SMART MUSCLE

Hardware Version 4.1

Software Version Release 1.1

Preliminary June 2015

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Hardware

Figure 1: Smart Muscle Connections

Compressed Air Inlet

Maximum 6 Bar through a 6mm inlet.

Bootloader Access

There is a 1mm hole next to the indicator LED which allows access to a button on the circuit board. Pressing this button whilst the Smart Muscle is powered on results in the Smart Muscle entering bootloader mode.

It is possible in this mode to update the firmware via CAN. This is not compatible with CANOpen, a USB-CAN bridge would be required. The Smart Muscle is controlled with an STM32F405 MCU from STMicroelectronics, consult AN2606 for information on the CAN bootloader protocol.

Power and Communication Connector

The standard 4 pin M8 connector provides power and communications for the Smart Muscle.

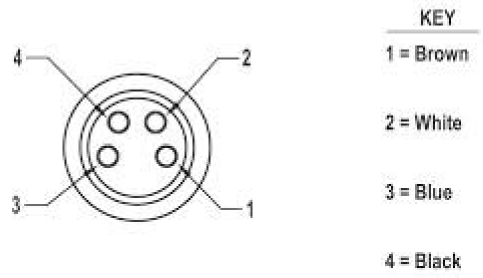

Figure 2: M8 Connector Pinout (Receptacle Shown)

Pin	Wire Colour	Signal
1	Brown	+24Vdc
2	White	CANH
3	Blue	GND
4	Black	CANL

Table 1: M8 Connector Pinout

LED Indicator

The LED Indicator is located next to the air inlet. This is a bi-colour LED (Red and Green). The LED shows the status of the Smart Muscle and uses the CANOpen standard indicator specification as set out in CiA document CiA 303-3. Note that the LED can display Red and Green simultaneously.

Error LED (Red)

The red LED shows errors in either the CAN physical layer (error frames, Bus-off etc) and missing messages.

Table 2 shows the supported LED activity states for the CAN Error LED. Refer to CiA 303-3 for an explanation of the Activity types (i.e 'Blinking' or 'Single Flash' etc).

LED Activity	State	Description
Off	No Error	Smart Muscle is operating normally
Blinking	Invalid Configuration	There is a general configuration Error
Single Flash	Warning Limit Reached	At least one of the error counters in the device has exceeded the warning level (too many error frames)
Double Flash	Error Control Event	A guard event (NMT-slave or NMT-master) or a heartbeat event has occurred
On	Bus-Off	The Smart Muscle CAN controller is bus-off. The device is configured to automatically attempt to re-connect

Table 2: CANOpen Error LED Activity

Run LED (Green)

The green LED indicates the status of the device on the CANOpen network.

Table 3 shows the LED activity states for the CAN run LED.

LED Activity	State	Description
Blinking	PRE-OPERATIONAL	The device is in PRE-OPERATIONAL state
Single Flash	STOPPED	The device is in STOPPED state
On	OPERATIONAL	The device is in OPERATIONAL state

Table 3: CANOpen Run LED Activity

Electrical

Power Considerations

Electrical Specification

The Smart Muscle is designed for use with a +24Vdc power supply. Different input voltages will adversely affect the response of the device and would require the muscle to be re-tuned.

Parameter	Conditions	Min	Typ	Max	Unit
Vin Operating Voltage		18	24	28	V
Typical Current Draw	Vin = 24V, Valve Duty Cycle = 100%			90	mA
CAN Terminal Voltage		-2		7	V
CAN Differential Input		-6		6	V

Table 4: Electrical Characteristics

Absolute Maximum Ratings

Parameter	Conditions	Min	Typ	Max	Unit
Vin Operating Voltage		-5		40	V
CAN Terminal Voltage		-4		16	V

Table 5: Absolute Maximum Ratings

CAN Bus

The CAN bus requires a terminating resistor at the end of the bus to suppress signal reflection . The Smart Muscles do not include terminating resistors as many Smart Muscles may be present on a single bus.

A 120ohm terminating resistor should be present between the CANH and CANL signals at the end of the bus.

Communication

CANOpen

The Smart Muscle aims to use the standard CANOpen protocol and supports PDO, SDO, NMT and EMCY messages.

Object Dictionary

The Smart Muscle has many manufacturer specific entries for tuning parameters.

Table 6 shows the relevant Object Dictionary (OD) entries for te Smart Muscle. Note that this table does not show *all* OD entries, mandatory and some other optional entries are also present as set out in the CANOpen specification.

