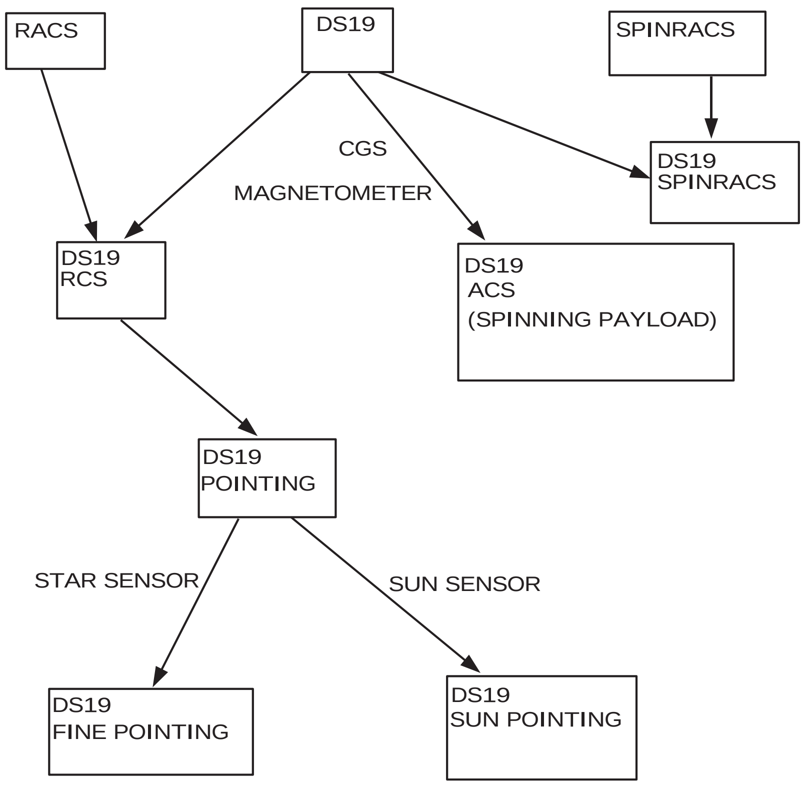

Figure 4.1. Heritage tree with the DS19 module as base.

4.1.3 RACS

Rate and attitude control system (RACS) is a pointing ACS designed by SE, seen in figure 4.2. RACS is constructed of a self contained module that uses a CGS as an actuator. The performance of RACS can be seen in table 4.1.

Table 4.1. Performance for RACS.

Accuracy	$\pm 0.7°$
Drift rate	$0.07°/s$

Figure 4.2. The RACS module

4.2 Attitude Control Functionality

In this section some functionalities for DS19+ and which additional components that is needed for them is described.

4.2.1 Rate Control System

A free falling sounding rocket, with low angular body rates, provides a near zero gravity environment. The Rate Control System (RCS) is used to control the body rate of the sounding rocket to provide this environment. To achieve zero gravity environment, two conditions must be fulfilled.

1. No acceleration of the body.
2. No angular body rates.

Condition one is met because the payload is in free fall above the atmosphere. The second condition is fulfilled with a working RCS. A working RCS will hold the rate of the payload less than 0.2°/s in all three axes. Control pulses from the RCS should be avoided during the measurmentphase.

This results in an environment of $10^{-4} - 10^{-5}$ g. To get as much time as possible in zero gravity environment the RCS shall minimize the rate as quick as possible. The RCS only controls the rates which makes it easy to integrate with the DS19 system, since only additional S/W is needed. The changes in the H/W is limited to an addition of a small CGS.

4.2.2 Pointing ACS

The pointing ACS is a control system with relatively low accuracy and stability requirements. These requirements is possible to meet with no extra sensors beside the IMS in the DS19. This makes the function easy to incorporate in DS19. The system shall be able to point with an total accuracy of 0.7°, 3-σ in all three axis. The incorporation with the DS19 is done in a similar way as with the RCS. The difference is that this system also controls the attitude for the rocket. This results in a more complex control strategy, with the effect that more CPU power is needed. But as the application is computed in a period where there are much CPU power unused, this should not cause a problem. There is also a difference in the CGS. The CGS for this application has to be larger than the one for the RCS. This is a result of that the sounding rocket has to perform more and larger maneuvers to control the attitude.

4.2.3 Sun Pointing ACS

The sun pointing ACS is similar to the pointing ACS. The difference is that it should be more precise, especially when pointing at the sun. This can be done with the help of sun sensors. They are used to determine the attitude towards the sun. The point of having several sensors is that the direction can be more accurately determined. The ACS should be able to follow a predetermined pointing sequence or be controlled via a real-time control from the ground control. The accuracy for the sun pointing ACS should be according to table 4.2.

Table 4.2. Performance for the sun pointing ACS.

Accuracy	±3.0 arcsec
Drift rate	2 arcsec/min
Resolution of the real-time control	$\pm(1 - 2)$ arcsec

This system can be seen as an extension of the pointing ACS with additional sensors. The CGS for this ACS should be rater similar to the one in the pointing ACS.

4.2.4 Fine Pointing ACS

This system shall function as the pointing ACS but with much better accuracy compared with the systems above. This system shall have an accuracy according to table 4.3.

Table 4.3. Performance for the fine pointing ACS.

Accuracy	$\pm(2-5)$ arcmin
Drift rate	10 arcsec/min
Resolution of the real-time control	$\pm(1-2)$ arcsec

These requirements could be met by adding a star sensor. The star sensor has the advantages that the attitude in all three directions can be calculated from one measurement. The ground control shall also be able to control the system with real-time commands from the ground.
This system can be designed from the pointing ACS in almost the same way as the sun pointing ACS. The difference between these systems is the sensors and some parts in the S/W.

4.2.5 ACS for Spinning Payloads

This system is an ACS thats only works for spinning payloads. The components that are needed are a 3-axis magnetometer and a CGS system. This ACS shall hold a payload that spins with $0.5-2.0$ rps and within an alignment of $1-2°$. The system shall also be able to control the spin rate. This is a system that is not normally used in the larger sounding rockets, therefore there will be no focus on it in this report. To expand the functionality of DS19 to this system only minor changes are needed. So if this type of ACS were to come into use, a new system could quickly be designed.

Chapter 5

Design of DS19+

The integration between the two systems can be done in many ways. In this chapter the components of the systems are analyzed and a preliminary design for DS19+ is derived.

5.1 Mechanical Design

In this section the mechanical design alternatives of DS19+ are described The design alternatives can be seen in figure 5.1.

5.1.1 Single Module System

This solution is based on one module containing all the parts of the system. The benefit with this is the reductions of joints between modules in the sounding rocket. This will increase the strength of the system.
There are some drawbacks with this solution. The first is the large amount of changes that has to be made to the DS19 module. Another is that the system has to be redesigned between flights due to the changes in the requirements.

5.1.2 Combined Sensor and CGS Module

The structural changes from the single module design to this design is that the sensors and CGS is moved from the DS19 module to a separate module. This design has the benefit of a more intact DS19 module. The drawbacks is that it has to be redesigned between missions and that the extra sensors not can be positioned freely.

5.1.3 Modularized Design

This design has an intact DS19 module and has two extra modules. One for the CGS and one for the extra sensors.

The two separate modules for sensors and CGS is chosen because in most flights the sensor module is not needed and can then be easily excluded. The structure also gives extra freedom for the position of the sensors. The construction of the CGS can also easily be made by an external manufacturer.

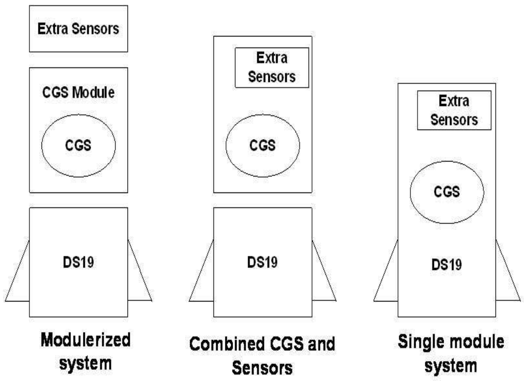

Figure 5.1. The design alternatives.

5.2 Cold Gas System

The CGS for the payload is chosen to have the schematic design according to figure 5.2. The regulators and latching valve is used to control the gas pressure by the solenoid valves. The roll thrusters are activated in pairs to reduce the effect on the transverse axes. The configuration makes it possible to use two pressure levels. This is necessary because then large errors can be quickly corrected and the minimum error that can be corrected is still sufficiently small. The minimum error that can be corrected depends on the gas pressure, minimum active time for the solenoid valves and the size of the nozzles.

5.2.1 Thruster Configuration

The position of the thrusters are chosen according to figure 5.3.
The thruster position is chosen in straight angles to be able to control all possible transverse axes. This is the best choice if the direction of the thrusters not can be changed during the flight. The position of the roll thrusters, that are the thrusters that is position in pairs by the x axis, are chosen to reduce the effect on the transverse axes from them. The roll thrusters are only operated in pairs to get a clean roll maneuver. These thruster is not necessary placed in the same plane as the transverse thrusters.

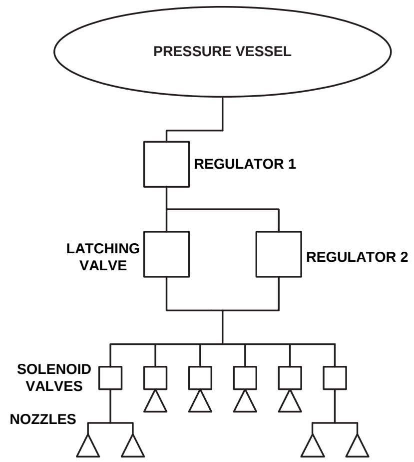

Figure 5.2. Schematic design of the CGS.

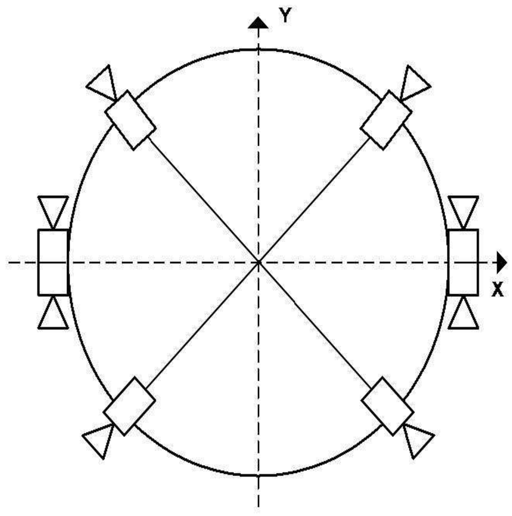

Figure 5.3. The thruster configuration.

