WPI

FES HYBRID EXOSKELETON

FIRMWARE DESIGN SPECIFICATION

Version *<1.0>*

06/05/2019

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VERSION HISTORY

All versions of this document, due to changes post origination, will be tracked:

Version #	Implemented By	Revision Date	Approved By	Approval Date	Reason
1.0	*Michael Conrad*	*6/5/2019*	*In process*	*<mm/dd/yy>*	Initial Design Definition draft

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1 INTRODUCTION

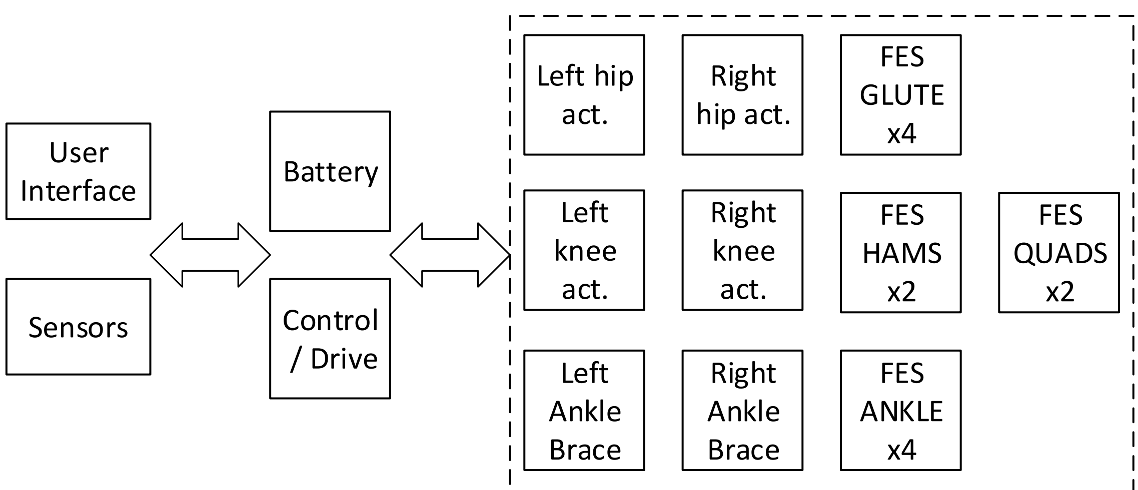
1.1 PURPOSE OF THE PRODUCT DESIGN SPECIFICATION DOCUMENT

This design specification defines the Firmware requirements for an initial trial of mobility device for individuals with a spinal cord injury and neurological impairment to activate muscles and sensory receptors post the cervical region of the spinal cord through mixed use of Functional Electrical Stimulation (FES) and mechanical robotics as a hybrid system. It is intended to serve the purpose of accessibility of the impaired with minimal assistance of the arms in a physical therapy (PT) setting for gating.

The Firmware Specification document documents and tracks the necessary information required to effectively define firmware architecture and interconnects in order to give the development team guidance on firmware of the system to be developed for initial testing. The intended audience is a predetermined design team in the educational confines of Worcester Poly Tech (WPI) rules and regulations.

2 GENERAL OVERVIEW AND DESIGN GUIDELINES/APPROACH

The FES device is an existing proven design owned by the original author of this specification. It is capable of stimulating twelve muscles independently, assumed to be the quadriceps, hamstrings, calves, tibias, and glutes. The confines of how FES is done are not within the scope of the requirements within this document, assumed to work in concert with this system through existing interface. In parallel to the FES, mechanical actuators will be used for both enhanced activation and safety at the hips and knees. Both will use a common power source and control, all communication and sensors are also inputs to the control interface.



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2.1 ASSUMPTIONS / CONSTRAINTS / STANDARDS

The FES system, as previously mentioned, is assumed to be fully functional and usable for this application. No update or usability to this existing FES hardware is assumed to be within the scope of these requirements, for this test application.