Entry	Index (hex)	Sub-Index	Description	Data Type	r/w
Pressure	2109	1	Current Pressure [mBar]	0003	ro
Temperature	2108	1	Current Temperature [degC/100]	0003	ro
Enable	2140	1	~~Device Enable (0 = DISABLE, 1 = ENABLE)~~ This object is deprecated in software V1.1, device is enabled only when in OPERATIONAL mode.	0001	rw
Mode	2140	2	Allows multiple operating modes (only mode '1' is currently implemented)	0005	rw
Save OD	2140	3	When set to '0x7F' the Object Dictionary is stored into non-volatile memory	0005	rw
Bootloader Request	2140	4	When set to '0xAF' the Smart Muscle resets into bootloader mode	0005	rw
Pressure Demand	2140	5	Pressure Demand [mBar relative] (0..6000)	0006	rw
Pressure Error	2140	A	Pressure demand minus current pressure [mBar]	0006	ro
Deadband	2120	1	Pressure error deadband, device will not servo whilst within the deadband [mBar]	0005	rw
Liveband	2120	2	The integrator in the PID control loop only functions when the pressure error is within the 'liveband' to prevent excessive I values when the error is high	0005	rw
P Gain Inlet	2120	3	Proportional gain for the inlet	0008	rw
P Gain Outlet	2120	4	Proportional gain for the outlet	0008	rw
I Gain Inlet	2120	5	Integral gain for the inlet	0008	rw
I Gain Outlet	2120	6	Integral gain for the outlet	0008	rw
Integrator Limit	2120	7	Maximum value for the integral calculation to prevent integrator windup	0008	rw
D Gain Inlet	2120	8	Differential gain for the inlet	0008	rw
D Gain Outlet	2120	9	Differential gain for the outlet	0008	rw
Minimum Pulse Points	2120	A	Minimum pulse offers a simple way to tune the valves against a varying force on the valve plunger due to differential pressure from valve inlet to valve outlet. For more information see 'Tuning'.	0005	rw
Minimum Pulse Inlet	2121	[1..8]		0006	rw
Minimum Pulse Outlet	2122	[1..8]		0006	rw
Compensation Enable	2120	19	Compensation is used to tune against the relative flow rates through the valves at different differential pressures. For more information see 'Tuning'.	0005	rw
Inlet Compensation	2120	[B..11]		0008	rw
Outlet Compensation	2120	[12..18]		0008	rw

Table 6: Relevant Object Dictionary Entries

Data Types

CANOpen supports many different data types and assigns them a number.

Table 7 shows a list of data types supported in CANOpen. It does not show *all* data types that are supported by the protocol.

CANOpen Index	Data Type	Number of Bits
0001	Boolean	-
0002	Signed Integer	8
0003	Signed Integer	16
0004	Signed Integer	32
0005	Unsigned Integer	8
0006	Unsigned Integer	16
0007	Unsigned Integer	32
0008	Floating Point (Float)	32
0009	Visible String	-

Table 7: CANOpen Data Types

Operation

Basic Operation

Start-up

The Smart Muscle will start operating when connected to a power supply. It *always* starts up in CAN 'PRE-OPERATIONAL' mode and the 'Enable' entry is set to 0.

As both valves are 'normally closed' there may be any pressure in the muscle from previous usage. When the Smart Muscle powers on it will read the current pressure and set the pressure demand to the same value, this means when the device is enabled the muscle will not servo.

Runtime

The Pressure Demand entry in the object dictionary controls the target pressure which the Smart Muscles control loop aims for. The 'Enable' entry needs to be set to '1' for the muscle to operate as well as the device being in CANOpen 'OPERATIONAL' mode.

The 'Pressure Demand' value is measured in millibar.

The Smart Muscle will attempt to keep track of the ambient air pressure as this could fluctuate anywhere up to 100mB. When the device is instructed to 'Zero' relative pressure the outlet valve will open fully. Once the muscle has fully exhausted and reached a consistent pressure it will take an averaged reading of the ambient pressure and subtract it from all subsequent measurements.

Object Dictionary Memory Store

The object dictionary is stored in non-volatile memory and retrieved on every start-up. If any tuning values are altered the Smart Muscle needs to be instructed to store the new values in memory. If the the new values are not stored the old values will be loaded on the next power cycle.

To store any changes made to any Object Dictionary entries write 0x7F to entry 'Save OD'. The device will then commit the Object Dictionary to memory.

Note: Not all entries are stored, 'Pressure Demand' for example is reset upon each power cycle.

Tuning

Minimum Pulse Tuning

The Nass Cartridge13 valves used in the Smart Muscle are digital solenoid valves, that is they only have 2 states; open and closed. Variable flow rates are achieved through pulse width modulation (PWM). These valves are normally closed, this means a spring holds the plunger closed against up to 6 Bar pressure.

One of the valves characteristics is there is a minimum 'on' pulse length before the valve actually opens; this value is not consistent over the operating range of the valve. For example, if there is 6 Bar present at the inlet and 0 Bar (relative) at the outlet then the minimum pulse is very short as the high pressure on the inlet helps push the valve plunger against the spring. If there is 5.8 Bar at the outlet the differential pressure is much smaller, the plunger is pushed much less by the difference in pressure, therefore the minimum pulse length is much higher.

The minimum pulse tuning can help remove this phenomenon by finding the shortest pulse length required at any point to start an airflow. This is done with the following Object Dictionary entries:

- Minimum Pulse Points
- Minimum Pulse Inlet
- Minimum Pulse Outlet

The change in minimum pulse is not quite linear over the full range (but not far off). 'Minimum Pulse Points' describes the number of points along the full range that a minimum pulse has been calibrated, minimum pulse values are interpolated in-between these calibrated values. The maximum number of minimum pulse points can be 8.
The inlet and outlet entries are 8-value arrays that hold the minimum pulse values at up to 8 points.