This configuration for the thrusters are valid for systems that controls the attitude. Another thruster design has to be chosen if the system only is to control the body rate. This because of that some thrusters is not needed in that design.

5.3 Budgets

This section contains the mass, gas and power budget for DS19+.

5.3.1 Mass Budget

The changes in the weight is some loss in the weight due to the synergism effect that occur when the systems is merged, such as the removal of similar components used in both systems, for example IMS and battery.
There is two benefits that can occur when the weight is lowered for the sounding rocket either can the weight of the payload be increased, which gives room for more experiments or the maximum apogee is increased, which results in a increase of the time for the experiment phase of the flight.

5.3.2 Gas Budget

In this section the gas consumption for DS19+ is discussed.
To estimate the amount of gas needed in the CGS system, data from typical sounding rockets are used, see table 5.1. This table shows the moment of inertia and other physical properties two sounding rockets.

Table 5.1. Rocket Properties for Sounding Rockets.

	Small	**Large**
Moment of Inertia, Roll (kg m^2)	10	23
Moment of Inertia, Pitch/Yaw (kg m^2)	1000	2700
Lever, Roll (m)	0.22	0.22
Lever, Pitch/Yaw (m)	1.3	2

The gas consumption for the RACS sounding rocket can be found in [7], this consumption is listed in table 5.3 and the physical properties for the rocket is listed in table 5.2.

Table 5.2. Physical Properties for RACS.

Moment of Inertia, Roll (kg m^2)	10
Moment of Inertia, Pitch/Yaw (kg m^2)	500
Lever, Roll (m)	0.22
Lever, Pitch/Yaw (m)	1.000

The acquisition maneuver consists of several phases. One roll rate reduction from $90°/s$ to $0°/s$ and one transverse rate reduction from $25.7°/s$ to $0°/s$ and also one $180°$ transverse reorientation maneuver.
The RACS ACS is a system that can perform a large amount of maneuvers. Most of the reorientation maneuvers is not necessary in other ACS. The gas that is used by RACS for a nominal ACS mission is according to table 5.4.

Table 5.3. Amount of Gas needed for RACS.

Maneuver description	Impulse [Ns]	Gas Mass [kg]
Acquisition maneuver	614	0.97
$5 * 30°$ ($0°$ off thruster axis)	515	0.82
$2 * 40°$ ($45°$ off thruster axis)	187	0.30
$10 * 45°$ roll	290	0.46
180° transverse reentry maneuver	220	0.35
Spin-up before reentry	80	0.13
Duty-cycle pulsing	60	0.1
Dumping	15	0.02
Total impulse	1981	3.15

Table 5.4. Amount of Gas needed for RACS in nominal flight.

Maneuver description	Impulse [Ns]	Gas Mass [kg]
Acquisition maneuver	614	0.97
Maneuvers during flight	300	0.5
180° transverse reentry maneuver	220	0.35
Spin-up before reentry	80	0.13
Duty-cycle pulsing	60	0.1
Dumping	15	0.02
Total impulse	1289	2.07

From this information the amount of gas that the typical sounding rockets use are derived, by looking on how the moment of inertia and the levels, i.e the distances between the center of mass and the nozzle, have changed. The impulse amount needed for a maneuver that uses an impulse of $\boldsymbol{M_2}$ for another rocket becomes:

$$\boldsymbol{M_1} = \frac{\boldsymbol{I_1 R_2}}{\boldsymbol{I_2 R_1}} \boldsymbol{M_2} \tag{5.1}$$

Where the values represent the following:

- M_1 is the moment needed for rocket one.
- M_2 is the moment needed for rocket two.
- I_1 is the moment of inertia for rocket one.
- I_2 is the moment of inertia for rocket two.
- R_1 is the length of the level for rocket one.
- R_2 is the length of the level for rocket two.

The results from these calculations are shown in table 5.5 where the terms $\frac{\boldsymbol{M_1}}{\boldsymbol{M_2}}$ are shown for each axis for the rockets. Where M_2 is the moment needed for RACS.

Table 5.5. Scaling factors for gas consumption.

	Small ($\frac{M_1}{M_2}$)	Large ($\frac{M_1}{M_2}$)
In Roll	1	2.3
In Pitch and Yaw	1.54	2.7

Table 5.6. Amount of gas needed for the standard rockets.

	Small (17 in)	**Large (22 in)**
Maneuver description	**Impulse [Ns]**	
Acquisition maneuver	891.6	1617.8
Maneuvers during flight	408	770
180° transverse reentry maneuver	339	594
Spin-up before reentry	80	184
Duty-cycle pulsing	90	162
Dumping	20	20
Total impulse	1828.6	3347.8

Table 5.4 are used as a base for the making of table 5.6 which shows the gas consumption for a nominal flight with the standard rockets.
As shown in table 5.6 the amount of gas needed for the rockets are very shifting between the rockets. Therefore the best design is to have the CGS in a separate module.

5.3.3 Power Budget

This budget is done in order to investigate if the battery in DS19 has enough power to support the complete DS19+ system.

Power Consumption

The parts that consume energy in the system are the DMARS, which is the internal measurement unit (IMU) in DS19, power distributing unit (PDU), attitude sensors, the pressure sensors, the CGS and the servo system for the canards.

- The DMARS has a consumption of 1 A in the nominal case according to [11] and a flight does nor last for more than 30 min. The power consumption of the DMARS is according to these numbers 0.5 Ah.
- The PDU in the RACS system has a power consumption of 0.055 Ah according to [15]. The PDU in the DS19 has a similar structure as this one. A restrictive number on the power consumption is then 0.1 Ah.
- To get a restrictive power consumption for the extra sensors, several sensors are studied. The highest power consumption for the sensors where found to be 0.4 Ah.

- The power consumption of all three pressure sensors is set to 0.25 Ah. This number is derived from the fact that one old pressure sensor from the RACS consumes 0.055 Ah according to [15].
- To empty the CGS completely in the RACS 0.113 Ah is needed according to [4]. The CGS for this application is up to 1.7 times as large as the RACS system. Therefore a consumption of 0.2 Ah is a restrictive number on the consumption.
- The power consumption that is needed for the canard servos is also derived from the RACS CGS power consumption. This because of that the servo system works in a similar way as the CGS. The servo system is naturally much smaller and therefore easier to empty. A restrictive number for the power consumption for the servo system are 0.1 Ah.

The results of the power consumption will be according to table 5.7.

Table 5.7. Power consumption.

Activity	**Consumption [Ah]**
Pressure sensors	0.25
DMARS	0.5
PDU	0.1
CGS	0.2
Servo system	0.1
Attitude sensors	0.4
total	1.55

Conclusions

From table 5.7 the worst case power consumption is 1.55 Ah and according to [1] the power that can be generated from the battery in the DS19 is 2.2 Ah. This gives a resulting over capacity of 42%. For the ACS were no extra sensors is used the power consumption is as low as 1.15 Ah which result in a over capacity of 91%. The power consumption is calculated with a run time of 30min, which is longer then any run time for the system.
This gives the result that the battery power is sufficient to support the complete system. If this had not been the case the battery system would have been extended with either a new sort of batteries in the DS19 module or extra batteries in the DS19 or CGS module.

5.4 Electrical Interfaces

The merging of the system results in several new interfaces that has to be added in the DS19 module. These interfaces emerge because new signals are needed in the system. These signals result in the new or changes interfaces listed in table 5.8.

There is also some extra data that has to be sent by the telemetry from the DS19 to the ground. This will only cause some minor changes in the telemerty (TM) format.

Table 5.8. New or changed interfaces.

From	To
DMARS	**PDU**
PDU	**CGS**
PDU	**Extra Sensors**

The extra data that need to be sent between the DMARS and the PDU is listed in table 5.9. In the same way the new signals for PDU to CGS and PDU to Extra Sensors is listed in tables 5.10 and 5.11.

Table 5.9. New signals between PDU and DMARS.

Control signals for the CGS.
Data from the CGS.
Control signals for the sensors.
Data from the sensors.

Table 5.10. New signals between PDU and CGS.

Control signals for the solenoid valves.
Control signals for the latching valve.
Measured pressures from the CGS.
Power supply and ground connection to the CGS.

Table 5.11. New signals between PDU and Attitude Sensors.

Control signals to the sensor.
Data from the sensor.
Power supply and ground connection to the sensor.

5.4.1 Design Options

There are several designs for the electric interfaces between DMARS and PDU. Three alternative designs are:

Reassociation: Remove signals from the present interface to create room for new important signals.

Rebuilding: Rebuild all the interfaces to fit in all signals.

Sharing: Share the existing pins between the signals.

The first design is easy to implement and results in minor changes to the DS19 module. The drawback with this design is that it does not free enough space for the sun pointing ACS, the real-time control and the RCS, this due to that a interface towards the payload is needed during this control to stop the control pulsing during sensitive measuring phases.
The second design gives the best interfaces but also the largest changes in the DS19 module. This design is the best one if further changes has to be done in the system.
The third solution is time demanding and difficult to implement and it does not solve any problem better then any of the other designs.
The PDU has to be rebuild for all solutions. This because an interface towards the CGS is needed and there are no space for this interface in the present design, see [10].

5.4.2 Implemented Design

The design that is chosen for implementation is the design that is based on reassociation of the pins. It is chosen based on that it is easy to implement and that there exist signals that currently are unused that can be removed.
The choice of design results in that the sun pointing ACS, RCS and real-time can not be done. Therefore is these control systems excluded from the rest of the report.
The changes in the interfaces needed to be done for this design are described in the following sections.

5.4.3 DMARS-PDU

The changes that has to be done in this interface for the chosen design is reassociation of pins according to table 5.12 and table 5.13.

Table 5.12. Pin reassociation in 44 pins DMARS to PDU interface.

pin	New signal	Old function
22	CGS bottle pressure	IMS temperature
23	CGS regulated pressure	Deck temperature
33	Opening command solenoid valve 1	Empty
34	Opening command solenoid valve 2	Empty
35	Opening command solenoid valve 3	Empty
36	Opening command solenoid valve 4	Empty
37	Opening command solenoid valve 5	Empty
38	Opening command solenoid valve 6	Empty
39	Opening command latching valve	Empty

Table 5.13. Pin reassociation in 26 pins DMARS to PDU interface.

pin	New signal	Old function
22	TX extra sensor RS232 interface	TX GPS RS232 interface
23	RX extra sensor RS232 interface	RX GPS RS232 interface

5.4.4 PDU-Sensors

The interface between the PDU and the arm-safe plug has free pins that can be used for communication with the attitude sensors. The changes that has to be done in this interface are the ones described in table 5.14.