It is assumed that any legal permission will be granted, through Institutional Review Board (IRB) or other party to fulfill the requirements of this instrument for testing on human subjects.

All Food and Drug (FDA) standards, Occupational Health and Safety Administration (OSHA) standards, and general safety and ethical guidelines will be followed in the development and testing of this device.

3 ARCHITECTURE DESIGN

This design **shall** include FES and other hardware necessary to allow for accessible standing, walking, climbing and sitting by an impaired user with Spinal Cord Injury (SCI) as previously defined, with minimal assistance through use of crutches, parallel bars, or a walker. It **shall** be wearable, **shall** be dressed, and **shall** be able to be fully controlled by a single user with impairment to the lower limbs.

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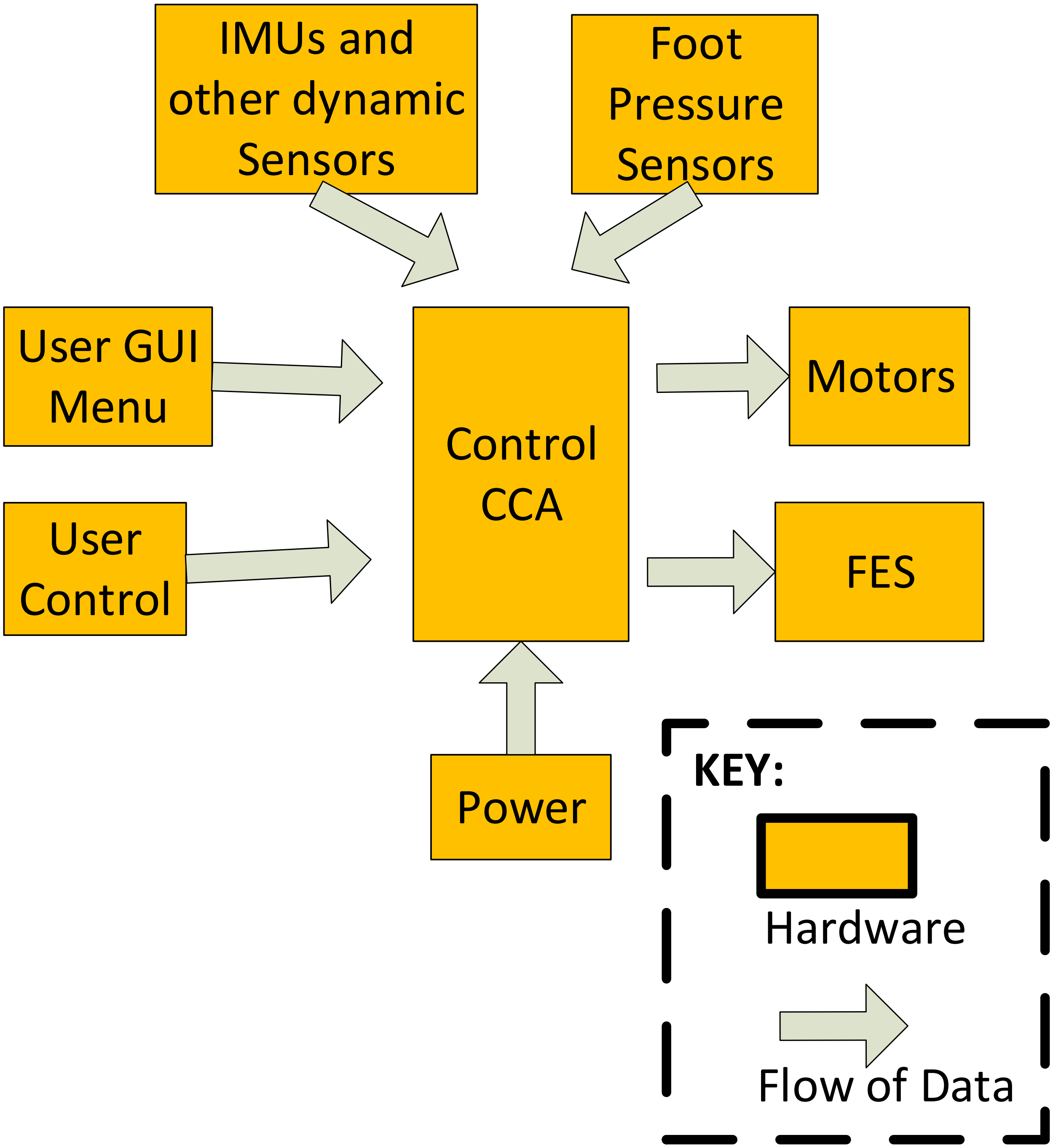
3.1 LOGICAL VIEW



