

REACTION WHEEL

5 Nms RW4-5.0

Interface Control Document

RL-TOR-ICD-00033 v1.0

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Document History

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1 Scope

This document details the mechanical, electrical and software interfaces for the RW-5.0 reaction wheels. Available models are:

- RW4-5.0-28-RS485

2 Mechanical

A detailed mechanical ICD can be provided upon request that includes:

- Mass properties
- Dimensions
- Mechanical Interfaces

2.1 Remove Before Flight

The following items are removed before flight:

Item	Remove?	Notes
Kapton bearing covers	May remove	1x Kapton tape pieces, protect bearings from debris on ground

3 Environmental

3.1 Storage

The wheel must be stored in a clean environment to keep dust out of the bearings. The humidity must be kept low to prevent corrosion of the steel rotor. The wheel may be stored in a sealed bag with desiccant.

3.2 Thermal

The table below details the operational and survivable temperature range for the product.

Table 1: Allowable Temperature Range

Criteria	Range
Survival Temperature	-40°C to +100°C
Operating Temperature	-30°C to +85°C at interface

The temperature is defined as the temperature of the base plate in the nominal mounting configuration.

3.3 Pressure

The wheel will operate in sea-level atmosphere and in hard vacuum. It has not been qualified to operate at high altitude atmospheres, and should not be powered during ascent unless additional testing is performed to show that there is no danger of arcing.

All materials meet the standard outgassing requirements of TML < 1%, CVCM < 0.1%.

3.4 Vibration

The wheel is designed to survive typical launch environments. It has been qualified to NASA GEVS levels (14.1Grms for 2 minutes/axis).

4 Electrical

4.1 Architecture

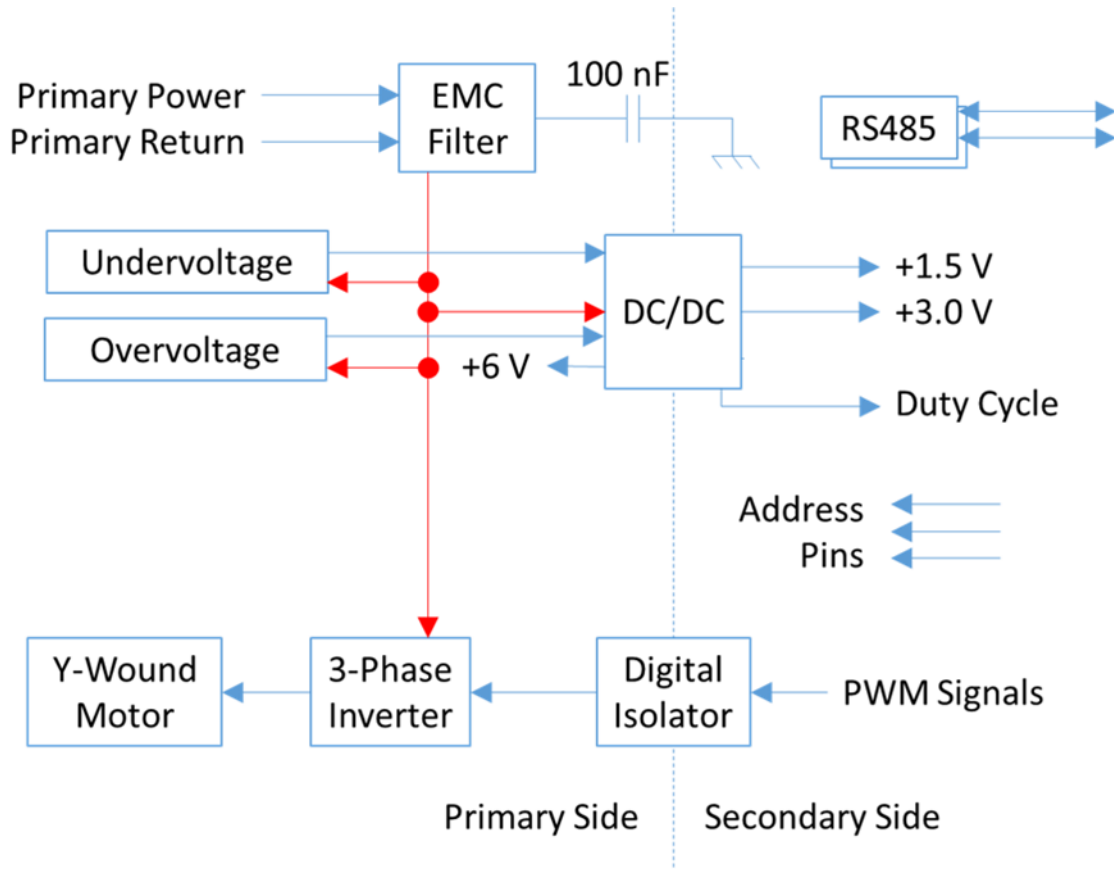


Figure 1: Power Architecture

4.1.1 Regenerative Braking

The wheel makes use of regenerative braking when slowing the rotor under moderate torque. This will result in the wheel consuming a net negative amount of power, pushing current back out onto the spacecraft power bus. The spacecraft power system design must be able to accommodate this.

In an emergency, if the power line becomes disconnected from the power system (such as if turned off via a relay switch) regeneration will increase the voltage at the wheel until the overvoltage threshold is reached. This will cause the wheel to reset and cease regeneration.

4.2 Connections

4.2.1 Primary Connector

The wheel is fitted with a single 15-position micro-D socket receptacle. Note, where multiple contacts have the same pin name they are connected within the reaction wheel.

Table 2: Primary Connector

Attribute	Device Connector
Manufacturer	Omnetics
Manufacturer Part Number	A99089-015
Specification	MIL-DTL-83513
Number of Contacts	15
Gender	Female

Table 3: Primary Connector Pin-out

Pin	Pin Name	Signal Type
1	Address 1	Chassis or Open
2	Address 2	Chassis or Open
3	Secondary Return	Chassis
4	RS485_0_A	RS485 Bus 0 – A Side
5	Secondary Return	Chassis
6	Primary Return	DC Power Return
7	Primary Return	DC Power Return
8	Primary Power	DC Power Input
9	Address 0	Chassis or Open
10	RS485_1_B	RS485 Bus 1 – B Side
11	RS485_1_A	RS485 Bus 1 – A Side
12	RS485_0_B	RS485 Bus 0 – B Side
13	Primary Return	DC Power Return
14	Primary Power	DC Power Input
15	Primary Power	DC Power Input

4.2.2 Programming Header

This board implements a plug-of-nails style programming and debugging JTAG interface for development and programming purposes. This is a modified 10-pin JTAG port with FRAM power and WP override. This interface is not accessible once the RWA has been assembled.

4.3 Interface Specifications

This document only provides specifications for the primary power and communications interface. The factory JTAG interface will not be accessible after assembly.

4.3.1 Power

Table 4: Power Specification

Property	Value
Nominal Primary Voltage	+22 V to +34 V DC relative to primary return
Absolute Maximum Voltage	-65 V to +63 V DC relative to primary return
Isolation	100 nF in parallel with 1MΩ 100 V Hipot test permissible
Overvoltage threshold	+52.6 V @ 25 C, 50 mV/K temperature variation, overvoltage shall be limited to 0.5s pulses at <10% duty cycle
Undervoltage threshold	+20.7 V Turn on, +14.5 V Turn off

The power supply uses an undervoltage lockout (UVLO) circuit to prevent brownout behaviour at low input voltages. There is a large hysteresis on the limit to prevent oscillation. When the input voltage is too low, the DC/DC converter is inhibited and no power will reach the secondary circuits. The startup regulator and oscillator will remain active, so a modest input current will remain.

The power supply uses an overvoltage limit circuit to prevent damage from very high bus voltages. This circuit is implemented with a simple Zener diode, and thus has a significant temperature variation – the limit voltage increases with increasing temperature. There is no hysteresis on the limit, and so chatter may be possible. Activation of this circuit should only happen in an emergency, so this is considered acceptable. The startup regulator and oscillator remain active in an overvoltage condition. In this case the power dissipated in the startup linear regulator can become significant: maybe 10 mA across a 45 V drop. The startup regulator does not have overtemperature protection, so the time spent in the overvoltage condition must be strictly limited.

4.3.1.1 Primary Return

The Primary Return (DC Power Return signal) is the return for the Primary Power (DC power input signal).

4.3.1.2 Secondary Return (Chassis)

Secondary Return (Chassis) is the reference for all other signals. The secondary return is isolated from the primary return by a 1 Mohm resistor.

4.3.2 Address

The address inputs allow the network address of the wheel to be set. Inputs must either be left open-circuit (digital '1') or connected to Secondary Return (digital '0'). The wheel will determine its address only once, at power-on.

Table 5: Address Specification

Property	Value
Absolute Maximum Voltage	+/- 30 V DC, relative to secondary return
Input Resistance	4.75 kΩ
Pull-up Resistance	40 kΩ

4.3.3 Communications

The device has two RS485 transceivers. They may be used as two half-duplex 2-wire buses, or used together as a 4-wire bus. As a 4-wire bus, the wheel is interoperable with legacy RS422 signals.