Table 5.14. Pin reassociation in 25 pins PDU to arm-safe plug interface.

pin	New signal	Old function
6	Power feeding	Empty
7	Power feeding	Empty
12	TX extra sensor	Empty
13	RX extra sensor	Empty
22	Power ground	Empty
23	Power ground	Empty

5.4.5 PDU-Valves

The communication between the PDU and the valves could be done through a new interface with pin association according to table 5.15.

Table 5.15. Pin association in 25 pins PDU to VALVES interface.

pin	New signal	pin	New signal
1	+5V bottle pressure measure	14	Operating solenoid valve 3
2	-5V bottle pressure measure	15	Operating solenoid valve 3
3	Out bottle pressure measure	16	Operating solenoid valve 4
4	Out bottle pressure measure	17	Operating solenoid valve 4
5	+5V regulated pressure measure	18	Operating solenoid valve 5
6	-5V regulated pressure measure	19	Operating solenoid valve 5
7	Out regulated pressure measure	20	Operating solenoid valve 6
8	Out regulated pressure measure	21	Operating solenoid valve 6
9	Empty	22	Operating latching valve
10	Operating solenoid valve 1	23	Operating latching valve
11	Operating solenoid valve 1	24	Empty
12	Operating solenoid valve 2	25	Empty
13	Operating solenoid valve 2		

5.4.6 Changes in the TM format

The change that has to be done in the TM format are that other data has to be sent to ground control depending on which control function that is active.
The changes that has to be done are the following:

- If the BGS control is active changes in the TM format according to table 5.16 has to be done.
- If the ACS control is active changes in the TM format according to table 5.17 has to be done.

Table 5.16. Changes in the TM during BGS control.

New Data	Old Data
For the 100 Hz data	
No changes	
For the 20 Hz data	
Information on which control that is active.	Empty
For the 4 Hz data	
The bottle pressure for the CGS. The regulated pressure for the CGS. The starting time for the ACS control. The lowest starting altitude for the ACS control.	Temperature DS19 structure Temperature DS19 gyro Empty Empty

Table 5.17. Changes in the TM during ACS control.

New Data	Old Data
For the 100 Hz data	
The command word to the CGS valves. The regulated pressure for the CGS.	Reference attitude in pitch. Reference attitude in yaw.
For the 20 Hz data	
Information on which control that is active. Reference quaternion 1. Reference quaternion 2. Reference quaternion 3. Reference quaternion 4.	Empty Command signal pitch canards. Command signal yaw canards. Return signal from pitch servo. Return signal from yaw servo.
For the 4 Hz data	
The bottle pressure for the CGS. The regulated pressure for the CGS. The starting time for the ACS control. The lowest starting altitude for the ACS control.	Temperature DS19 structure Temperature DS19 gyro Empty Empty

5.5 Software Expansion for DS19+

The changes that are needed in the S/W for the combined system is addition of new control strategies for the ACS control. Mainly how the CGS will be controlled based on the present attitude and rate. This results in a control routine that has to be computed during the ballistic phase of the flight. This control routine is never done at the same time as the control routine for the boost guidance. Therefore is the CPU power in the present system enough for both applications. The only other thing that needs to be computed during the time the strategies are computed is the TM signal. This is already done in the present system so the difference should not be significant.

5.5.1 Existing Software

The code that is used as a ground for the DS19+ S/W is the flight S/W from the DS19 module. This S/W is flight proved and many of the functions that are used in it can be used in the ACS S/W without any modification or very small modifications.
The largest changes that are needed to be done are the functions that are used for the attitude control computation. This includes an attitude reference computation and the function that computes the control law.

5.5.2 New Functionality

There are two completely new functions that have to be implemented in the DS19+ for the ACS control.

ACS Control Function

The first one is a function that computes the control law for the ACS. This function uses a completely different strategy compared to the DS19 control algorithm. This is due to the use of other actuators and also the fact that the ACS controls the rocket in all three axis and the DS19 only controls it in two axis. For the ACS that uses extra sensors this function needs to consider the sensor information as well as the gyro information.
This function uses information from the IMS and the reference attitude as input for the ACS that does not use extra sensors. From this information the control signals to the valves is computed. This signal is then the output from the function. The function uses the control laws described in chapter 6.

ACS Reference Computation

The second is a function that takes the time as input and returns the reference and reentry flag as output. The attitude reference is given in quaternions, the quaternions are described in appendix A. The function is the same for all ACS that has a requirement on the reference attitude.

The function matches the time to the index in a table. If there is a new attitude there will be a transition phase that uses linear interpolation between the present and new attitude.
This function is not the same as the reference computation for the BGS because the ACS needs a fix reference in all three axis. The BGS uses a reference that is calculated from a formula that only returns a reference in pitch and yaw.

5.5.3 Design Considerations

The changes that has to be done in the other functions is that in all communication functions ACS commands has to be added. A changing command between BGS and ACS also has to be added, to determine which of the attitude control laws and reference computation that is to be used. This criteria is used in the top level control.
A study of the feasibility of the combination of the code has also been done. From this study the results are that there is enough computation power and memory capacity in DS19 to handle both a BGS and a pointing ACS.

5.6 Conclusions

The design that is chosen for the system is specified in this section.
The design that is chosen is a modularized design for the structure of the system, this is done to get a flexible system that has a minimum of changes in the DS19 module. The budgets that is done indicates that the power supply from DS19 is enough to support the complete system. Therefore is there no need to include extra batteries in DS19+. The budget for the gas is done in order to know how large the CGS has to be for a specific sounding rocket.
The chosen design for for the electrical interfaces in the system is based on reassociation of pins to make room for the new data. The reassociation is done according to section 5.4.2. The changes in the TM format also has to be done for this application. This design does only free enough space for the pointing ACS. If any other attitude control application is done a redesign for the IMS and specially the interfaces is recommended. The changes in the TM format also has to be redesigned.
The software design is therefore done for a DS19+ with a pointing ACS. The computer and memory capacity in DS19 is enough for this system.

Chapter 6

Control Law

In this chapter the control law concept that is used for the ACS and RCS is discussed.

6.1 Control Concepts

Several concepts can be considered for use in both the ACS and RCS control. The report will focus on Bang-Bang control for the control system. This is because the thrusters only has two states, open or closed. There are two forms of control strategies that can be implemented, both of these use Bang-Bang control. The first one is a minimization of a loss function. The other one is the use of fuzzy control. The first strategy gives more calculations for the flight computer but has the advantages that already flight proved code can be used for the implementation, therefore that strategy is chosen.
There are two sorts of Bang-Bang control with loss functions that can be implemented.
The first one is the Bang-Bang control for 3-dimensional control, where the complete control is computed from one algorithm. This algorithm uses the attitude error in all axes and also the angular velocity in all axes. This results in an algorithm that is very precise. A drawback with this is that it is very complex to do and results in difficult calculations and optimization problems.
The other alternative is to handle each axis separately and then combine them into one control algorithm. This is somewhat less optimized for the whole problem. But the computations is much easier and faster. There is some loss in the solution due to that the problem only is optimized for the different axes and not the whole problem.
For the ACS, a combination of these methods is used. The control is constructed that way to optimize the control for the cases in the flight.
For the RCS, the Bang-Bang control is also chosen but the switching lines is only depending on the body rate of the rocket. Therefore the switching criteria will be

straight lines in the plane. In this case the 3-axis problem is divided into 3 1-axis problem. This simplifies the solution and implementation.

6.2 Control Law for ACS

There are some differences between the control for small and large maneuvers. The largest different is that the error has to be sufficiently small for small maneuvers so that only local optimum switching criteria have to be studied and not global optimum switching criteria as in large control. Due to this the control law for small maneuvers can be divided into three separate control laws, one for each axis. The control law for large maneuvers has to have one control law for the whole system except the roll axis which is possible to control separately.
Therefore are the control functions for the large and small control are studied separately.

6.3 Control Law for Small Maneuvers

The control law that is chosen for this case is a one axis loss function. This control law will result in a switching criteria for the thrusters that are lines in the phase plane. This plane has the angular velocity and the attitude error as axis. The lines are derived from the solution to an optimization problem. The solution is obtained by minimizing the Hamilton function H. These computations are similar to those in [6]. These calculations are similar for all axes.

$$\min H = L + V_\varphi \dot{\varphi} + V_\omega \dot{\omega} \quad (6.1)$$

$$(6.2)$$

Where φ is the attitude error, ω the angular velocity and V_φ and V_ω are loss functions. The following relation holds for the derivate:

$$\dot{\varphi} = \omega \quad (6.3)$$

$$\dot{\omega} = au \quad (6.4)$$

Where a is the angular acceleration produced by the thrusters and u is the control signal. u has the following properties:

$$u \in \{0, 1, -1\}$$

L is a function of λ and u. λ is a design parameter that represents the trade off between gas consumption and maneuver time.

$$L = 1 + \lambda |u| \quad (6.5)$$

$$\lambda \geq 0$$

The function that is going to be minimized then gets the form:

$$\min_u H = 1 + \lambda|u| + V_\varphi \omega + V_\omega a u \tag{6.6}$$

This results in three cases for the minimization:

$$\min_u H = \begin{cases} 1 + V_\varphi \omega & , u = 0 \\ 1 + \lambda + V_\varphi \omega + V_\omega a & , u = 1 \\ 1 + \lambda + V_\varphi \omega - V_\omega a & , u = -1 \end{cases} \tag{6.7}$$

These equations gives the following result:

$$u = \begin{cases} 1 & , -\lambda > V_\omega a \\ -1 & , \lambda < V_\omega a \\ 0 & , -\lambda \leq V_\omega a \leq \lambda \end{cases} \tag{6.8}$$

The equations for motion from Hamilton is:

$$\frac{\partial H}{\partial \varphi} = -\dot{V}_\varphi \qquad \frac{\partial H}{\partial V_\varphi} = \dot{\varphi} = \omega$$
$$\frac{\partial H}{\partial \omega} = -\dot{V}_\omega \qquad \frac{\partial H}{\partial V_\omega} = \dot{\omega} = au$$
$$\frac{\partial H}{\partial t} = \frac{dL}{dt} \qquad H = L + V_\varphi \dot{\varphi} + V_\omega \dot{\omega}$$

In combination with the results from above and these equations the following result is derived.

$$\frac{\partial H}{\partial \varphi} = 0 \Rightarrow V_\varphi = C \tag{6.9}$$

$$\frac{\partial H}{\partial \omega} = V_\varphi \Rightarrow \dot{V}_\omega = -V_\varphi = -C \Rightarrow V_\omega = -Ct + D \tag{6.10}$$