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Logic and Communication

The Hybrid Exoskeleton **shall** be controlled by a single Circuit Card Assembly (CCA) with processing that **shall** be through a Xilinx Zynq 7000 series System on Chip (SoC) or equivalent device that also houses a Field Programmable Gate Array (FPGA). Programing and control by external computing **shall** be able to be done through an Uninterruptable Serial Bus (USB), Ethernet, Bluetooth wireless, and Joint Test Action Group (JTAG).

User Interface

The user interface to enable controls for this test application will be through an Ethernet packet send via an external computer to the controller, and a packet will be returned with sensor data. The initial packet will contain a start, FES control, motor control, and actuator control. The response will contain all sensory data collected at the control interface.

FES Control

Two eight-bit words will be collected for each of the 12 FES channels.

The first is the FES Voltage which ranges from 75 to 250 volts in 25 volt increments "00000000" being off and "11111111" being 250 volts.

The second word is a proprietary algorithm to determine force/torque of joint extension and contraction using a combination of current attenuation, pulse-width, repetition, and frequency modulation. "00000000" is off, and "11111111" is maximum force, with no change in voltage.

Four bits in the initial control word and a second word form the Activation of the FES. The voltage and force/torque do not control activation. The 12 bit word is as follows:

Word	FES#	Joint
xxxxxxxxxxx**1**	1	Right Quad
xxxxxxxxxx**1**x	2	Left Quad
xxxxxxxxx**1**xx	3	Right Ham
xxxxxxxx**1**xxx	4	Left Ham
xxxxxxx**1**xxxx	5	Right Tib
xxxxxx**1**xxxxx	6	Left Tib
xxxxx**1**xxxxxx	7	Right Calf
xxxx**1**xxxxxxx	8	Left Calf
xxx**1**xxxxxxxx	9	Right Glute
xx**1**xxxxxxxxx	10	Left Glute

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x**1**xxxxxxxxxx	11	Right Ab
1xxxxxxxxxxx	12	Left Ab

Motor Control

Motor control is based on two eight-bit words for torque.

The 16 bits together form an unsigned integer in steps of 1.526mA/count. The last bit on the second word forms the least significant bit. An example are two words “00011001” & “10011001” that form a decimal 6,553, that corresponds to 10 amps.