Table 6: RS485 Specification

Property	Value
Absolute Maximum Voltage	-9 V to +13 V, relative to secondary return
Polarity	B > A in Mark (Idle) state A > B in Space (ON) state
Differential Output Voltage	>1.5 V into 54Ω termination
Short-circuit Output Current	250 mA max
Input Differential Threshold	-0.20 V to -0.01 V
Input resistance	> 48 kΩ each signal
ESD Rating	±20 kV HBM (IEC 61000-4-2)

There is no provision for termination inside the wheel. If it is needed, it should be spliced into the harness at the ends of the bus. For a spacecraft with short, slow RS485 buses it is typically not required or useful.

5 Software

5.1 Protocol Layer 2 (Data Link Layer)

5.1.1 Asynchronous Serial

The RS485 communications ports use an asynchronous serial protocol. The parameters are programmed into the unit bootloader at the factory, and special-order units with different parameters are available.

Table 7: Asynchronous UART Configuration

	Hex value
Data Bits per Byte	8
Parity	None
Stop Bits	1
Nominal Baud Rate	115200, (230400 at request)

Each word begins with a start bit with space (0) value. Eight data bits follow, with the LSB sent first and the MSB last. Finally, a stop bit is sent with mark (1) value. Once the stop bit has concluded the output transmitter may be disabled if there are no further words to follow.

5.2 Protocol Layer 3 (Network Layer)

NSP is the Nanosatellite Protocol, originally developed at UTIAS/SFL for use on the CanX nanosatellites. This in turn is descended from the Simple Serial Protocol (SSP) used by UTIAS/SFL and Dynacon on the MOST and CHIPSAT spacecraft as well as the Dynacon reaction wheels in the wider market.

The reaction wheel uses NSP messages for all communication.

5.2.1 SLIP Encoding

NSP messages are encoded for transmission on asynchronous or I2C serial channels use SLIP framing, as described in RFC 105. This is required in order to indicate the beginning and end of NSP messages.

Table 8: SLIP Framing Special Characters

	Hex value
FEND	0xC0
FESC	0xDB
TFEND	0xDC
TFSEC	0xDD

Each NSP message is transmitted with a FEND character added to the beginning and end. Whenever FEND would occur within the message it is replaced by two bytes: FESC TFEND. Whenever FESC would occur within the message it is replaced by FESC TFESC.

5.3 Protocol Layer 4 (Transport Layer)

5.3.1 Command and Reply

The wheel generates telemetry messages in response to command messages received. In the usual case, a single telemetry message will be sent as quickly as possible after reception of the command.

Some commands will take a period of time to execute and will only generate a telemetry message when they are complete. The wheel should be considered to own the communications bus while such a command is executed, so do not send additional commands to it or any other unit until the reply is complete.

While some NSP devices can generate multiple telemetry messages in response to a single command, the wheel will not. The P/F bit will be set for all replies, indicating that they are stand-alone final messages.

Notwithstanding the above, the wheel will not generate messages that are not linked to a command. The host spacecraft must poll it to determine its status and to read telemetry

5.3.2 NSP Message Format

Table 9: NSP Message Fields

Length	Field
1 byte	Destination Address
1 byte	Source Address
1 byte	Message Control Field
0 or more bytes	Data Field
2 bytes	Message CRC

Each NSP message has the format shown above. The shortest possible messages are 5 bytes (with zero data, not counting framing).

The wheel supports a maximum data length of 260 bytes, giving a total message length of 265 bytes. Note that network-layer framing may add additional bytes to the message as it is transmitted.

5.3.3 NSP Addresses

All NSP messages contain a destination and a source address. A reply message will be sent with a destination address equal to the source address of its command message. Similarly, the source address will be set equal to the destination address from the command.

The user is free to pick one or more NSP addresses for flight computers and other units that may talk to the wheel. Avoid choosing the SLIP framing characters FEND (0xC0) and FESC (0xDB), as well as the reserved address 0x00. By convention the flight computer would normally use NSP address 0x11.

The wheel pays no particular attention to the source address of commands, and will accept commands from any unit on the bus.

5.3.4 Wheel Address and Port Selection

The wheel bootloader may support incoming communication on a number of communication ports: potentially up to two RS485 ports. In addition, there may be cases where outgoing reply packets are sent on a different port from the

command packet. For example, a 4-wire RS485 link can be implemented by receiving commands on one 2-wire RS485 port and sending replies on a different 2-wire RS485 port.

A wheel may respond to different NSP addresses on different ports. On any given port, incoming commands with different NSP addresses may cause replies to be issued on different ports.

The RW4 has two NSP state machines, and can handle simultaneous interactions on both ports. There are two possible contention situations:

- If a reply is generated on a port that is currently receiving an incoming message, the incoming message is abandoned and the reply is sent out. This probably results in an RS485 bus contention.
- If a reply is generated on a port that is already sending out a reply, the reply in progress is not interrupted. The new reply is abandoned – there is no attempt to queue it.

Contention should not occur in a well-managed spacecraft.

The wheel uses the following NSP addresses:

Table 10: Default NSP Addresses

Address 0	Address 1	Address 2	NSP Address	Command Port	Telemetry Port
Short	Short	Short	0x40	RS485_0	RS485_1
Short	Short	Short	0x50	RS485_1	RS485_1
Short	Short	Short	0x60	RS485_0	RS485_0
Short	Short	Short	0x70	RS485_1	RS485_0
Open	Short	Short	0x41	RS485_0	RS485_1
Open	Short	Short	0x51	RS485_1	RS485_1
Open	Short	Short	0x61	RS485_0	RS485_0
Open	Short	Short	0x71	RS485_1	RS485_0
Short	Open	Short	0x42	RS485_0	RS485_1
Short	Open	Short	0x52	RS485_1	RS485_1
Short	Open	Short	0x62	RS485_0	RS485_0
Short	Open	Short	0x72	RS485_1	RS485_0
Open	Open	Short	0x43	RS485_0	RS485_1
Open	Open	Short	0x53	RS485_1	RS485_1
Open	Open	Short	0x63	RS485_0	RS485_0
Open	Open	Short	0x73	RS485_1	RS485_0
Short	Short	Open	0x44	RS485_0	RS485_1
Short	Short	Open	0x54	RS485_1	RS485_1
Short	Short	Open	0x64	RS485_0	RS485_0
Short	Short	Open	0x74	RS485_1	RS485_0
Open	Short	Open	0x45	RS485_0	RS485_1
Open	Short	Open	0x55	RS485_1	RS485_1
Open	Short	Open	0x65	RS485_0	RS485_0
Open	Short	Open	0x75	RS485_1	RS485_0
Short	Open	Open	0x46	RS485_0	RS485_1
Short	Open	Open	0x56	RS485_1	RS485_1
Short	Open	Open	0x66	RS485_0	RS485_0
Short	Open	Open	0x76	RS485_1	RS485_0
Open	Open	Open	0x47	RS485_0	RS485_1
Open	Open	Open	0x57	RS485_1	RS485_1
Open	Open	Open	0x67	RS485_0	RS485_0

Open	Open	Open	0x77	RS485_1	RS485_0
------	------	------	------	---------	---------

Short = Address pin shorted to Secondary Return in the harness

Open = Address pin left unconnected

In the normal spacecraft configuration with four reaction wheels, it is advised that the following addresses be used:

- X1
- X2
- X4
- X7

In the event of a failure of any one address input pin or harness straps the wheel will go to one of these addresses:

- X0
- X3
- X5
- X6

Thus, a single failure will never place two wheels at identical addresses.

5.3.5 Message Control Fields

Table 11: Message Control Field

Bit	Description
7 (MSB)	“Poll/Final” Bit
6	“B” Bit
5	“ACK” Bit
4-0	Command Code

The message control field packs four values into a single byte. The command code is an enumerated value between 0x00 and 0x1F that determines how the data field should be interpreted.

The “ACK” bit is ignored on commands coming into the wheel. On telemetry reply messages sent by the wheel it is set to indicate successful execution of the command, or cleared to indicate that the command cannot be executed.

The “B” bit is copied unchanged from a command message into its reply message. The wheel does not use it internally.

The “Poll/Final” bit is interpreted differently for command and telemetry messages. For a command, the bit is “Poll”. If it is set to ‘1’ then the wheel will generate a telemetry message in reply. If it is cleared to ‘0’ then the command will be executed, but no response telemetry message will be sent.

For a telemetry message, the bit is “Final”. If a reply consists of a single telemetry message, then the bit is set to ‘1’. If a reply is too large to fit into a single message then the final message has the bit set to ‘1’ and the others have the bit cleared to ‘0’.

5.3.6 Data Field

The interpretation of the data field is dependent on the command code in the message control field. Some command codes may have no data, some may require a certain fixed number of data bytes, and some can accept a variable data length.

5.3.7 Message CRC

Each NSP message contains a 2 byte (16-bit) CRC to guard against errors in transmission. The 16-bit CCITT polynomial is used: $x^{16} + x^{12} + x^5 + 1$. The initial shift register value is 0xFFFF. Bytes are fed into the CRC computation starting with the destination address, and concluding with the last byte of the data field. Within a byte, bits are fed in LSB first.