The steady state solution for the Hamilton function is:

$$\min_u H = 0 \tag{6.11}$$

This result must also be valid for $u = 0$ therefore must $C = -\frac{1}{\omega}$. The switching lines can be derived from equation 6.8.

$$\lambda = V_\omega a \qquad (ON) \tag{6.12}$$
$$\lambda = -V_\omega a \qquad (OFF) \tag{6.13}$$

These criterias can be rewritten with the values from above. Where t_1 and t_2 is on and off times for the control.

$$\lambda = a(\frac{t_1}{\omega} + D) \qquad (ON) \tag{6.14}$$
$$\lambda = -a(\frac{t_2}{\omega} + D) \qquad (OFF) \tag{6.15}$$

A combination of these gives:

$$\lambda = \frac{a(t_1 - t_2)}{2\omega} \tag{6.16}$$

This gives the following change in the attitude for the system.

$$\Delta\varphi = \dot{\varphi}\Delta t \tag{6.17}$$

$$\Delta t = t_1 - t_2 = \frac{2\omega\lambda}{a} \tag{6.18}$$

$$\Delta\varphi = \frac{2\omega^2\lambda}{a} \tag{6.19}$$

The criteria to switch on the system is then set to:

$$\varphi_1 = \frac{\omega^2}{2a} \tag{6.20}$$

This results in a switch off criteria that is:

$$\varphi_2 = \varphi_1 + \Delta\varphi = \frac{\omega^2}{2a}(1 + 4\lambda) \tag{6.21}$$

This gives the switching criteria:

$$U = \begin{cases} a & ; \varphi < -\varphi_2 \\ -a & ; \varphi > -\varphi_1 \\ 0 & ; -\varphi_2 \leq \varphi \leq -\varphi_1 \end{cases} \tag{6.22}$$

To reduce the duty pulsing that can occur for small errors a dead band is introduced in the equation. The dead band is symmetrical around zero and it is δ wide. A reducing factor, ρ, is also introduced. ρ is a reduction factor that is introduced to avoid overshoots. This is done because of the large negative effect an overshot has on the system. This results in the modified switching criteria.

$$
\begin{aligned}
&\underline{\omega} > 0: \\
&\varphi > \delta: && U = -a \\
&\varphi < \delta: && U = \begin{cases} a & ; \varphi < -\varphi_2 - \delta \\ -a & ; \varphi > -\frac{\varphi_1}{\rho} \\ 0 & ; -\varphi_2 - \delta \leq \varphi \leq -\frac{\varphi_1}{\rho} \end{cases} \\
&-\delta \leq \varphi \leq \delta: && U = \begin{cases} -a & ; \varphi > -\omega\sqrt{\frac{2\delta}{a\rho}} + \delta \\ 0 & ; \varphi \leq -\omega\sqrt{\frac{2\delta}{a\rho}} + \delta \end{cases} \\
\\
&\underline{\omega} < 0: \\
&\varphi < -\delta: && U = a \\
&\varphi > \delta: && U = \begin{cases} a & ; \varphi < \frac{\varphi_1}{\rho} \\ -a & ; \varphi > \varphi_2 + \delta \\ 0 & ; \frac{\varphi_1}{\rho} \leq \varphi \leq \varphi_2 + \delta \end{cases} \\
&-\delta \leq \varphi \leq \delta: && U = \begin{cases} a & ; \varphi < -\omega\sqrt{\frac{2\delta}{a\rho}} - \delta \\ 0 & ; \varphi \geq -\omega\sqrt{\frac{2\delta}{a\rho}} + \delta \end{cases}
\end{aligned}
\tag{6.23}
$$

One more variable that is introduced in the switch criteria is a hysteresis function that make the system hold a specific output during a time interval. This is done to make sure that the thrusters does not go on and off every interval, when the system is close to the switching criteria in the phase plane.

6.3.1 Fine Control

The fine control is done in the same way as the small control. The difference is that other numbers is used for the criteria and that a lower pressure is used which makes it possible to correct small errors.

6.4 Control Law for Large Maneuvers

The large maneuver control law is based on the control law for the RACS control, that can be found in [5]. This control law is based on the same Hamilton function as for the small maneuvers.
The control of the sounding rocket is divided in two parts transverse and roll control. This can be done because of that the coupling between the roll axis and the transverse axes is sufficiently small. This simplifies the development of the control system.
The control that is derived for the control is based on (6.22). Where the transverse maneuver is the main contributor to the time and fuel consumption.

6.4.1 Roll Control

The roll control is divided into two separate procedures.

Rate reduction: This procedure reduces the roll rate before the the attitude control starts.

Attitude control: In this procedures the roll attitude is controlled. The control algorithm that is used are similar to the attitude control for small maneuvers 6.23.

6.4.2 Transverse Control

The transverse control will be designed as if the thrusters can be used in an arbitrary direction in the transverse plane. This is not true because the thrusters is mounted with a straight angle between them. This approach is however valid because the real problem is solved by ξL where L is the idealized loss function and ξ is the factor:

$$\xi = \frac{1+\sqrt{2}\lambda}{1+\lambda}$$

This is done because the thrust is in fix directions and not in arbitrary directions as the loss function is calculated for, this according to [5]. The control strategy is based on several locally optimal trajectories. The the most optimal is chosen from loss functions for the system. The local trajectories are based on the trajectories from RACS ACS, described in [5].
These trajectories describe solution of how the payload can go from the present state to the wanted state. A loss function is calculated for each trajectory and then the smallest of them is chosen as base for the control. The choice between the trajectories are done for every call to the large control.
The trajectories are:

L_1 This loss function represent a trajectory that is made of one turn towards the reference attitude, a coast phase and a deceleration phase.

L_2 This loss function represent a trajectory that consists of a deceleration to a complete halt followed by a attitude maneuver in one axis.

L_3 This loss function represent a trajectory that consists of a coast phase followed by a deceleration and finally a maneuver in one axis.

L_4 This loss function has a trajectory made of a coast phase followed by a combined turn and deceleration. This function is valid for small equatorial rates.

L_5 This function has a trajectory made of an acceleration towards the reference attitude. This function is valid for small equatorial rates.

L_4 and L_5 is needed because the others has discontinuities for small equatorial rates. The drawback with them is that they are only valid for a restricted domain. The loss functions are only valid for specific intervals. If the state of the sounding rocket is outside the valid interval the loss function is set to infinity. At least one function is always valid.

6.5 Control Law for RCS

The Control law used in the RCS is the same as the one used for rate reduction in the ACS. This control is also based on Bang-Bang control and uses a Hamilton function similar to the Hamilton function in the attitude control. The loss function for the rate control has the following form:

$$L = \sqrt{(\frac{C_x \omega_x}{a_x})^2 + \frac{C_\perp^2}{a_\perp^2}(\omega_y^2 + \omega_x^2)}$$

Where a is the angular acceleration and C is a weight constant for each axis. The loss function inserted in the Hamiltonian then results in a control law with the following form:

$$u = \begin{cases} a & ; \omega \leq -f(a, C, \lambda, L) \\ -a & ; \omega \geq f(a, C, \lambda, L) \\ 0 & ; -f(a, C, \lambda, L) < \omega < f(a, C, \lambda, L) \end{cases}$$

Where $f(a, C, \lambda, L)$ is a function determined by the minimization of the Hamilton function. This is the principle for both large and small angular rates. The difference between them is the constants. The switching between them is based on a similar logic as the switching between the attitude control functions.

Chapter 7

Architectural Software Design

The S/W for the system is divided in two subsystems.

- The S/W for the IMS.
- The S/W for the Guidance and control (G&C) application.

The S/W for subsystem one is designed and written by the developer of the IMS. This design is therefore not considered in the rest of the report. Instead the architectural design of the G&C application will be discussed. The architectural design for the top level of DS19+ is mainly the same as for the DS19. Therefore much of the architectural design is derived from [9].

7.1 System Design

The main functions of the G&C application are listed in table 7.1. The design is focused on the functions and changes that are generated from the adding of the ACS functionality to the system. The final program shall be written in C to be compatible with the existing code.

Table 7.1. Purpose of the G&C application S/W.

Impact point calculations.	
Parameter scheduling.	
Telemetry compilation.	
Command calculations for:	Canards
	Thruster valves
Attitude control calculations for:	BGS application
	ACS application

7.2 Interfaces

The interfaces can be divided into three parts:

- All S/W interfaces between IMS and G&C.
- The signals from the G&C application to the digital output and to the digital to analog converter (DAC).
- All other S/W to H/W communication.

The design only handles the first two parts listed above. The third part is handled by the IMS S/W.
The interfaces between the different S/W applications are handled by a header file. This file shall be included in both IMS and G&C application files. The interchange of data is partly done through partly pointer references in the program and by global data. All signals to or from the H/W that not is handled by the G&C application is routed through the S/W of the IMS.
A schematic description of the system is seen in figure 7.1.

7.3 Initialization

The initialization is handled by a function that is called by the IMS at startup for the system. The function sets all variables and parameters that has to be predefined. The function is divided into subfunctions for the different subsystems of the S/W.

7.4 Guidance and Control Calculations

This section contains a short description of the functions in the G&C application. A description of functions and data flow for the G&C application can be seen in figure 7.2.

7.4.1 Parameter Scheduler

This function selects predefined parameters from tables using the time since lift-off, velocity, attitude and position parameters. The function then interpolates a value from the table which is returned to the program. The values that can be stored in the table is for instance parameters for the BGS control.

7.4.2 Impact Point Calculations

This function takes IMS data as input and calculates the apogee altitude, time to impact, impact point and the corrections of the attitude reference. This information is then returned to the main function.