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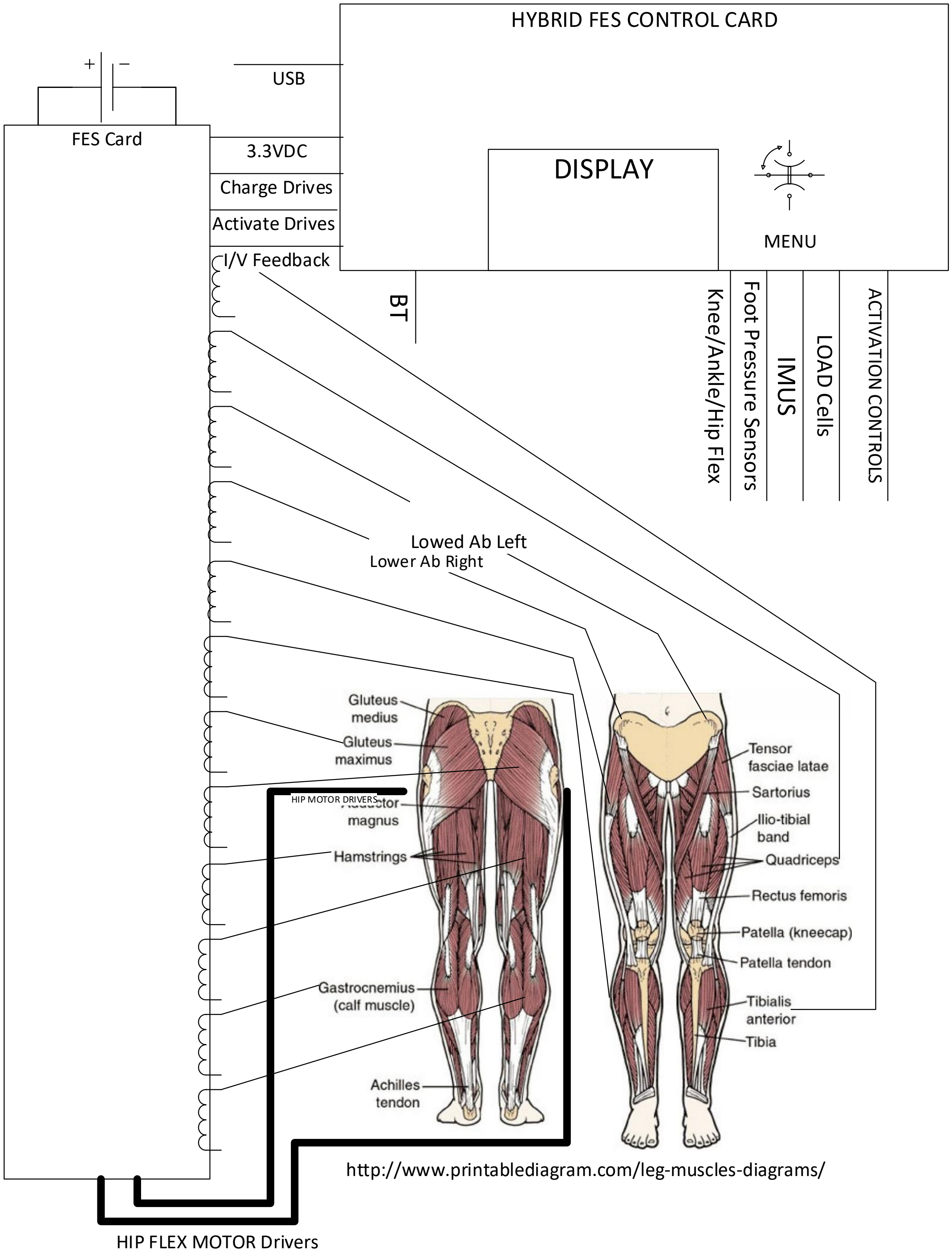

Figure 1 - Exo-Hybrid Architecture

3.2 HARDWARE ARCHITECTURE

The Hardware architecture that interfaces this control device with operator and EXO includes both an Ethernet communication and two connectors for feedback (left and right).

3.2.1 Diagram of Ethernet BYTEs

The following initial package is to be sent from the computer via Ethernet to the Control CCA:

BYTE#	SIGNAL	NOTE
1	Start Byte	"ON=1, On=1, Left-Knee, Right-Knee, FES11, FES10, FES9, FES8"
2	FES Byte	"FES7, FES6, FES5, FES4, FES3, FES2, FES1, FES0"
3	Right_Hip1	Atlas Motor Driver Torque Byte 1
4	Right_Hip0	Atlas Motor Driver Torque Byte 0
5	Left_Hip1	Atlas Motor Driver Torque Byte 1
6	Left_Hip0	Atlas Motor Driver Torque Byte 0
7	FES1_Voltage	Right Quad Voltage
8	FES1_Force	Right Quad Force/Torque
9	FES2_Voltage	Left Quad Voltage
10	FES2_Force	Left Quad Force/Torque
11	FES3_Voltage	Right Ham Voltage
12	FES3_Force	Right Ham Force/Torque
13	FES4_Voltage	Left Ham Voltage
14	FES4_Force	Left Ham Force/Torque
15	FES5_Voltage	Right Tib Voltage
16	FES5_Force	Right Tib Force/Torque
17	FES6_Voltage	Left Tib Voltage
18	FES6_Force	Left Tib Force/Torque
19	FES7_Voltage	Right calf Voltage
20	FES7_Force	Right calf Force/Torque
21	FES8_Voltage	Left Calf Voltage
22	FES8_Force	Left Calf Force/Torque
23	FES9_Voltage	Right Glute Voltage