The following fragment of C code, courtesy of Henry Spencer, illustrates how the CRC can be computed.

```
#define POLY 0x8408 /* bits reversed for LSB-first */  
  
unsigned short crc = 0xffff;  
  
while (len-- > 0) {  
    unsigned char ch = *bufp++;  
    for (i = 0; i < 8; i++) {  
        crc = (crc >> 1) ^ ((ch ^ crc) & 0x01 ? POLY : 0);  
        ch >>= 1;  
    }  
}
```

5.3.8 Error Conditions

The wheel will ignore NSP command messages where the destination address does not correspond to its own NSP address. NSP messages with invalid CRC, invalid encapsulation, too short or too long are also ignored. In none of these cases will any reply message be generated.

If an NSP command message is in error due to an unknown command code, or if the data field is not consistent with the requirements of the command code, and if the “Poll” bit is set, then a NACK reply message will be generated. This message will be the same length as the command message, and contain the same data field. The command code will be the same, as will the “B” bit. The “ACK” bit will be cleared to ‘0’.

5.4 Protocol Layer 5 (Session Layer)

5.4.1 Operating Modes

Power-on starts the unit in bootloader mode.

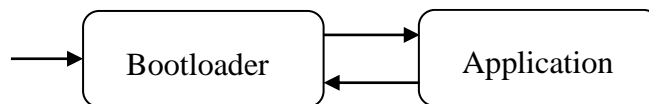


Figure 2: Mode Transition Diagram

5.4.1.1 Bootloader to Application Transition

The wheel will transition from bootloader to application mode upon receipt of an “INIT 0x20050000” command.

5.4.1.2 Application to Bootloader Transition

Any transition from application mode to bootloader mode is accomplished through a processor reset. Reset is caused by the following conditions:

- An undervoltage is detected on Primary Power
- An overvoltage is detected on Primary Power
- An "INIT" command with no data is received.
- An exception or unexpected interrupt occurs

5.4.2 Byte Order

All multi-byte values transported in the data field of NSP messages are in little-endian format. That is, the least-significant byte is stored first, and the most-significant byte is stored last.

5.4.3 Command Codes

Table 12: Command Codes

Hex Value	Command	Bootloader	Application
0x00	PING	Yes	Yes
0x01	INIT	Yes	Yes
0x02	PEEK	Yes	Yes
0x03	POKE	Yes	Yes
0x04	DIAGNOSTIC	Yes	Yes
0x06	CRC	Yes	Yes
0x07	READ FILE	No	Yes
0x08	WRITE FILE	No	Yes
0x09	READ EDAC	No	Yes
0x0A	WRITE EDAC	No	Yes
0x0B	GATHER EDAC	No	Yes

The table above shows the command codes that can be used by the host spacecraft to communicate with the wheel.

5.4.3.1 Ping (0x00)

The PING command is typically used during testing to verify communications. Incoming data is ignored. The reply packet contains a human-readable text string containing:

- The type of device and the manufacturer
- The name, version and build of the software that is currently running on the target processor.

Table 13: Command Format

Byte	Description
Bytes 0 – N	Zero or more bytes, ignored by the NSP module

Table 14: Reply Format

Byte	Description
Bytes 0 – N	Human-readable ASCII string. No NULL termination.

5.4.3.2 INIT (0x01)

The INIT command is used to change the operating mode of a wheel. In all cases, if a reply has been requested (“Poll” bit set to ‘1’) then the reply will be sent before the processor state is changed.

The wheel will respond to an INIT with no data by completely resetting the device, returning to bootloader mode. If it is in bootloader mode, it will respond to an INIT with 4 bytes of data by running an Application Module at the corresponding address.

As a special case, the command INIT 0xDEADBEEF is used once in the factory to write-protect the bootloader FRAM. The bootloader FRAM can only be unlocked by issuing a POKE while the /WP pin on the test connector is held high.

An INIT command with an address will be NACKed if the device is not in bootloader mode.

An INIT command with an address in the bootloader or user FRAM will cause an application image to be loaded from FRAM into RAM (see application image section for format). Once the application has been loaded, the processor will branch to the specified starting point and run the program. In the special case where the starting point is zero, no jump will be made and the processor will remain in bootloader mode.

An INIT command with an address in either RAM area will cause a program branch to that address. It is assumed that a program resides at that address: either copied from FRAM by a previous command, or loaded from the first 128 kB of bootloader FRAM on a reset, or loaded directly from a series of POKEs.

Table 15: Normal Command Format

Byte	Description
Bytes 0 – 3	32-bit integer address of program to start

Table 16: Reboot Command Format

Byte	Description
	No payload bytes

Table 17: Normal Reply Format

Byte	Description
Bytes 0 – 3	32-bit integer address of program to be started

Table 18: Reboot Reply Format

Byte	Description
	No payload bytes

5.4.3.3 PEEK (0x02)

The PEEK command is used to read the device memory. Short and long formats of this command are available for historical reasons. Short commands can be distinguished from long commands by their lengths.

PEEK access to FRAM can be of any length, and without alignment restriction, provided it does not cross the boundary from bootloader FRAM to user FRAM. PEEKs to other memory areas must obey one of the following restrictions:

- Length = 1
- Length = 2, aligned to even address
- Length = 4*N, aligned to multiple of 4

PEEKs to unimplemented memory locations may be expected to generate hardfault exceptions

Table 19: Short Command Format

Byte	Description
Bytes 0 – 3	32-bit address to start peeking data
Byte 4	Number of bytes to read. A value of 0 indicates that 256 bytes should be read.

Table 20: Long Command Format

Byte	Description
Bytes 0 – 3	32-bit address to start peeking data
Byte 4 – 5	Number of bytes to read.

Table 21: Reply Format

Byte	Description
Bytes 0 – 3	32-bit address of the start of data
Bytes 4 – N	One or more bytes read from the target memory

5.4.3.4 POKE (0x03)

The POKE command is used to write the device memory.

POKE access to FRAM can be of any length, and without alignment restriction, provided it does not cross the boundary from bootloader FRAM to user FRAM. POKEs to other memory areas must obey one of the following restrictions:

- Length = 1
- Length = 2, aligned to even address
- Length = 4*N, aligned to multiple of 4

POKEs to unimplemented memory locations may be expected to generate hardfault exceptions. POKEs to write-protected FRAM will not generate any sort of error return, but the target memory will not be altered.

Table 22: Command Format

Byte	Description
Bytes 0 – 3	32-bit address to start poking data
Bytes 4 – N	1 - 256 bytes to write to the target memory

Table 23: Reply Format

Byte	Description
Bytes 0 – 3	32-bit address where data write began
Bytes 4 – N	1 – 256 bytes written to the target memory

5.4.3.5 DIAGNOSTIC (0x04)

The DIAGNOSTIC command gathers error count data from the wheel.

Table 24: Command Format

Byte	Description
Bytes 0 – N	Address of the diagnostic channel to read, as an 8-bit integer

Table 25: Reply Format

Byte	Description
Bytes 0 – N	List of one or more diagnostic result structures

Table 26: Diagnostic Result Structure Format

Byte	Description
Byte 0	Address of the diagnostic channel read, as an 8-bit integer
Bytes 1 – 4	Diagnostic value from the addressed channel, generally as a 32-bit integer

5.4.3.6 CRC (0x06)

CRC command is used to calculate a checksum on an area of flash memory. The CRC uses the same 16-bit polynomial, with the same bit order, as is used for NSP messages.

CRC addresses are not restricted as to alignment, for any of the memory areas. A CRC must not cover both bootloader FRAM and user FRAM. CRC access to unimplemented memory can be expected to generate hardfault exceptions.

The CRC command can potentially be used to request the CRC of the wheel's entire memory. The worst case would be the CRC of a 256 kB FRAM chip which takes 340 msec from command to reply (assuming no additional realtime processor load from the application program). The application control loop may be stalled during this time, preventing fine speed control.

Table 27: Command Format

Byte	Description
Bytes 0 – 3	Address of the first byte to CRC as 32-bit integer
Bytes 4 – 7	Address of the last byte to CRC as 32-bit integer

Table 28: Reply Format

Byte	Description
Bytes 0 – 3	Address of the first byte in CRC as 32-bit integer
Bytes 4 – 7	Address of the last byte in CRC as 32-bit integer

Byte	Description
Bytes 8 – 9	CRC result as 16-bit integer

5.4.3.7 READ FILE (0x07)

The Read File command returns one or more “files”, which are four consecutive bytes of EDAC protected memory. A read from address 0 is a special case, and an additional mode byte is returned.

Note that because of the single byte of addressing, not all of the EDAC memory can be accessed by this command.

When multiple telemetry files are read by a single command, they are guaranteed to be internally consistent (i.e. from the same control frame). Files can be read in any order, and a single file can be read multiple times.

Table 29: Command Format

Byte	Description
Bytes 0	EDAC address divided by 4 (0 – 255). 0 for mode, 1 – 255 for normal.

Table 30: Reply Format

Byte	Description
Bytes 0 – N	List of File Reply structures. The first byte of each structure determines its type.

Table 31: Normal Reply Structure

Byte	Description
Byte 0	Non-zero EDAC address divided by 4 (1 – 255)
Bytes 1 – 4	EDAC data bytes read from memory

Table 32: Mode Reply Structure

Byte	Description
Byte 0	0
Byte 1	Command type read from EDAC
Bytes 2 – 5	Command value read from EDAC

5.4.3.8 WRITE FILE (0x08)

The Write File command stores one “files”, which are four consecutive bytes of EDAC protected memory. A write to address 0 is a special case, and an additional mode byte is stored.