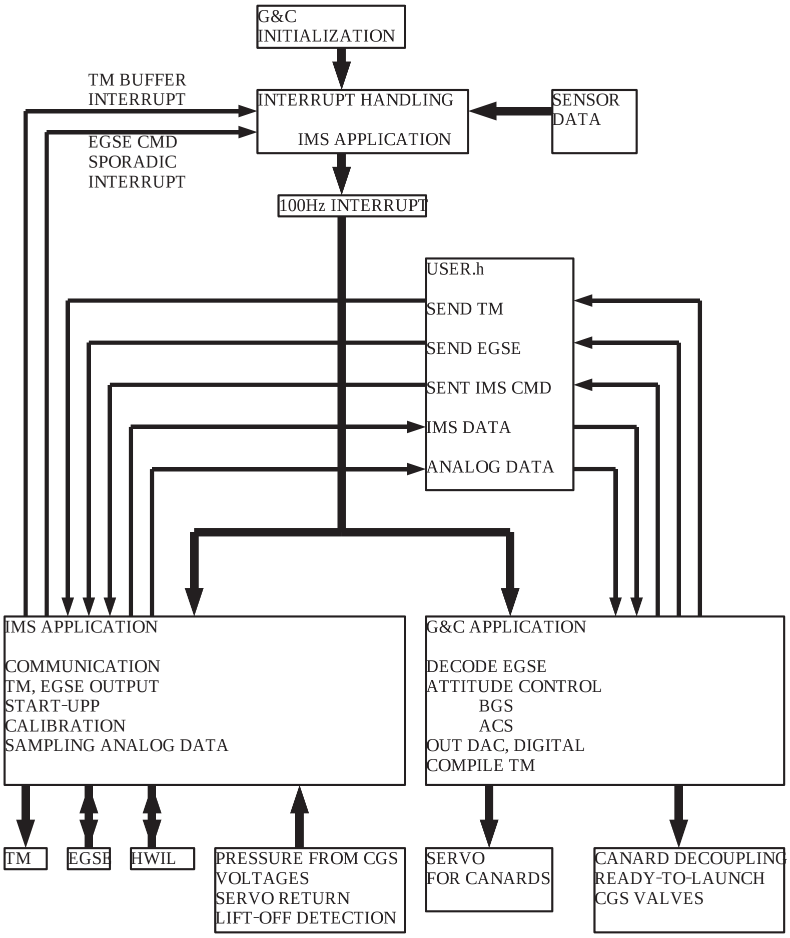

Figure 7.1. Schematic description of the S/W architecture. The thiner arrows represent data flows and the thicker arrows represent the calling of different applications.

7.4.3 Telemetry Compilation

This function creates a TM format from given inputs. This format is then sent to the IMS application to be routed to the ground control. The TM format contains 100Hz, 20Hz and 4Hz data.

In the 100 Hz data is for example the quaternions from the IMS sent. In the 20 Hz data is for example the results from the impact point calculations sent. Finally in

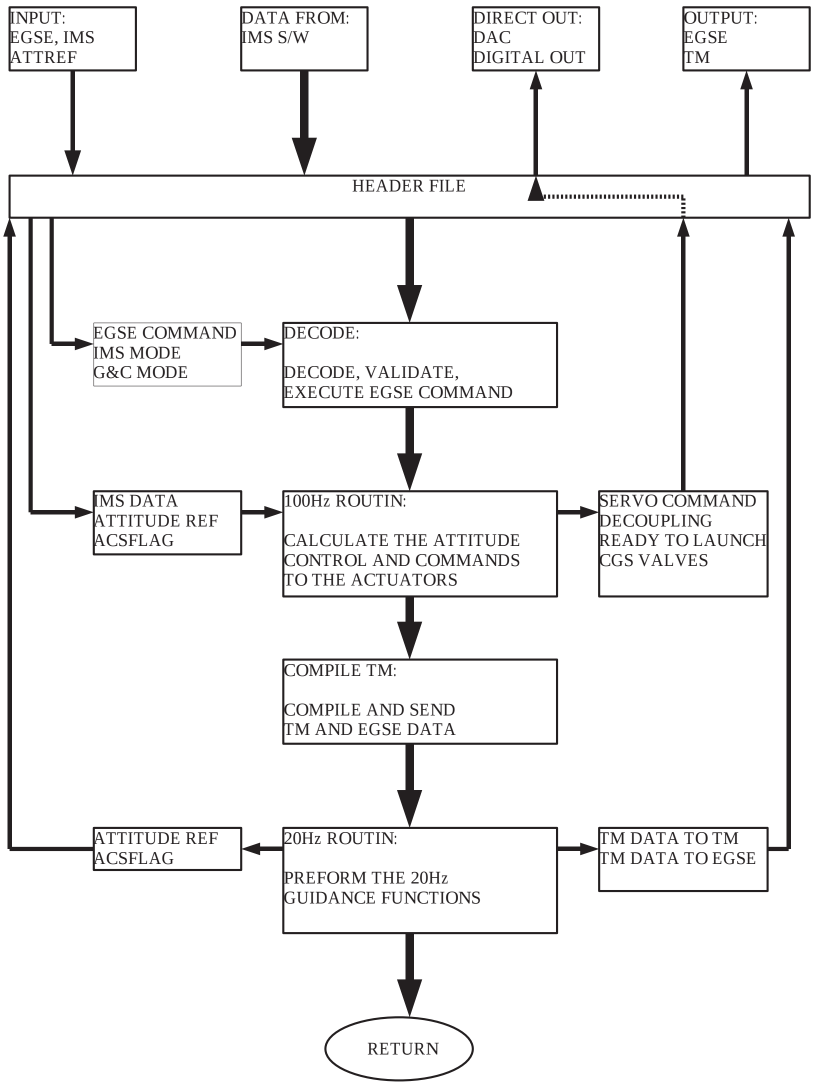

Figure 7.2. Function and data flow for the B&C application. The thin lines represent data flow and the thick lines represent functional flow.

the 4 Hz data information that is not time crucial is sent.

The data in the 20 Hz and 100 Hz data is changed depending on if the ACS control or the BGS control is used. This can be determined from the variable ACSflag.

7.4.4 Time Computation

In this function the time since lift-off is calculated.

7.4.5 EGSE Decoding

In this function the commands sent from the Electric ground support equipment (EGSE) is decoded. These are commands for both the control system and the IMS.

7.4.6 20-Hz Control Routine

This routine uses a modulo 5 computation of the time to divide the computation into five parts. This function calls the functions depending on which part that is executed. The functions that are called are:

- Impact point calculations
- Parameter scheduler
- ACS flag setting
- BGS reference attitude
- ACS reference attitude

The last two functions are never called simultaneous. The ACSflag determines which one of them that will be called.

7.4.7 ACS Flag Setting

This function takes the time since lift-off, the altitude and a control command from the EGSE as input. The output is a boolean variable that denotes true or false. The output is false if the BGS control is to be used and true if the ACS control is to be used.

7.4.8 BGS Reference Attitude

This function is called by the 20 Hz routine with IMS data as input. The function then calculates the reference attitude from the in data and the scheduled parameters. The reference attitude is then returned from the function.

7.4.9 ACS Reference Attitude

This function is called at 20 Hz. The input data to the function is the flight plan. The reference attitude , remaining time for the acquisition for the maneuver and the reentry flag that indicates when the reentry maneuver is to be initialized, are the output from the function.

7.4.10 100-Hz Control Routine

This function is a top level routine that calls the following functions:

- 20-Hz control routine
- BGS control
- ACS control

The two control functions are never called in the same 100-Hz routine. The ACSflag determines which one of the functions that is going to be called.
The function also determines when the rocket is ready for launch and when the canards is to be decoupled. The digital output and the output on the digital to analog converter (DAC) is also handled. Through the digital output is the commands for the valves and the signals ready to launch and canards decoupling sent. The signals that uses the DAC is the commands for the servos that control the canards.

7.4.11 Ready for Launch Flag Computation

This function computes the ready to launch signal. The signal is computed from the status of the sounding rocket.

7.4.12 BGS Control

This function uses data from the IMS and the reference attitude as input, the control signal to the servos is then computed with a PID control algorithm.

7.4.13 ACS Control

This function uses IMS data and reference attitude as input. The output is computed with a control function that uses several control algorithms. The control algorithm is chosen based on the attitude and rate error.
The output from this function is control signals to the CGS valves.

7.4.14 ACS Large Control

This function is used by the ACS attitude control if the attitude error are large. The function is divided into two different parts, a reorientation maneuvers part and a reentry maneuver part.

7.4.15 ACS Small Control

This function is used for small errors and when the regulated pressure level is high. It uses the present error and old outputs as input and the output is control signals for the valves in the CGS.

7.4.16 ACS Fine Control

This function is used for small errors and low regulated pressure. This function is similar to the ACS small control. This function only uses other constants than the ACS small control.

7.4.17 ACS Pressure Transit Low

This function is used as a transit function between the small and fine control. The purpose of the function is to reduce the pressure in the system from high to low without any appearance of unwanted body rates.

7.4.18 ACS Pressure Transit High

This function works in a similar way as the transit function for low pressure. The difference is that this function takes the pressure from low to high.

7.4.19 ACS Valve Control

This function takes the commands from the control functions as inputs and computes the digital command signals that is sent to the valves.

7.4.20 ACS Control Selection

This function uses the the previous control mode, the pressure level and the attitude error as inputs. From this data the function chooses which control mode that is going to be used.

7.5 Software Module Hierarchy

This section contains a short description of the S/W hierarchy. The top level hierarchy is shown in figure 7.3.
The applications developed by the IMS manufacturer is marked IMS in the figure.
The hierarchy for the G&C application is shown in figure 7.4.

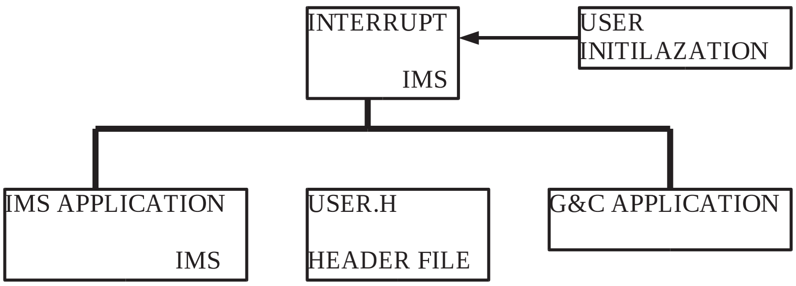

Figure 7.3. The top level design for the system.