Example:
A typical system would use 4 minimum pulse points, these are automatically calculated at regular intervals inside the Smart Muscle. In this case they would be at 0, 2000, 4000 and 6000 mBar.

Table 8 and Drawing 3 shows an example distribution for the inlet.

Pulse Point	Pressure at pulse point (mBar)	Minimum pulse
0	0	680
2	2000	820
3	4000	1040
4	6000	1250

Table 8: Example minimum pulses

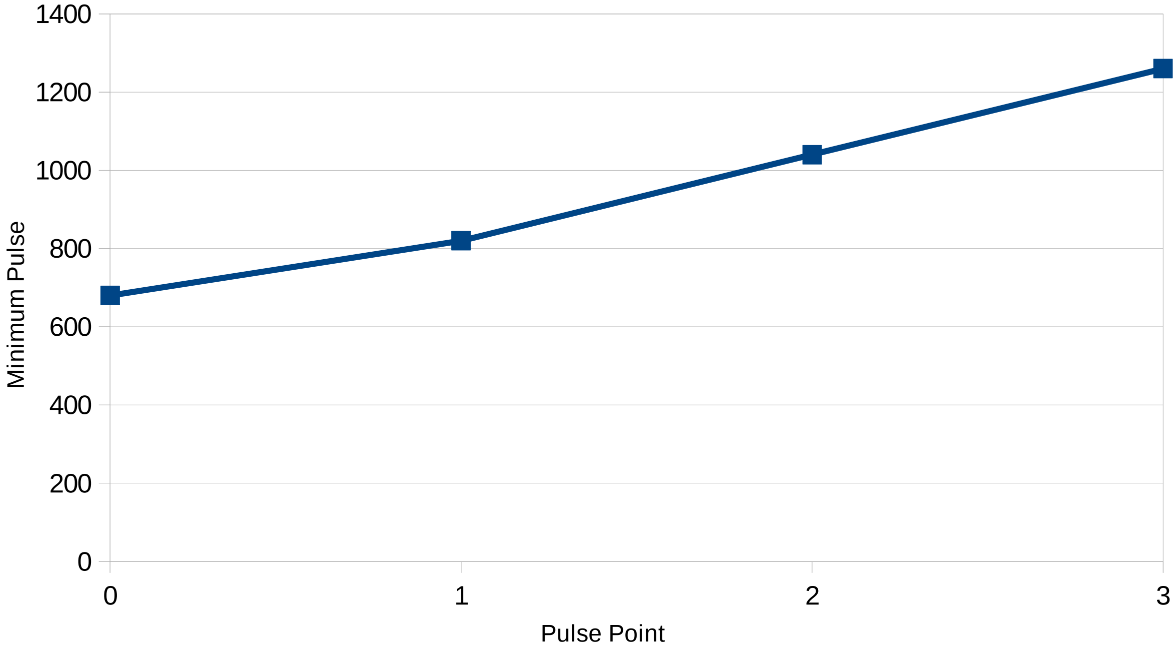

Figure 3: Graph of example minimum pulse distribution

The suggested way to manually tune this parameter is to make sure all three PID gains are set to 0, then at0 Bar set the demand high, increase the minimum pulse value at the first minimum pulse point until the pressure first starts to increase. This is the minimum pulse for 0 Bar. Repeat this process for the remaining pulse points taking note that the outlet and inlet *will* be different.

Compensation Tuning

Apart from the minimum pulse phenomenon there is a second phenomenon that needs to be tuned against before PID control will function correctly. This is the rate of change of airflow in response to the change in pulse length at different pressure differentials.

Table 9 shows an example of this phenomenon. Assuming the Smart Muscle has been tuned for minimum pulse then the airflow at that minimum pulse for any pressure differential is the same; in this case it is 0.01 l/min If we increase the minimum pulse by a set amount (add 20 counts), we then measure the new airflow. As we can see the difference between the airflows depends heavily on the pressure differential. This means a 'Proportional' gain would result in sluggish response at low differentials and unstable response at high differentials. For reliable PID tuning this airflow differential must be consistent at all pressure differentials.

Pressure at [mBar]		**Pressure Differential [mBar]**	**Airflow at [l/min]**		**Airflow Difference [l/min]**
Valve Inlet	**Valve Outlet**		**Min Pulse**	**Min Pulse +20**	
6000	500	5500	0.01	0.2	0.19
6000	3000	3000	0.01	0.07	0.06
6000	5500	500	0.01	0.02	0.01

Table 9: Example Airflow Change

The compensation algorithm is a 6th order polynomial.

$$(A7)+(A6)x+(A5)x^2+(A4)x^3+(A3)x^4+(A2)x^5+(A1)x^6$$

where;
A7 = Object Dictionary Entry Sub-Index 1
A6 = Sub-Index 2
A5 = Sub-Index 3
A4 = Sub-Index 4
A3 = Sub-Index 5
A2 = Sub-Index 6
A1 = Sub-Index 7