Note that because of the single byte of addressing, not all of the EDAC memory can be accessed by this command.

When multiple parameter files are written by a single command, they are guaranteed to be internally consistent (i.e. into the same control frame). Files can be written in any order, and a single file can be written multiple times.

If a Write File command fails due to improper formatting then no modification to EDAC memory is made.

Table 33: Command and Reply Format

Byte	Description
Bytes 0 – N	List of File Store (Reply) structures. The first byte of each structure determines its type.

Table 34: Normal Store Structure

Byte	Description
Byte 0	Non-zero EDAC address divided by 4 (1 – 255)
Bytes 1 – 4	Data bytes to write to EDAC memory

Table 35: Mode Store Structure

Byte	Description
Byte 0	0
Byte 1	Command type to store
Bytes 2 – 5	Command value to store

Table 36: Normal Reply Structure

Byte	Description
Byte 0	Non-zero EDAC address divided by 4 (1 – 255)
Bytes 1 – 4	EDAC data bytes read from memory

Table 37: Mode Reply Structure

Byte	Description
Byte 0	0
Byte 1	Command type read from EDAC
Bytes 2 – 5	Command value read from EDAC

5.4.3.9 READ EDAC (0x09)

The Read EDAC command returns bytes from EDAC memory. The read process is atomic. Long and short command formats are available.

Table 38: Short Command Format

Byte	Description
Bytes 0 – 1	EDAC address to start reading
Byte 2	Number of bytes to read. A value of 0 indicates that 256 bytes should be read.

Table 39: Long Command Format

Byte	Description
Bytes 0 – 1	EDAC address to start reading
Bytes 2 – 3	Number of bytes to read.

Table 40: Reply Format

Byte	Description
Bytes 0 – 1	EDAC address where reading started
Bytes 2 – N	The data bytes read from EDAC memory

5.4.3.10 WRITE EDAC (0x0A)

The Write EDAC command writes bytes into EDAC memory. The write process is atomic.

Table 41: Command Format

Byte	Description
Bytes 0 – 1	EDAC address to start reading
Bytes 2 – N	Data bytes to write to EDAC memory

Table 42: Reply Format

Byte	Description
Bytes 0 – 1	EDAC address where reading started
Bytes 2 – N	The data bytes written to EDAC memory

5.4.3.11 GATHER EDAC (0x0B)

The Gather EDAC command allows multiple separate ranges of EDAC memory to be read in an atomic manner.

Table 43: Command Format

Byte	Description
Bytes 0 – N	List of gather command structures

Table 44: Gather Command Structure

Byte	Description
Bytes 0 – 1	EDAC address to start reading
Bytes 2 – 3	Number of bytes to read

Table 45: Reply Format

Byte	Description
Bytes 0 – N	List of gather result structures

Table 46: Gather Result Structure

Byte	Description
Bytes 0 – 1	EDAC address where reading started
Bytes 2 – 3	Number of bytes read
Bytes 4 – N	Data bytes

5.5 Protocol Layer 6 (Presentation Layer)

5.5.1 Fault Handling

The application program can detect several different fault conditions:

- Over temperature and under temperature
- Rotor overspeed
- Motor overcurrent
- Hall sensor error
- Temperature delta

For all faults, except hall sensor error, the fault threshold (temperature, speed, current) can be adjusted. A Hall sensor error is declared when the HALL_IMPOSSIBLE or HALL_SKIP count increments. Each of these fault conditions sets a unique fault flag. Each fault can be masked.

If an unmasked fault occurs, the motor drive is turned off. The rotor will slowly coast to a halt under friction alone.

The user can detect a fault by reading FLAGS_ACTIVE. The user can clear a fault by writing '0' to the corresponding fault flag. Once all fault flags are clear or masked, the wheel will resume normal function.

Users are cautioned against clearing or masking faults without understanding the cause. The fault logic exists to protect the hardware. For example, running at high torque with the overtemperature faults masked risks damaging the motor from overheat.

5.5.2 Memory Map

Table 47: Processor Memory Map

Address Range	Function
0x00000000 – 0x0003FFFB	Program RAM
0x0003FFFC – 0x0003FFFF	Program RAM ECC trap word
0x20000000 – 0x2003FFFF	Bootloader FRAM
0x20040000 – 0x2007FFFF	User FRAM
0x40000000 – 0x4002F000	Hardware registers
0x5FFF8000 – 0x5FFFFFFB	Data RAM0
0x5FFFFFFC – 0x5FFFFFFF	Data RAM0 ECC trap word
0x60000000 – 0x60007FFB	Data RAM1
0x60007FFC – 0x60007FFF	Data RAM1 ECC trap word

The supervisor memory can be directly accessed with PEEK and POKE commands, and CRCs calculated with CRC commands. It is represented as a single 32-bit memory space, sparsely populated.

Note that the memory-map used for the serial commands differs from the internal CPU memory map, to accommodate the FRAM. This is mapped at address 0x20000000 for compatibility with existing tooling. The CPU memory at that address internally has been remapped to 0x60000000.

5.5.2.1 Program RAM

Code is executed from this memory. At reset the first 256 kB of bootloader FRAM is copied into program RAM.

5.5.2.2 Data RAM

Data RAM0 is used for bootloader and stack. It is cleared to 0 at power-up and after a reset. Data RAM1 is free for application data.

5.5.2.3 Bootloader FRAM

This non-volatile memory is programmed at the factory, and then write-protected. Starting at the lowest address it stores the bootloader. It may also store application programs and/or special test programs. The bootloader FRAM cannot be changed by the user.

5.5.2.4 User FRAM

This non-volatile memory will be delivered from the factory with the application program loaded. The program can be patched or replaced at any time using a sequence of POKE commands. This permits software updates after delivery, and even on-orbit.

5.5.2.5 Application Images

Application image structures are stored in FRAM, to be loaded and executed by INIT commands. The format is:

Table 48: Application Image Structure

Offset	Length	Function
0x00	4	RAM target address (32-bit unsigned integer)
0x04	4	Data length (32-bit unsigned integer)
0x08	4	Start address (32-bit unsigned integer)
0x0C	Variable	1 or more bytes of image data

When an INIT command is executed on an application image the processor will copy a number of bytes equal to “Data length” from the “image data” field to the “RAM target address”. It will then branch to the start address, which should be a pointer into RAM. In the special case that the start address is zero, no branch is made.

No integrity checks are made on the image format. Bad data (target address outside of RAM, data length too long, etc) will result in faults.

Two copies of the application image are stored on the wheel, one in the bootloader FRAM, one in the user FRAM. The image in the user FRAM is the preferred copy and is used when the wheel is initialized to address 0x20050000. The application image in the bootloader FRAM can be used by initializing to address 0x00002000.

5.5.2.6 Error Mitigation

The RAM areas are protected from Single Event Upset (SEU) by hardware Error Correcting Codes (ECC). Each 8-bit byte is stored along with a 5-bit syndrome code. When the byte is read, the syndrome is re-calculated. Single-bit errors are automatically and transparently corrected and fixed. Multi-bit errors cannot be fixed. Both RAM areas are hardware scrubbed on a timescale of seconds.

The FRAM areas are protected by a hardware power switch. Whenever FRAM is not being used it is powered down. When FRAM is required the switch is turned ON and a 1 msec delay is observed before access. In typical orbital use the FRAM is turned ON for 380 msec after every reset, and is then OFF for normal operation.

5.5.2.7 ECC Trap Words

The last words in the RAM areas have their ECC compromised, as the stored syndrome code is always '0'. When the stored word is '0', the ECC shows no errors. If a byte with a single '1' bit is written, a single-bit error is simulated. ECC hardware will correct the error. If a byte with two '1' bits is written, a multi-bit error is simulated. ECC hardware will count the error, but will be unable to correct it.

The trap words can be used on the ground for self-test purposes. These words should not be used for actual data storage.

5.5.3 Diagnostics

The diagnostics contain a series of read-only integers that relate to the health of the wheel.