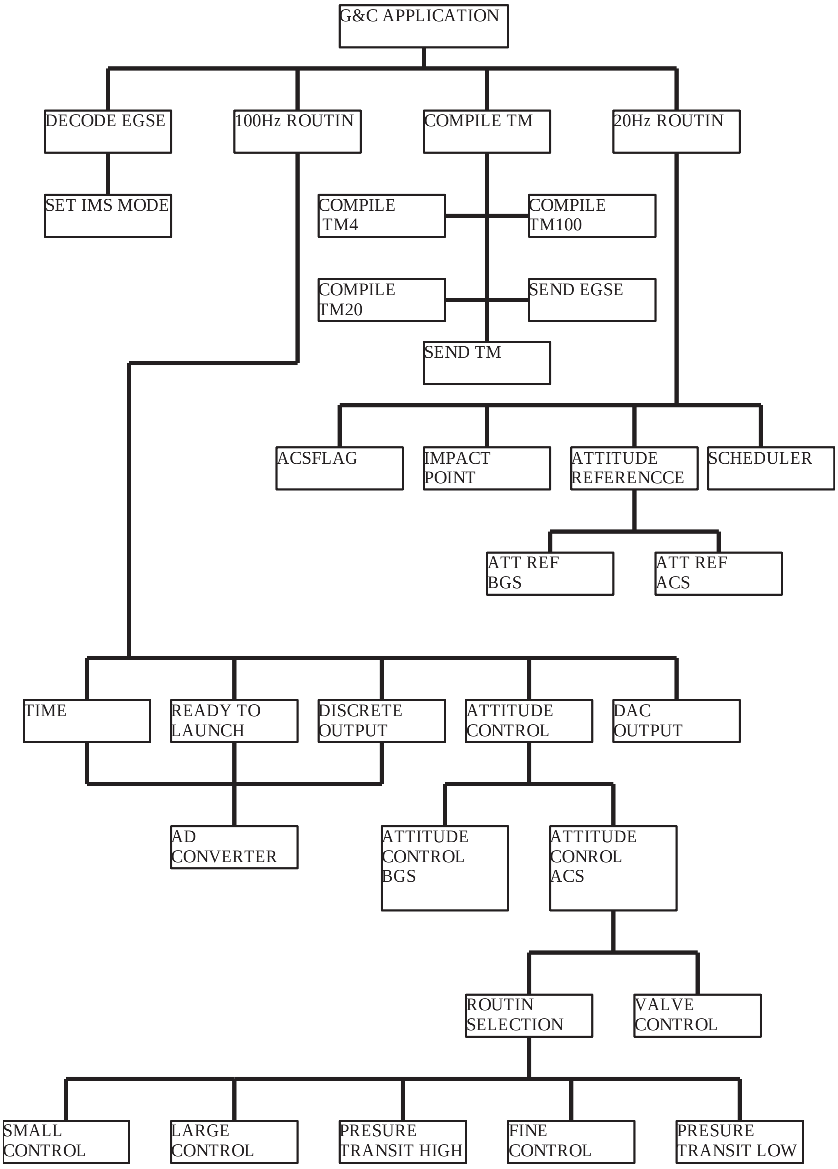

Figure 7.4. The hierarchy for the G&C application.

Chapter 8

Preliminary Software Design

This chapter deals with the detailed design for the the program. The structure of the subprograms for the application is described.

8.1 Compiler

The compiler that is used for compiling the program is a Cross Code C/C++ compiler. The code has to be compiled for a Motorola processor to get the best real-time results for the functions.

8.2 Program Functions

In this section the functions for the ACS specific tasks for DS19+ is described in detail.

Main Function for the Attitude Control

The input to the function is:

- The attitude in quaternions from the IMS.
- The reference attitude in quaternions.
- A reentry flag.
- The remaining time for the acquisition maneuver.

The function needs to have the following stored data between calls:

- The command for the latching valve.
- The attitude in quaternions from the previous call.

- The previous output from the function.
- Ready flag for the transit low function.
- The updated angular rate.
- The current position in the phase plane.

The output from the function is the command word to the valves in the CGS.
The function first uses the data to calculate the angular body rates and to transform the attitude to a polar frame in the thruster plane. The attitude error is then calculated with this information. The select function is then called to determine which control function that is going to be used for the command computation. After this is done the chosen control function is called. The return from the control function is a control signal for the thrusters.
The command signal takes the following values:

- 0, means all thrusters off.
- 1, means that the thrusters in the positive direction is on.
- -1, means that the thrusters in the negative direction is on.
- 2, means that all thrusters in the axis are on. This value is only valid for the transverse axes.

These signals is then sent to the valve control that computes the command word for the valves which is used as an output from the function.

Control Selection

This function handles the selection of control mode in the ACS control. The input to the function is:

- The attitude error.
- The angular body rates.
- The previous commands to the valves.
- The reentry flag.
- A ready flag set by the transit low function.
- The remaining time for the acquisition maneuver.
- The command to the latching valve.
- The current position in the phase plane.
- The updated angular rate.

The previous control mode has to be saved between the calls to the function and also the a stabilization flag for the payload. This flag is also used by the attitude reference function for the ACS. The output from this function is a command word that indicates which control mode that has been chosen.

The function has a state diagram according to figure 8.2. The switches is calculated every time the function is called. When changing to a new mode the function sets the data needed in that mode.

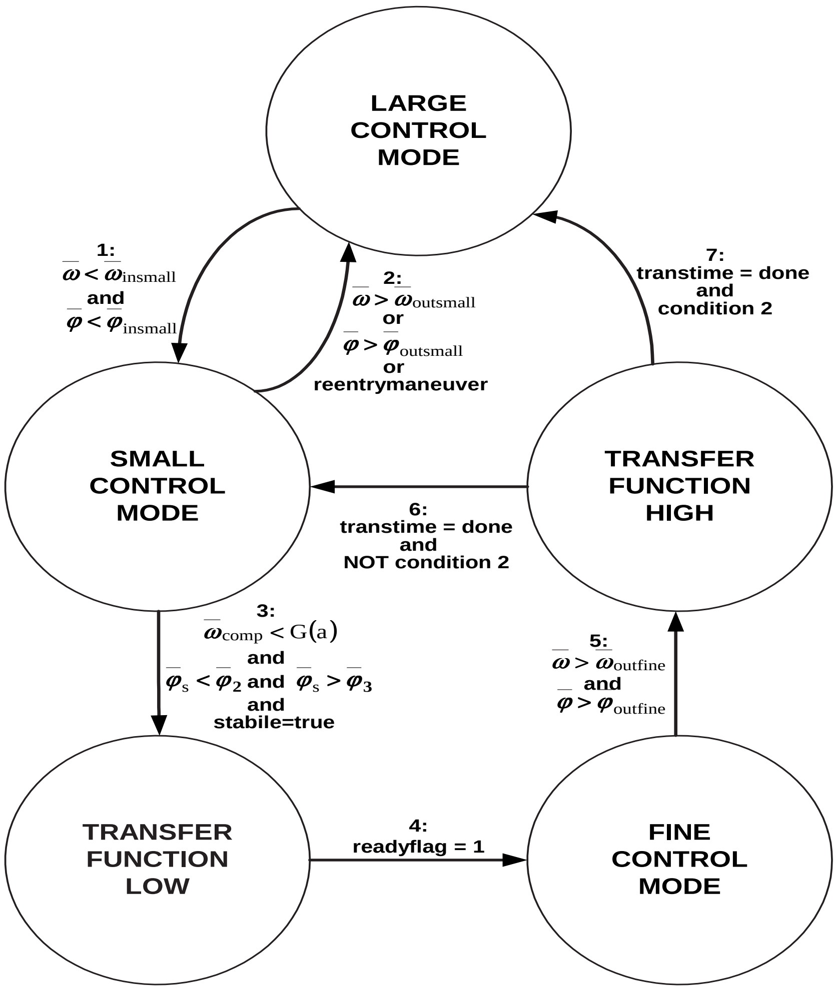

Figure 8.1. A state diagram over the select function.

Valve Control

The input to this function is the commands that is calculated in the control routines. The function then maps these commands to the command word that is returned. In the command word every bit represent a thruster.

Large Control

This function needs the following input:

- The attitude error.
- The angular body rates.
- The reentry flag.
- The previous output from the function.
- The remaining time for the acquisition maneuver.
- The angular acceleration for the axes.
- The total error in the transverse plane.
- The quaternions for a transformation from the body frame to a equatorial-polar frame.

The data that has to be stored between the calls is the loss time for the function. The output from the function is the control signal to the valves.
First the function checks the reentry flag. If the flag is true the reentry maneuver is initialized. If the flag is false the control function is executed.
The reentry maneuver consists of roll rate and transverse rate control. The reentry maneuver first controls the transverse rates and attitude errors. If these are sufficiently small the function activates the roll thrusters to increase the spin of the rocket. If the transverse rates are to large the function activates the thrusters to reduce these.
The control function consist of two parts roll control and transverse control.
The roll control is first initialized to reduce the roll rate, for this the RCS control is used whit a hysteresis function added to it. After that the roll control waits until the transverse error is sufficiently small before the roll error is corrected. The control law from section 6.4 is used for this.
The command signal for each axis is then sent as an output.

Small Control

This function needs the following input:

- The attitude error.
- The angular body rates.

- The previous valve command.
- The angular acceleration.
- The switching lines in the phase plane.
- The present point in the phase plane.
- The remaining time for the acquisition maneuver.

The sequential operating time for the thrusters has to be saved between the calls to the function. This information is used for the prediction of the angular increment and body rate increment. The old values for these variables also has to be saved, for use in the next call.
The output from the function is the control signals for the thrusters.
This function computes the control for each axis separately. The function first predict the angle increment and body rate for the axis. This is done in the following way:

- If the positive on counter is greater than zero the rate is increased with a constant times the angular acceleration and the angle increment is changed with the body rate.
- If the negative on counter is greater than zero the computations is as above but with a change in the sign.
- If the off counter is greater than a given constant the values is changed with a body specific parameter.
- If the off counter is lower than the constant the old values is used for the parameters.

The control law from section 6.3 is then applied. The result is used as output from the function.
The sequential operating time for the thrusters is then updated. This is done in the following way for each axis:

1. If the thrusters is used in the positive direction of the axis the positive on counter is increased by one and the other counters is set to zero.
2. If the thrusters is used in the negative direction of the axis the negative on counter is increased by one and the other counters is set to zero.
3. If no thrusters is used in the axis the off counter is increased by one and the other counters is set to zero.

Fine Control

The inputs needed in this function are:

- The attitude error.
- The angular body rates.
- The previous valve command.
- The angular acceleration.

The output from the function is:

- Commands for the thrusters.

The data that has to be saved between the calls are:

- The time for how long the control has been consecutively in fine mode.
- The switching lines in the phase plane.
- The present point in the phase plane.
- The sequential operating time for the thrusters.
- The filtered angular rate.
- The reference attitude.

The function first calculates the stability of the system. This is done by checking the angular velocity and attitude error compared to constants.
The attitude control is then computed in a similar way as for the small control. The stabilization flag is used to select between two control routines in this part of the function. The control function that is used when the rocket is unstable is a simplified version of the control law. The control used for the stabilized case is the complete control function.
After this the sequential operating time for the thrusters is updated in a similar way as to the update in the small control.
The function then returns the control command to the valves.

Pressure Transit Low

The inputs needed in this function are:

- The present command to the latching valve.
- The attitude error.
- The angular body rates.
- The angular acceleration for the payload.

The outputs from the function are:

- Commands for the thrusters.
- The command to the latching valve.
- A ready flag.