Table 49: Diagnostic Channels

Channel	Function	Format
0x02	Data RAM0 SEU count	16-bit unsigned integer x 2 Low bytes: Single bit error count High bytes: Multi bit error count
0x03	Program RAM SEU count	16-bit unsigned integer x 2 Low 2 bytes: Single bit error count High 2 bytes: Multi bit error count
0x04	Bootloader retries count (from most recent reset)	Byte 0: 8-bit unsigned integer Bytes 1-3: '0'
0x05	Serial number	32-bit unsigned integer Unique, but maybe not sequential
0x06	FRAM status bytes	Byte 0: Bootloader FRAM status Byte 1: User FRAM status Bytes 2-3: '0'
0x07	RS485-0 NSP Framing error count	32-bit unsigned integer
0x08	RS485-0 Runt count	32-bit unsigned integer
0x09	RS485-0 Oversize count	32-bit unsigned integer
0x0A	RS485-0 Bad CRC count	32-bit unsigned integer
0x0B	RS485-0 FIFO overflow count	32-bit unsigned integer
0x0C	RS485-0 Incoming discarded count	32-bit unsigned integer
0x0D	RS485-0 Outgoing discarded count	32-bit unsigned integer
0x0E	RS485-1 NSP Framing error count	32-bit unsigned integer
0x0F	RS485-1 Runt count	32-bit unsigned integer
0x10	RS485-1 Oversize count	32-bit unsigned integer
0x11	RS485-1 Bad CRC count	32-bit unsigned integer
0x12	RS485-1 FIFO overflow count	32-bit unsigned integer
0x13	RS485-1 Incoming discarded count	32-bit unsigned integer
0x14	RS485-1 Outgoing discarded count	32-bit unsigned integer
0x1F	Data RAM1 SEU count	16-bit unsigned integer x 2 Low bytes: Single bit error count High bytes: Multi bit error count
0x20	EF_ID1	32-bit unsigned integer
0x21	Uptime counter	Centi-sec (32-bit unsigned integer)

Channel	Function	Format
0x22	RTC high word	32-bit unsigned integer
0x23	RS485-0 Incoming count	32-bit unsigned integer
0x24	RS485-0 Outgoing count	32-bit unsigned integer
0x28	RS485-1 Incoming count	32-bit unsigned integer
0x29	RS485-1 Outgoing count	32-bit unsigned integer

FRAM status bytes can be expected as:

Byte Value	Description
0x40	FRAM chip is unlocked
0xCC	FRAM chip is write-protected

RS485 port error counters are zeroed at power-on and any reset

5.5.4 EDAC Memory

For historical reasons, the memory area used to store commands and telemetry is referred to as “EDAC Memory”. In older wheels, this special area was subject to software-based triple-voting and scrubbing. In the new RW4 wheel every single flip-flop is protected against upset. There is no more or less protection for the EDAC Memory, but the name is preserved.

The memory area is 1536 bytes long. EDAC memory can be read with READ EDAC, GATHER EDAC and READ FILE commands, and written with WRITE EDAC and WRITE FILE commands. The MODE_STORE command will save EDAC memory into non-volatile User FRAM. While the overlap between EDAC and FILE addresses is maintained for historical compatibility, it is recommended to use the READ_FILE and WRITE_FILE commands (rather than *EDAC commands) for the floating-point values in the first 1024 bytes.

Table 50: EDAC Memory Contents

EDAC Address	File Address	Function	Format
0x000 – 0x003	0x00	Command Value	Command Dependent
0x00C – 0x00F	0x03	VBUS	Volts (IEEE-754)
0x01C – 0x01F	0x07	VDD	Volts (IEEE-754)
0x020 – 0x023	0x08	VCC	Volts (IEEE-754)
0x024 – 0x027	0x09	6V	Volts (IEEE-754)
0x040 – 0x043	0x10	TEMP0	°C (IEEE-754)
0x044 – 0x047	0x11	TEMP1	°C (IEEE-754)
0x048 – 0x04B	0x12	TEMP2	°C (IEEE-754)
0x04C – 0x04F	0x13	TEMP3	°C (IEEE-754)
0x050 – 0x053	0x14	TEMP_MCU	°C (IEEE-754)
0x054 – 0x057	0x15	SPEED	Rad/sec (IEEE-754)
0x058 – 0x05B	0x16	MOMENTUM	N-m/sec (IEEE-754)
0x068 – 0x06B	0x1A	PWM	Duty cycle (IEEE-754)
0x06C – 0x06F	0x1B	HALL_DIGITAL	Enum in IEEE-754 float
0x080 – 0x083	0x20	SPEED_P_GAIN	Amps / rad / sec (IEEE-754)
0x084 – 0x087	0x21	SPEED_I_GAIN	Amps / rad (IEEE-754)
0x088 – 0x08B	0x22	SPEED_D_GAIN	Amps / rad / sec ² (IEEE-754)
0x094 – 0x097	0x25	MAX_GAIN_SPEED	Rad/sec (IEEE-754)
0x098 – 0x09B	0x26	MIN_GAIN_SPEED	Rad/sec (IEEE-754)
0x0A0 – 0x0A3	0x28	INERTIA	kg-m ² (IEEE-754)

EDAC Address	File Address	Function	Format
0x0A4 – 0x0A7	0x29	MOTOR_KT	N-m/A (IEEE-754)
0x0A8 – 0x0AB	0x2A	GAIN_SCHEDULE1	(IEEE-754)
0x0AC – 0x0AF	0x2B	GAIN_SCHEDULE2	(IEEE-754)
0x0B0 – 0x0B3	0x2C	GAIN_SCHEDULE3	(IEEE-754)
0x0B4 – 0x0B7	0x2D	GAIN_SCHEDULE4	(IEEE-754)
0x0B8 – 0x0BB	0x2E	PROPORTIONAL_OVERRIDE	(IEEE-754)
0x0BC – 0x0BF	0x2F	CONTROL_TYPE	(IEEE-754)
0x0C8 – 0x0CB	0x32	MAX_SPEED_AGE	sec (IEEE-754)
0x0CC – 0x0CF	0x33	LIMIT_SPEED	Rad/sec (IEEE-754)
0x0D4 – 0x0D7	0x35	LIMIT_CURRENT	Amps (IEEE-754)
0x0E4 – 0x0E7	0x39	MOTOR_RESISTANCE	Ohms (IEEE-754)
0x0EC – 0x0EF	0x3B	SINUSOID_PHASE	Rad (IEEE-754)
0x0F0 – 0x0F3	0x3C	SINUSOID_FREQ	Hz (IEEE-754)
0x0F4 – 0x0F7	0x3D	SINUSOID_OFFSET	Rad/sec or Volts (IEEE-754)
0x100 – 0x103	0x40	PREVIOUS_SPEED	Rad/sec (IEEE-754)
0x104 – 0x107	0x41	SPEED_INTEGRATOR	Amps (IEEE-754)
0x108 – 0x10B	0x42	SPEED_LAST_ERROR	Rad/sec (IEEE-754)
0x10C – 0x10F	0x43	ACCEL_TARGET	Rad/sec (IEEE-754)
0x12C – 0x12F	0x4B	TORQUE_T0	Nm (IEEE-754)
0x130 – 0x133	0x4C	TORQUE_T1	Nm (IEEE-754)
0x134 – 0x137	0x4D	TORQUE_T2	Nm (IEEE-754)
0x138 – 0x13B	0x4E	TORQUE_T3	Nm (IEEE-754)
0x13C – 0x13F	0x4F	TORQUE_T4	Nm (IEEE-754)
0x168 – 0x16B	0x5A	SLEEP_DUTY	Fraction (IEEE-754)
0x16C – 0x16F	0x5B	DCDC_FREQ	Hz (IEEE-754)
0x178 – 0x17B	0x5E	DRIVE_FREQ	Hz (IEEE-754)
0x17C – 0x17F	0x5F	DCDC_SLOPE	
0x180 – 0x183	0x60	DCDC_OFFSET	
0x184 – 0x187	0x61	RESPONSE_AMPLITUDE	Rad/sec (IEEE-754)
0x188 – 0x18B	0x62	RESPONSE_PHASE	Rad (IEEE-754)
0x190 – 0x193	0x64	KT_ESTIMATE	N-m/A (IEEE-754)
0x194 – 0x197	0x65	R_ESTIMATE	Ohms (IEEE-754)
0x198 – 0x19B	0x66	DV_ESTIMATE	Volts (IEEE-754)
0x19C – 0x19F	0x67	DRY_FRICTION_ESTIMATE	Nm (IEEE-754)
0x1A0 – 0x1A3	0x68	WET_FRICTION_ESTIMATE	N-m/rad/sec (IEEE-754)
0x1A4 – 0x1A7	0x69	AERO_FRICTION_ESTIMATE	N-m/rad ² /sec ² (IEEE-754)
0x1A8 – 0x1AB	0x6A	RUNDOWN_TIME	sec (IEEE-754)
0x1C0 – 0x1C3	0x70	FAULT_OVERTEMPO	°C (IEEE-754)
0x1C4 – 0x1C7	0x71	FAULT_UNDERTEMP2	°C (IEEE-754)
0x1C8 – 0x1CB	0x72	FAULT_OVERTEMP3	°C (IEEE-754)
0x1CC – 0x1CF	0x73	FAULT_TEMP_DELTA	°C (IEEE-754)
0x1D0 – 0x1D3	0x74	FAULT_OVERSPEED	Rad/sec (IEEE-754)
0x1D4 – 0x1D4	0x75	FAULT_OVERCURRENT	Amps (IEEE-754)
0x200 – 0x203	0x80	TEMP_R0	Ohms (IEEE-754)
0x204 – 0x207	0x81	TEMP_R2	Ohms (IEEE-754)
0x208 – 0x20B	0x82	TEMP_R3	Ohms (IEEE-754)

EDAC Address	File Address	Function	Format
0x20C – 0x20F	0x83	ADC_RAW_VBUS	Ratio (IEEE-754)
0x3C0 – 0x3C3	0xF0	RESERVED	32-bit unsigned int
0x3C4 – 0x3C7	0xF1	RESERVED	32-bit unsigned int
0x3C8 – 0x3CB	0xF2	RESERVED	32-bit unsigned int
0x5C3		MODE	8-bit enum
0x5CE		HALL_IMPOSSIBLE	8-bit unsigned int
0x5CF		HALL_SKIP	8-bit unsigned int
0x5D0		CONTROL_OVERFLOW	8-bit unsigned int
0x5D1		SPEED_TABLE_SIZE	8-bit unsigned int
0x5D2		USED_TABLE_SIZE	8-bit unsigned int
0x5D6		IDLE_INHIBIT	8-bit boolean
0x5D7		FLAGS_ACTIVE	8-bit bitmap
0x5D8		FAULTS_MASK	8-bit bitmap
0x5D9		FLAG_OVERTEMP0	8-bit boolean
0x5DA		FLAG_UNDERTEMP2	8-bit boolean
0x5DB		FLAG_OVERTEMP3	8-bit boolean
0x5DC		FLAG_TEMP_DELTA	8-bit boolean
0x5DD		FLAG_OVERSPEED	8-bit boolean
0x5DE		FLAG_OVERCURRENT	8-bit boolean
0x5DF		FLAG_HALL_ERROR	8-bit boolean
0x5E0		HALT	8-bit boolean
0x5E1		RESET_ENABLE	8-bit bitmap
0x5E2		RESERVED	8-bit bitmap
0x5E3		STARTUP_DELAY	8-bit integer
0x5E4		LOCKUP	8-bit boolean

5.5.4.1 Command Value

Accessing file 0 causes an extra mode byte to be transferred. By writing to this file the mode of the wheel can be commanded. By reading this file the current mode can be determined.

If this parameter is accessed through EDAC writes and reads instead of file reads and writes there is no explicit mode byte transferred. It is possible to read and write the number associated with the command, but this is not advised.

5.5.4.2 VBUS

This read-only parameter returns the voltage on the primary power bus. It is inferred by measuring the duty cycle of the DC/DC converter.

5.5.4.3 VDD

This read-only parameter returns the voltage on the +1.6 V nominal secondary output from the DC/DC converter.

5.5.4.4 VCC

This read-only parameter returns the voltage on the +3.3 V nominal secondary output from the DC/DC converter

5.5.4.5 TEMP[0|1]

These read-only parameters return the temperature of the motor windings.

The sensors are NTC devices, so an open-circuit failure causes an apparent low temperature reading.

5.5.4.6 TEMP[2|3]

These read-only parameters return temperatures on the circuit board. TEMP2 is located immediately next to the processor. TEMP3 is located adjacent to the motor drive transistors.

5.5.4.7 TEMP_MCU

This read-only parameter returns the temperature of the MCU. The sensor is internal to the MCU.

5.5.4.8 SPEED

This read-only parameter returns the speed of the rotor.

5.5.4.9 MOMENTUM

This read-only parameter returns the angular momentum of the rotor. It is derived from the SPEED multiplied by INERTIA.

5.5.4.10 PWM

This read-only parameter returns the commanded duty cycle of the PWM signal to the motor drivers.

5.5.4.11 HALL_DIGITAL

The wheel has three Hall-effect sensors (numbered 0 to 2), each one generating a binary value. The value of these three bits is encoded into this parameter.

Table 51: Hall_Digital Bitfield

Hall 2	Hall 1	Hall 0	HALL_DIGITAL
0	0	0	0.0
0	0	1	1.0
0	1	0	2.0
0	1	1	3.0
1	0	0	4.0
1	0	1	5.0
1	1	0	6.0
1	1	1	7.0

5.5.4.12 SPEED_[P|I|D]_GAIN

These read-only parameters set the gains for the PID closed-loop speed controller. See CONTROL_TYPE for the formula to determine the gains.

5.5.4.13 MIN_GAIN_SPEED, MAX_GAIN_SPEED

These read/write parameters bound the speed used as an input to the speed controller gain formula.

By setting these two parameters to the same value the speed dependence of the gains can be effectively disabled.

5.5.4.14 INERTIA

This read/write parameter sets the rotor inertia. It is used to scale between acceleration and torque, and momentum and speed.

5.5.4.15 MOTOR_KT

This read/write parameter sets the motor torque constant.

5.5.4.16 GAIN_SCHEDULE[1..4]

These four read/write parameters are used to set the speed control gains, in those cases when PROPORTIONAL_OVERRIDE is zero. First, the characteristic speed ω is determined based on the actual and setpoint speeds and on MAX_GAIN_SPEED and MIN_GAIN_SPEED.

$$\omega = \text{MIN}\left(\text{MAX}\left(\left|\omega_{\text{actual}}\right|, \left|\omega_{\text{target}}\right|, \omega_{\text{MIN}}\right), \omega_{\text{MAX}}\right)$$

The critical gain and period are modeled as a function of the characteristic speed. The four GAIN_SCHEDULE parameters are written as G1..G4.

$$Ku = G2 \cdot \omega^{G1}$$

$$Pu = G4 \cdot \omega^{G3}$$

5.5.4.17 PROPORTIONAL_OVERRIDE

This read/write parameter is used to override the gain settings, usually in a factory gain tuning context. When non-zero, the gains are set accordingly:

$$Kp = \text{PROPORTIONAL_OVERRIDE}$$

$$Ki = 0.0$$

$$Kd = 0.0$$

5.5.4.18 CONTROL_TYPE

This read/write parameter is used to determine the control type, using the Ziegler-Nichols method.

The value stored in CONTROL_TYPE is truncated to an integer.

If the value is negative, then SPEED_P_GAIN, SPEED_I_GAIN and SPEED_D_GAIN are read-write parameters, set by the user.

If the value is 1, a PI controller is used:

$$Kp = 0.45 \cdot Ku$$

$$Ki = 1.2 \cdot Kp / Pu$$

$$Kd = 0.0$$

If the value is 2, a PID controller is used:

$$Kp = 0.6 \cdot Ku$$

$$Ki = 2.0 \cdot Kp / Pu$$

$$Kd = 0.125 \cdot Kp Pu$$

In the case of any other value, a P controller is used:

$$Kp = 0.5 \cdot Ku$$

$$Ki = 0.0$$

$$Kd = 0.0$$

5.5.4.19 MAX_SPEED_AGE

This read/write parameter determines which digital Hall sensor transitions are used to determine the SPEED telemetry. Transitions are discarded if they are older than MAX_SPEED_AGE in time, if a complete rotor revolution has occurred since them, or if a rotor direction reversal is detected.

MAX_SPEED_AGE is relevant at very low rotor speeds. A larger value will allow more Hall sensor transitions to be used, giving a less noisy speed estimate. However, it will also increase the latency in speed measurements which may cause closed-loop speed control modes to become unstable.

5.5.4.20 LIMIT_SPEED

This read/write parameter sets the maximum speed that closed-loop modes will target. The magnitude of the speed target used in speed, torque, momentum and acceleration modes is clamped to this value. This is particularly significant in torque and acceleration modes – if communication with the flight computer is lost for any reason the rotor will slowly accelerate until this limit is reached.

5.5.4.21 LIMIT_CURRENT

This read/write parameter sets the greatest motor drive current used by closed-loop modes. Reducing this value will limit the torque that the wheel can generate.

5.5.4.22 MOTOR_RESISTANCE

This read/write parameter sets the motor nominal resistance.

5.5.4.23 SINUSOID_[PHASE, FREQ, OFFSET]

Please see SINUSOID mode for details

5.5.4.24 PREVIOUS_SPEED

This read-only parameter contains the SPEED file from the previous control frame. It is expected that it might be used in the future to generate torque telemetry, but at present it is unused.

5.5.4.25 SPEED_INTEGRATOR

This parameter contains the closed-loop controller integrator, scaled in amps of actuation. It is technically a read/write parameter, and it is possible for the user to write this for test purposes.

5.5.4.26 SPEED_LAST_ERROR

This read-only parameter contains the controller error from the previous control frame. It is used with the differential gain term of the closed-loop controller.

5.5.4.27 ACCEL_TARGET

This parameter contains the speed setpoint used by the acceleration controller. The controller will add the acceleration to this file each frame. It is technically a read/write parameter, and it is possible for the user to write this as a way to force a new speed while remaining in acceleration/torque mode.

5.5.4.28 TORQUE_[T0..T4]

These five read-only parameters record the instantaneous torques measured in the last five control frames. T0 is the result of the most recent control frame. T4 is four frames old. The torque is computed as:

$$\text{TORQUE} = \text{INERTIA} * (\text{SPEED} - \text{PREVIOUS_SPEED}) * 100 \text{ Hz}$$

Torque telemetry at low speed should be used with caution. The speed estimate is only updated when new hall sensor pulses are seen (or a very long period elapses). If there has been no hall sensor pulse in the previous control frame then $\text{SPEED} == \text{PREVIOUS_SPEED}$ and so $\text{TORQUE} == 0$.

5.5.4.29 SLEEP_DUTY

This read-only parameter shows the fraction of the last 10 msec control frame that the processor has spent in the sleep mode. It provides a conservative measure of real-time margin.

A value of 1.0 would indicate continual sleep. A value of 0.0 would indicate that the processor is never sleeping, possibly due to the IDLE_INHIBIT parameter.

5.5.4.30 DCDC_FREQ

This read-only parameter shows the frequency of the internal DC/DC converter, averaged over the last 10 cycles. The expected value is on the order of 100 kHz.

5.5.4.31 DRIVE_FREQ

This read/write parameter sets the switching frequency of the motor drive inverter. Permissible values are in the range of 100 kHz to 300 kHz.