A time parameter has to be saved between the calls for the function.
The function conducts a series of tasks that results in that the regulated pressure is lowered in a way that does not result in any increase in the body rates.
This function is divided into several parts. First there is a coast phase for the control. After that a loss function is calculated and from this the command to the thrusters is calculated and also the active time for the thrusters is calculated. After this the output for the thrusters is set to the calculated value for that time. Then the latching valve is closed and a new loss function is calculated to determine which thrusters that is to be used during the pressure dumping. Then the the commands to the thrusters are sent. Finally the ready flag is set to true.

Pressure Transit High

This function needs no input. The output from the function is an open command to the latching valve.

8.2.1 Attitude Reference ACS

This function does not need any input.
The outputs from this function are:

- The attitude in quaternions.
- The reentry flag.
- The remaining time for the acquisition maneuver.

The saved data in this function are:

- A flag that indicates a new maneuver.
- A counter that indicates the flight plan index.
- A counter that indicates the sequential stable time for the payload.

First the function checks if there is a new maneuver. After that the output variables for the function is set. Then the stable time counter is updated and if the stable time is the same as the stable time in the flight plan the new maneuver flag is set.

8.2.2 Ready to Launch

The changes in this function is the following:
The bottle pressure and the regulated pressure in the CGS has to be above a certain value to give the ready to launch signal. The implementation is done similar to the pressure checks for the BGS servo system.

8.2.3 20-Hz Routine

The changes for this module are the following:

- For (time after lift-off modulo 5) = 0:

  The function that sets the ACSFLAG is called.

- For (time after lift-off modulo 5) = 3:

  The BGS attitude reference function is called if ACSFLAG is false. If the ACSFLAG is true the ACS attitude reference function is called.

The ACSFLAG is an input from the 100-Hz routine and also an output from this function.

8.2.4 100-Hz Routine

The changes that are needed in this function are the following:
The ACSFLAG has to be sent to the 20-Hz routine. The function attcnt is called when ACSFLAG is false and the function attcntacs when it is true.
All the digital outputs is saved in parameters that is added together before the sending of the command.

8.2.5 Choice of Control Mode

This function needs the following input:

- Time after lift-off.
- Altitude.
- A test flag that can set the ACSFLAG.

The output from the function is the variable ACSFLAG that indicates which control routine that has to be chosen.
The ACSFLAG is set true if Time after lift-off is higher then a predefined value, the altitude is high enough and that decoupling of the canards is done or that the test flag is true. If non of these holds the output is set to false.

8.3 Implementation

First a development environment for the code has to be chosen. The environments that are used for these type of developments is C, Fortran and MATLAB. The benefit with MATLAB is that it has a short development time and the drawback is that it has a long execution time for the simulation. C has a benefit of short execution time but has a long development time. Fortran has approximately the same properties as C.
Due to the nature of the system and that the duration for the simulation is short the MATLAB environment is chosen for the development.
The control system has been implemented according to this chapter. Rocket specific constants are chosen to be the same as for the RACS sounding rocket. The constants has been retrieved from [8].
The final flight code shall be developed in C and Assembler.

Chapter 9

Verification and Simulation

In this chapter the simulation of the control law and a model for the system is described. The results from the simulation is also discussed.

9.1 Rocket Dynamics

To be able to test the control system for the sounding rocket a model of the rocket dynamics has to be derived. To determine the model a coordinate frame for the model has to be chosen. Several frames can be used, but the chosen frame is a frame fix in the launch pad, for a more detailed description see B.3.

The model has the following states:

Three states describing the position of the sounding rocket in the coordinate frame:

x	x-position
y	y-position
z	z-position

Three states representing the velocity for the sounding rocket:

V_x	Velocity in x-direction
V_y	Velocity in y-direction
V_z	Velocity in z-direction

Four states representing the transfer function described in quaternions from the inertial frame to the body frame. For more information see A:

$$\boldsymbol{q} = \begin{pmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{pmatrix}$$

Three states representing the angular velocity of the spacecraft, expressed in the initial frame:

ω_x Angular x-velocity
ω_y Angular y-velocity
ω_z Angular z-velocity

This model describes both the movement and attitude change of the sounding rocket. A difficulty with this system is that the step length when solving the equations are varying between the equations. A simulation of the attitude requires a small step size and a simulation of the movement requires a larger step size.
The fact that the two parts are independent of each other makes it easy to draw the conclusion that a simulation of only the attitude is enough.
The equations for the attitude dynamic is then derived from [16]:

$$\begin{aligned} \begin{matrix} \dot{x_1} \\ \dot{x_2} \\ \dot{x_3} \\ \dot{x_4} \end{matrix} &= \frac{1}{2} \begin{bmatrix} 0 & -x_5 & -x_6 & -x_7 \\ x_5 & 0 & x_7 & -x_6 \\ x_6 & -x_7 & 0 & x_5 \\ x_7 & x_6 & -x_5 & 0 \end{bmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{pmatrix} \\ \dot{\boldsymbol{\omega}} &= \boldsymbol{I}^{-1} \begin{pmatrix} T_X + N_X \\ T_Y + N_Y \\ T_Z + N_Z \end{pmatrix} \end{aligned} \tag{9.1}$$

where the T-elements are the description of the coupling between the rates and quaternions and the state and N-elements are the combined torque from the control torque and the torques from the disturbances. The disturbance is made of two parts in each axis. One constant part and one part that consist of impulses. The constant part are 0.02 Nm in the roll-axis and 0.1 Nm totally in the transverse axes. The impulse part consists of impulses that occurs simultaneously in both the roll and transverse axes. The magnitude of the impulse in roll is 0.2 Nms and 2 Nms totally in the transverse axes. This according to [2].
These equation is implemented in MATLAB. They are solved with the ode23s differential solver in MATLAB. This solver uses the Rosenbrock method to solve differential equations according to [12]. This type of solver is used on stiff differential equations, that is that the solver uses a fix step length to solve the equation.
The simulation of the the system runs the attitude control algorithms every 0.01 s whit the input from the latest simulation and the control torques from the CGS in the body frame as an output. Between each call the attitude for the system is simulated. The input to the simulation is the control torques and the torques from

the disturbances. Both of them is assumed to be constant for each interval. This way is chosen for the simulation to make shore that the control function only is called at 100Hz and to get a sufficiently good description of the system.

9.2 Result From Simulation

The result from the simulation of the system is shown in this section. The system is simulated for a nominal where there are no misalignments. The phase planes for a nominal case for the system looks as figure 9.1. The combined maximum error during the stable phase are less then 0.2°. This is a result that is better then the requirements in section 3.3. This can be a result of that the disturbance is implemented with a effect that is to small.

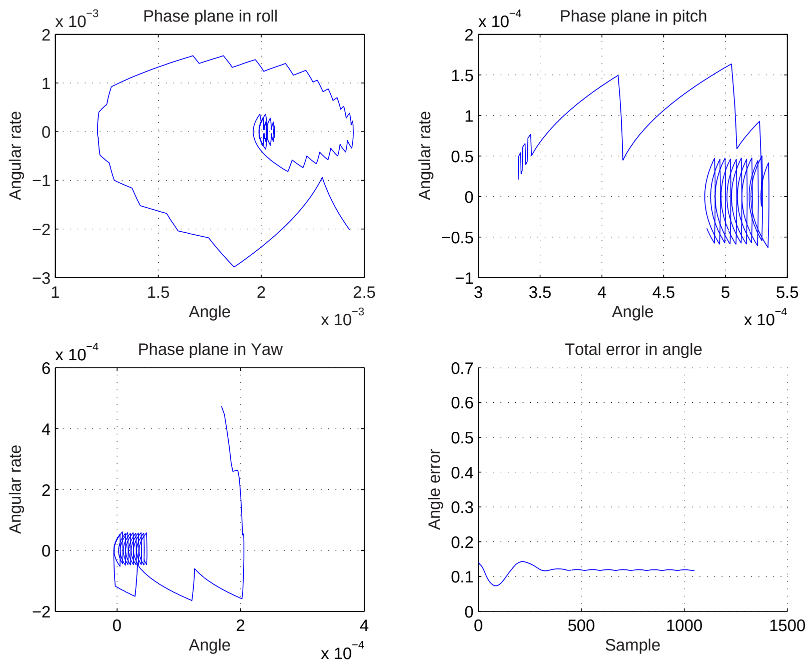

Figure 9.1. The phase planes for the system after a simulation.

The acquisition time for the system has also been investigated for the system, a histogram for the time is shown in figure 9.2. The maximum time for a acquisition are 28.3 s and the mean value for the maneuver are 19.4 s. These values are derived from a Monte-Carlo simulation of the system. These simulations has been done with the disturbance set to zero.

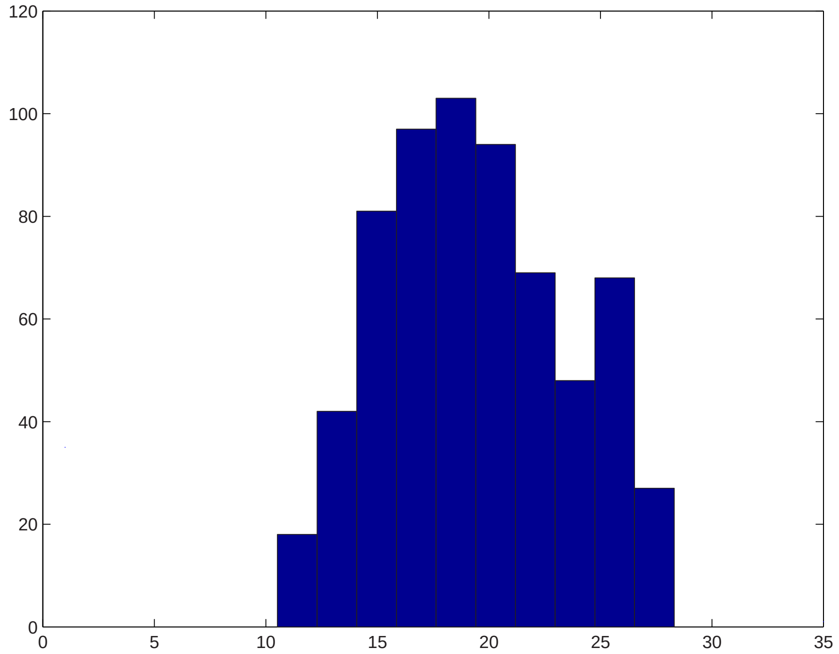

Figure 9.2. A histogram over the acquisition time for the payload.

As seen above are the requirement on the system from section 3.3 fulfilled. The system also seems to function as expected and can therefore be used for implementation in C and Assembler for further testing.