As a special case, a value of 0.0 will synchronize the motor drive inverter to the DC/DC converter.

5.5.4.32 DCDC_SLOPE and DCDC_OFFSET

These parameters determine the scaling between the observed DC/DC converter duty cycle and the VBUS telemetry.

5.5.4.33 RESPONSE_AMPLITUDE, RESPONSE_PHASE

These read-only parameters are updated every time SINUSOID_PHASE wraps around from 2π to 0. They measure the speed oscillation that has resulted from a SINUSOID_SPEED or SINUSOID_VOLTAGE command.

RESPONSE_AMPLITUDE is the amplitude of the speed sinusoid.

RESPONSE_PHASE is the phase of the speed sinusoid with respect to the excitation sinusoid – expect a negative number which indicates a phase lag.

5.5.4.34 KT_ESTIMATE, R_ESTIMATE

Every time that SINUSOID_VOLTAGE updates RESPONSE_AMPLITUDE and RESPONSE_PHASE, these two read-only parameters are also updated. They are the values of motor KT and R that best fit the response sinusoid, given the INERTIA parameter that is assumed to be known.

The user must copy these values over to MOTOR_KT and MOTOR_RESISTANCE as part of an initial calibration operation – this is not done automatically.

5.5.4.35 DRY_FRICTION_ESTIMATE, WET_FRICTION_ESTIMATE, AERO_FRICTION_ESTIMATE, RUNDOWN_TIME

When the RUNDOWN mode completes, these read-only parameters are updated. The friction estimates are the best fit to the function:

$$\text{TotalFriction} = \text{DryFriction} + \text{WetFriction} * \text{speed} + \text{AeroFriction} * \left[\text{speed} \right]^2$$

The sign of DRY_FRICTION_ESTIMATE is the same as the sign of the starting speed for the rundown. A rundown from a positive speed will result in a positive dry friction estimate, and a negative starting speed will result in a negative dry friction estimate. The wet friction estimate should always be positive.

RUNDOWN_TIME measures the time, in seconds, for the wheel speed to reach zero.

5.5.4.36 FAULT_OVERTEMP[0|3]

These read/write parameters set the fault limits for TEMP0 and TEMP3. If the temperature exceeds this threshold, even for a single measurement cycle, the corresponding fault flag will be set.

These limits detect overtemperature in the motor windings (channel 0) and the drive transistors (channel 3). These are areas that could be expected to get hot from continual high-torque operation.

5.5.4.37 FAULT_UNDERTEMP2

This read/write parameter set the fault limit for TEMP2. If the temperature is below this threshold, even for a single measurement cycle, the corresponding fault flag will be set.

The limit detects undertemperature in the processor (channel 2). This is a proxy for bearing temperature, and can be used to prevent very low temperature startup.

5.5.4.38 FAULT_TEMP_DELTA

This read/write parameter set the fault limit for the difference between TEMP2 and TEMP3. If the absolute value of this difference exceeds the threshold, even for a single measurement cycle, the corresponding fault flag will be set.

Both TEMP2 and TEMP3 are mounted to the PCA. A large temperature split between them suggests large power dissipation on the board.

5.5.4.39 FAULT_OVERSPEED

This read/write parameter set the fault limit for SPEED. If the absolute value of SPEED exceeds the threshold, even for a single measurement cycle, the corresponding fault flag will be set. This parameter is complementary to LIMIT_SPEED. While LIMIT_SPEED only works in closed-loop modes, FAULT_OVERSPEED works in all modes. By setting one limit higher than the other, the behavior of closed-loop modes can be changed – they can hold at LIMIT_SPEED, or they can fault immediately upon reaching a limit.

5.5.4.40 FAULT_OVERCURRENT

This read/write parameter set the fault limit for current. If the computed absolute value of motor current exceeds the threshold, even for a single measurement cycle, the corresponding fault flag will be set. This parameter is complementary to LIMIT_CURRENT. While LIMIT_CURRENT only works in closed-loop modes, FAULT_OVERCURRENT works in all modes.

For this limit to be effective, MOTOR_KT and MOTOR_RESISTANCE must be set correctly.

5.5.4.41 TEMP_R[0|2|3]

These read-only parameters return the calculated thermistor temperatures, corresponding to TEMP0, TEMP2 and TEMP3. The thermistors are specified at 10 kΩ at +25 C. These parameters are intended primarily for initial factory calibration.

5.5.4.42 ADC_RAW_VBUS

This read-only parameter shows the ratio of the determined from the DC/DC regulator used to calculate VBUS from the factory set slope and offset.

5.5.4.43 MODE

This parameter stores the wheel's current mode. It is more often accessed through file 0, where the mode and command value can be read or written simultaneously.

5.5.4.44 HALL_IMPOSSIBLE

This value counts the number of times that a transition to an "impossible" digital Hall-effect sensor configuration is seen. Impossible configurations are all "0", or all "1". This is an error condition, and would normally indicate failure of a sensor or loss of a rotor magnet. It is read/write, and can be written as zero to reset the count. The count range is 0..255. If an impossible configuration occurs with the count at 255 it will cycle back to 0.

5.5.4.45 HALL_SKIP

This value counts the number of times that a Hall-effect sensor pattern transitions to another pattern that should not be immediately adjacent. Adjacent sensor patterns are those that differ by only one bit.

5.5.4.46 CONTROL_OVERFLOW

This value counts the number of control frames where the control algorithm has not finished processing before the start of the next frame. This is an error condition, and would be expected to result in poor control. It is read/write, and can be written as zero to reset the count. The count range is 0..255. If a control overflow occurs with the count at 255 it will cycle back to 0.

Issuing a CRC command over a large memory range is one sure-fire way to cause the count to increase.

5.5.4.47 SPEED_TABLE_SIZE

This value shows the number of digital Hall sensor transitions that are held in the transition table. Transitions are discarded if they are older than MAX_SPEED_AGE in time, if a complete rotor revolution has occurred since them, or if a rotor direction reversal is detected.

5.5.4.48 USED_TABLE_SIZE

This value shows the number of digital Hall sensor transitions that are being used to compute the SPEED estimate. The speed estimator will attempt to use the following number of transitions, in order of decreasing preference:

5.5.4.49 IDLE_INHIBIT

If this value is zero then the processor will go into a power-saving idle mode when not needed. It wakes immediately when interrupted, and there is no performance penalty. If this value is non-zero then the processor will stay on continually. Changing this parameter will show a modest change in power consumption.

5.5.4.50 FLAGS_ACTIVE

This read-only bitmap shows the present state of the fault flag bits, regardless of their mask state. It is provided as a convenience, so that 7 individual flag registers do not have to be read.

Table 52: Flags_Active Bitfield

Bit	Function
0 (lsb)	FLAG_OVERTEMP0 value
1	FLAG_UNDERTEMP2 value
2	FLAG_OVERTEMP3 value
3	FLAG_TEMP_DELTA value
4	FLAG_OVERSPEED value
5	FLAG_OVERCURRENT value
6	FLAG_HALL_ERROR value
7	One or more unmasked faults are active

5.5.4.51 FAULTS_MASK

This read/write bitmap shows which flag bits can generate a fault. If a bit is set to '1', then the corresponding flag is masked and will not generate faults. If a bit is set to '0' then the flag is not masked and can generate faults.

Table 53: Faults_Mask Bitfield

Bit	Function
0 (lsb)	FLAG_OVERTEMP0 masked
1	FLAG_UNDERTEMP2 masked
2	FLAG_OVERTEMP3 masked
3	FLAG_TEMP_DELTA masked
4	FLAG_OVERSPEED masked
5	FLAG_OVERCURRENT masked
6	FLAG_HALL_ERROR masked
7	Unused

5.5.4.52 FLAG_[OVERTEMP0|UNDERTEMP2|OVERTEMP3|OVERSPEED|OVERCURRENT|HALL_ERROR]

These read/write Boolean values show that a particular type of event has occurred. When the event happens, the flag is set to '1'. It can be cleared by the user writing '0'. The user can also write '1' to intentionally simulate an event.

5.5.4.53 HALT

Writing a non-zero value to this parameter will cause the processor to intentionally become unresponsive (turn-off interrupts and busy-loop). It is intended as a mechanism to test watchdogs.

5.5.4.54 RESET_ENABLE

This read/write bitmap shows which processor errors can generate resets. If a bit is set to '1', then the corresponding reset is enabled.

Table 54: Reset_Enable Bitfield

Bit	Function
0 (lsb)	Watchdog reset enabled
1	Data RAM multi-bit error reset enabled
2	Program RAM multi-bit error reset enabled

Bit	Function
3	Data RAM1 multi-bit error reset enabled
4 – 7	Unused

The watchdog feature piggy-backs on the DC/DC converter frequency and voltage estimation process. A counter counts DC/DC converter pulses. After 10 pulses are counted, an interrupt is triggered. The interrupt clears the counter. If the timer reaches a count of 15, and if the watchdog is enabled, then a processor reset is triggered.

Multi-bit RAM errors, which cannot be corrected by internal ECC, can be configured to cause a CPU reset. Program RAM multi-bit errors will unconditionally cause a CPU reset. Single-bit errors are immediately corrected by hardware.

5.5.4.55 STARTUP_DELAY

A read-only value which when it is non-zero, the effective control mode is IDLE and the fault comparators are inhibited. It is decremented once every control frame (i.e. at 100 Hz) until zero.