Chapter 10

Conclusion and Further Work

10.1 Conclusions

This report handles the preliminary design for the DS19+ control system, which include both attitude control and boost control functions. The control laws for the system are derived from the RACS and DS19 systems.
A pointing attitude control function is added to the DS19 system to derive DS19+. This function is chosen because of the limited amount of free interfaces between the PDU and IMU and also that flight proved code from RACS can be used for the development of the system. The computer and memory capacity in DS19 is sufficient to support the DS19+ with pointing attitude control.
Hardware wise DS19+ is designed to consist of separate CGS and DS19 modules according to chapter 5, this is done to minimize the changes in the DS19 module. An advantage with this is that only small small changes will occur if the system is extended with extra attitude control functions that uses extra sensors. The design also gives extra freedom for the position of the sensors. The design also simplifies the construction of the CGS if it is built by an external manufacturer.
The electrical interfaces and TM format is changed according to the design in chapter 5. These interfaces has to be redesigned if another attitude control function is added to the DS19+ system.
The attitude control S/W for DS19+ is derived from the control laws in chapter 6. These control laws and a S/W function that is used to chose between the them are implemented in MATLAB with a model of the sounding rocket from chapter 9.
The model is used to perform simulations of the control system. The pointing error for the system is totally less then 0.2° 3-σ in all axis which fulfills the requirements of a total error less the 0.7° 3-σ in all axis. The result from the simulations can also be seen in chapter 9. As seen above and in chapter 9 the system fulfills the requirements on the DS19+ system found in section 3.3. The system should there-

fore be functional when it is implemented in C together with the boost guidance S/W from DS19 and some of the changes listed in the next section.
If other attitude control functions, such as fine pointing or sun pointing, have to be added to the DS19+ the IMU interfaces has to be redesigned to make room for the extra signals needed. Extra S/W is also needed for in the system to handle the data from the extra sensors. Therefore a new design has to be done if these functions are to be added to the system.

10.2 Further Work

The work that is left to make a completely functional DS19+ are:

Implement TM changes: The changes in the TM format has to be implemented.

Detailed design: Extend the preliminary design in this document to a detailed design and implement it in C and Assembler.

Flight table editing: Implement a simplified way to change the flight table, which is changed in the initialization file for the system. This is a poor solution because this is a variable for the flight and the other inputs in the file are constant for the system.

Split up the initialization: Split up the initialization in separate files for the initialization for the system and for the model and the simulation.

Implementation: The implementation of the code in C and Assembler.

Testing of the system: Further testing in the sounding rocket simulation program made by SE and hardware in the loop tests for the system to assure that it functions according to the requirements.

Changes in the H/W: The changes that is needed in the H/W has to be designed and implemented in the DS19 module.

Further development: Further development of the system into fine or sun pointing systems with extra sensors. This results in that a new or changed IMU has to be developed to make room for the new interfaces that is needed. Some changes in the software design also has to be done for the new functions.

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Appendix A

Quaternion

Quaternions are a way to describe a transformation from one coordinate system to another. The quaternions are based on the Euler angles for description of the transformation. The parameters are defined as follows:

Definition A.1

$$q_0 \equiv \cos\frac{\Phi}{2} \tag{A.1}$$

$$q_1 \equiv e_1 \sin\frac{\Phi}{2} \tag{A.2}$$

$$q_2 \equiv e_2 \sin\frac{\Phi}{2} \tag{A.3}$$

$$q_3 \equiv e_3 \sin\frac{\Phi}{2} \tag{A.4}$$

As seen these equation are not independent, but they have to satisfy the constraint:

$$q_0^2 + q_1^2 + q_2^2 + q_3^2 = 1 \tag{A.5}$$

These parameters can be seen as the components of a quaternion, defined as:

Definition A.2

$$\boldsymbol{q} \equiv q_0 + iq_1 + jq_2 + kq_3 \tag{A.6}$$

where i, j and k are the hyper imaginary numbers satisfying the conditions:

$$\begin{array}{ccccc} i^2 & = & j^2 & = & k^2 = -1 \\ ij & = & -ji & = & k \\ jk & = & -kj & = & i \\ ki & = & -ik & = & j \end{array}$$

This gives that the inverse of $\boldsymbol{q}$ is defined as:

Definition A.3

$$\boldsymbol{q}^* \equiv q_0 - iq_1 - jq_2 - kq_3 \tag{A.7}$$

The norm or length of the quaternion is defined as:

Definition A.4

$$|\boldsymbol{q}| \equiv \sqrt{\boldsymbol{q}\boldsymbol{q}^*} = \sqrt{\boldsymbol{q}^*\boldsymbol{q}} = \sqrt{q_1^2 + q_2^2 + q_3^2 + q_4^2} \tag{A.8}$$

The transformation matrix $\boldsymbol{A}$ that is based on the quaternion is described by:

$$A(\boldsymbol{q}) = \begin{bmatrix} q_0^2 - q_1^2 - q_2^2 + q_3^2 & 2(q_1q_3 + q_0q_2) & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1q_2 + q_0q_3) \\ 2(q_2q_3 + q_0q_1) & 2(q_1q_2 - q_0q_3) & q_0^2 - q_1^2 + q_2^2 - q_3^2 \end{bmatrix} \tag{A.9}$$

For a more detailed description of quaternion see [16].

Appendix B

Coordinate Systems

In this chapter the different coordinate systems that are used in the report are described.

B.1 Payload Fixt Coordinate System

This coordinate system is a body fix coordinate system where origin is the mass center of the payload and the x-axis goes through the nose of the sounding rocket. The other axis are chosen so that when the rocket is in the launch pad the y-axis points towards the rail.

B.2 Thruster Plane Coordinate System

This system is similar to the Payload fixt system. The difference is that this system is rotated $-45°$ in the y-z plane of the payload fix coordinate system.

B.3 Launch Pad Coordinate System

This is the chosen initial frame for the sounding rocket. Origin is placed at the bottom of the launch pad and the x-axis is a normal to the surface of the earth. The z-axis points towards the true north pole and the y-axis is placed so that a right handed orthogonal Cartesian system is formed.
This system is chosen as a inertial system based on the previous use of this system in sounding rocket applications.

Appendix C

User Manual

This Chapter is a description of the S/W that is produced for the attitude control and simulation.

C.1 File Structure

The file structure of the program are shown in figure C.1.

C.2 Input

The inputs to the function are the data listed in table C.1.

Table C.1. Inputs to the function.

Name	Description	Units
tend	This input variable is set in the function call and represent the execution length of the simulation	[s]
plotflag	This is a variable that controls the call to the plotfil in the main function. If it is set to one the function is called, for all other values the is not called.	[-]
tabell	This is the flight plane for the system. It is set in the initfile for the system. The variable is a matrix where each row represent different maneuver. The first column is the time for the acquisition for the maneuver, the second column the time for which the attitude has to be stable and the last columns are the attitude in quaternions.	[s],[s],[-],[-],[-],[-]

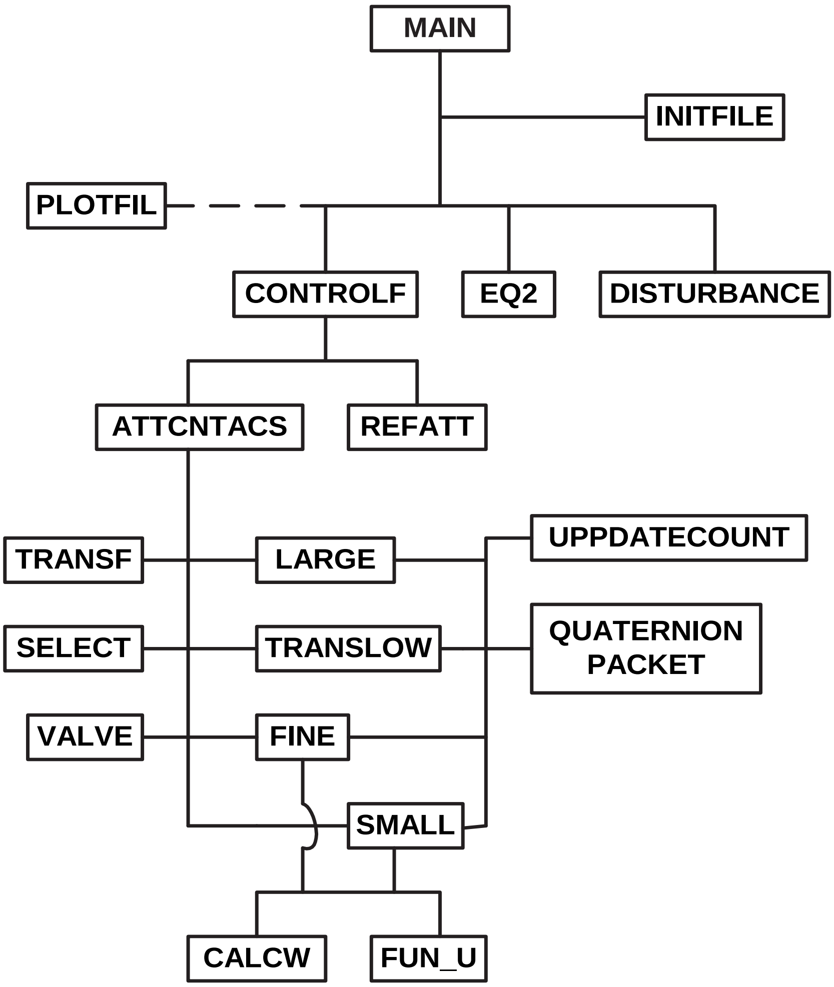

Figure C.1. The file structure of the MATLAB implementation of DS19+, where the lines indicates the interchanges between the files.

C.3 Output

The outputs to the function are the data listed in table C.2.

Table C.2. Outputs to the function.

Name	Description	Unit
x	This variable is a matrix where each row contains the state values for the system for specific time. There is one row for each 0.01 s of the simulation.	[-],[-],[-],[-], [rad/s],[rad/s],[rad/s]
xs	This variable contains the starting state of the simulation. The variable is the same as a row in the variable **x**.	[-],[-],[-],[-], [rad/s],[rad/s],[rad/s]
t	This is a vector containing all the times for which **x** is sampled.	[s]
qvec	This variable is a matrix containing the reference attitude for all times **t** in quaternions.	[-],[-],[-],[-]
us	This variable is a matrix containing the control commands to the thrusters for each time in **t**. The columns represent roll, pitch and yaw in that order.	[-],[-],[-]

C.4 Program Execution

The program is executed by typing the command main(tend,plotflag) in MATLAB. This can be done when MATLAB have access to all files in the program packet. The output is then saved in the file ACSsimulation.mat in the current directory.

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