At application start it is set to a value of 5, for a 50 msec delay. The intent is to let the rotor speed estimator settle before making any control actuation. This is most relevant if the application starts while the rotor is still spinning.

5.5.4.56 LOCKUP

When this value is non-zero, a processor lockup fault will be triggered on the next Hall-effect sensor transition. This is intended as a mechanism to test the lockup recovery code.

5.5.5 Command Modes

Table 55: Command Modes

Command Number	Command Name	Command Range	Command Units
0x00	IDLE	Ignored	
0x01	PWM	-1.0 to +1.0	Duty cycle
0x02	VOLTAGE	-Vbus to +Vbus	Volts
0x03	SPEED		Rads/sec
0x04	PWM_H1		Duty cycle
0x05	PWM_H2		Duty cycle
0x06	PWM_H3		Duty cycle
0x07	PWM_H4		Duty cycle
0x08	PWM_H5		Duty cycle
0x09	PWM_H6		Duty cycle
0x0A	VOLTAGE_H1		Volts
0x0B	VOLTAGE_H2		Volts
0x0C	VOLTAGE_H3		Volts
0x0D	VOLTAGE_H4		Volts
0x0E	VOLTAGE_H5		Volts
0x0F	VOLTAGE_H6		Volts
0x10	ACCEL		Rads/sec ²
0x11	MOMENTUM		N-m-sec
0x12	TORQUE		N-m
0x16	STORE_FILES	0 or 1	Bool
0x17	DEFAULT_FILES	0 or 1	Bool

Command Number	Command Name	Command Range	Command Units
0x18	PWM_P0		Duty cycle (-1.0 to +1.0)
0x19	PWM_P1		Duty cycle (-1.0 to +1.0)
0x1A	PWM_P2		Duty cycle (-1.0 to +1.0)
0x34	SINUSOID_SPEED		Rads/sec
0x35	SINUSOID_VOLTAGE		Volts
0x36	RUNDOWN	0 or 1	Bool

5.5.5.1 IDLE

In IDLE mode the motor drive is turned off. If it is spinning, the rotor is free to slow down under friction.

5.5.5.2 PWM

In PWM mode the motor is driven with a constant duty cycle. The command may be between -1.0 and 1.0. This is interpreted as a duty cycle between 0.0 and 1.0, in either the positive or negative direction.

PWM mode does not use closed-loop current or speed control, so it is not of great use in spacecraft fine control. However it does allow for extremely high torques (and very high power consumption!), so it may be used open-loop during slew maneuvers.

5.5.5.3 VOLTAGE

In VOLTAGE mode the motor is driven with a constant voltage. The desired voltage is divided by the VSENSE telemetry measurement to determine the PWM duty cycle. This mode is open-loop, in a manner similar to PWM mode, but has feed-forward compensation against supply voltage variations.

5.5.5.4 SPEED

In SPEED mode the rotor speed is servoed to the command value. The closed-loop speed controller outputs a voltage setpoint, which is in turn used by the voltage controller.

5.5.5.5 PWM_H[1..6]

In these modes the digital Hall-effect sensors are overridden, and the binary code is set to the H1..H6 value. Other than that, the mode is identical to PWM mode. It allows a particular PWM duty cycle to be driven onto a particular motor phase regardless of the rotor position. The rotor will typically not spin in these modes, but will oscillate about a particular electrical angle.

5.5.5.6 VOLTAGE_H[1..6]

In these modes the digital Hall-effect sensors are overridden, and the binary code is set to the H1..H6 value. Other than that, the mode is identical to VOLTAGE mode. It allows a particular voltage to be driven onto a particular motor phase regardless of the rotor position. The rotor will typically not spin in these modes, but will oscillate about a particular electrical angle.

5.5.5.7 ACCEL

When not in ACCEL mode, the ACCEL_TARGET file is set to SPEED. In ACCEL mode, the acceleration command is added to ACCEL_TARGET each control frame. ACCEL_TARGET is then used as the setpoint for the speed mode controller.

5.5.5.8 MOMENTUM

In MOMENTUM mode, the SPEED controller is used with a setpoint equal to the commanded MOMENTUM divided by the INERTIA file.

5.5.5.9 TORQUE

In TORQUE mode, the ACCEL controller is used with a setpoint equal to the commanded TORQUE divided by the INERTIA file.

5.5.5.10 STORE_FILES

If the STORE_FILES mode is entered with a value of exactly 1.0, all of the parameters will be stored to the user FRAM. The mode value will be set to 0.0, to indicate that the write has occurred and to prevent multiple writes. Whenever the wheel resets it will start with the stored parameters.

If the STORE_FILES mode is entered with a value of exactly 2.0, all of the parameters will be stored to bootloader FRAM. The mode value will be set to 0.0, to indicate that the write has occurred and to prevent multiple writes. This operation is used at the factory, while the bootloader FRAM is still unlocked, to store hardware-specific calibration parameters. After the bootloader FRAM has been locked, subsequent commands will fail silently.

This mode will set the motor drive to IDLE when commanded.

5.5.5.11 DEFAULT_FILES

If the DEFAULT_FILES mode is entered with a value of exactly 1.0, when the wheel next resets or power cycles, it will initialize with the default parameters from bootloader FRAM. Prior to reset but after the command is sent, the mode value will be set to 0.0 to indicate that the erasure has occurred and to prevent multiple erasures. This command has no effect on the parameters currently in the wheel parameter file, only on the parameters after the next reset.

This mode will set the motor drive to IDLE when commanded.

To permanently overwrite the stored parameters in the user FRAM with the stored parameters set at the factory, the operator must command DEFAULT_FILES with value 1.0, reset and initialize the wheel, and command STORE_FILES with value 1.0.

5.5.5.12 PWM_P[0..2]

The PWM_P[0..2] modes allow the duty cycle of a particular motor phase (0..2) to be set. Only the one phase is driven, and none of the phases is connected to ground.

5.5.5.13 SINUSOID_SPEED

This mode puts the wheel in a closed-loop state, tracking a sinusoidal speed profile. The amplitude of the sinusoid is given by the mode command, while the frequency and offset are given by the SINUSOID_FREQ and SINUSOID_OFFSET files.

$$\begin{aligned} \text{Setpoint} &= \text{amplitude} \cdot \sin(\text{SINUSOID}_{PHASE}) + \text{SINUSOID}_{OFFSET} \\ \text{SINUSOID}_{PHASE} &\leftarrow (\text{SINUSOID}_{PHASE} + \Delta t \cdot \text{SINUSOID}_{FREQ}) \text{ modulo } 2\pi \end{aligned}$$

This mode can be used to characterize the closed-loop frequency response of the wheel. Be careful not to use too large an amplitude, as overheating can occur. A 100 rad/sec amplitude 1 Hz sinusoid is used in the factory to test the overtemperature shutdown.

5.5.5.14 SINUSOID_VOLTAGE

This mode is equivalent to SINUSOID_SPEED, except that it applies a sinusoidal voltage profile to the motor.

5.5.5.15 RUNDOWN

This mode is used to estimate the friction in the reaction wheel. To use it:

1. Spin the wheel to some starting speed, usually using a SPEED command.
2. Send the command RUNDOWN 1.0. The motor will turn off, and the wheel will coast to a stop.
3. Poll the COMMAND variable, until it turns to 0.0.
4. Read the DRY_FRICTION_ESTIMATE, WET_FRICTION_ESTIMATE, and AERO_FRICTION_ESTIMATE parameters.
5. Read RUNDOWN_TIME.

RUNDOWN will only collect data when COMMAND is exactly 1.0. When the wheel speed hits zero, it clears COMMAND to 0.0.

5.6 Special Features

5.6.1 Virtual Oscilloscope

Various internal waveforms can be drive out of one of the RS485 ports, while the other port remains in normal operation for commands and telemetry. This is of no use on-orbit, but can be useful to help debug issues in an integrated system where it is hard to use an oscilloscope probe.

It is not envisaged that customers will want to use this functionality. In the event that it is needed, please contact Rocket Lab for further details and scripts to configure the functionality

5.6.2 Inducing Processor Faults

It is useful to intentionally trigger various processor fault states, to verify the fault handler behavior.

Fault Type	Trigger Command	State
Hardfault	POKE 0x01 to 0xCAFEBAFE	Bootloader or application

Note that these faults are executed immediately upon receipt of the POKE command. No NSP reply will be sent.

5.6.3 Inducing Memory ECC errors

The CPU ECC functionality can be tested by using the poke and peek commands to write and read values from specific addresses. These addresses are configured with the internal CPU ECC test functionality.

- Data SRAM0: Address 0x5ffffffc
- Data SRAM1: Address 0x60007ffc
- Code "ROM": Address 0x0003fffc

For each of those addresses, 32-bits (4 bytes) have ECC syndrome data overridden to be all zeros. Therefore, writing non-zero data to the address will set-up a memory error, which will then be detected via the ECC circuitry. Either an explicit read (PEEK command) or else the periodic memory scrubbing, will trigger the ECC error handling.

Either single bit, or double bit errors can be produced, by setting one or two bits in the appropriate location. (Note that the SRAM ECC is per-byte, while the "ROM" ECC works on 16-bit words.)