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24	FES9_Force	Right Glute Force/Torque
25	FES10_Voltage	Left Glute Voltage
26	FES10_Force	Left Glute Force/Torque
27	FES11_Voltage	Right Ab Voltage
28	FES11_Force	Right Ab Force/Torque
29	FES12_Voltage	Left Ab Voltage
30	FES12_Force	Left Ab Force/Torque

This package is to be returned from the Control CCA via Ethernet:

BYTE#	SIGNAL	NOTE
1	Start Byte1	"11111111"
2	Start Byte2	"00000000"
3	IMU-Counter_Left_Foot(23downto16)	
4	IMU-Counter_Left_Foot(15downto8)	
5	IMU-Counter_Left_Foot(7downto0)	
6	IMU-Acc_Z_Left_Foot(15downto8)	
7	IMU-Acc_Z_Left_Foot(7downto0)	
8	IMU-Acc_Y_Left_Foot(15downto8)	
9	IMU-Acc_Y_Left_Foot(7downto0)	
10	IMU-Acc_X_Left_Foot(15downto8)	
11	IMU-Acc_X_Left_Foot(7downto0)	
12	IMU-Gyro_Z_Left_Foot(15downto8)	
13	IMU-Gyro_Z_Left_Foot(7downto0)	
14	IMU-Gyro_Y_Left_Foot(15downto8)	
15	IMU-Gyro_Y_Left_Foot(7downto0)	
16	IMU-Gyro_X_Left_Foot(15downto8)	
17	IMU-Gyro_X_Left_Foot(7downto0)	
18	IMU_rhall_Left_Foot(15downto8)	
19	IMU_rhall_Left_Foot(7downto0)	
20	IMU_Temperature_Left_Foot(15downto8)	
21	IMU_Temperature_Left_Foot(7downto0)	

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22	IMU-Counter_RIGHT_Foot(23downto16)	
23	IMU-Counter_RIGHT_Foot(15downto8)	
24	IMU-Counter_RIGHT_Foot(7downto0)	
25	IMU-Acc_Z_RIGHT_Foot(15downto8)	
26	IMU-Acc_Z_RIGHT_Foot(7downto0)	
27	IMU-Acc_Y_RIGHT_Foot(15downto8)	
28	IMU-Acc_Y_RIGHT_Foot(7downto0)	
29	IMU-Acc_X_RIGHT_Foot(15downto8)	
30	IMU-Acc_X_RIGHT_Foot(7downto0)	
31	IMU-Gyro_Z_RIGHT_Foot(15downto8)	
32	IMU-Gyro_Z_RIGHT_Foot(7downto0)	
33	IMU-Gyro_Y_RIGHT_Foot(15downto8)	
34	IMU-Gyro_Y_RIGHT_Foot(7downto0)	
35	IMU-Gyro_X_RIGHT_Foot(15downto8)	
36	IMU-Gyro_X_RIGHT_Foot(7downto0)	
37	IMU_rhall_RIGHT_Foot(15downto8)	
38	IMU_rhall_RIGHT_Foot(7downto0)	
39	IMU_Temperature_RIGHT_Foot(15downto8)	
40	IMU_Temperature_RIGHT_Foot(7downto0)	
41	IMU-Counter_Left_Ankle(23downto16)	
42	IMU-Counter_Left_Ankle(15downto8)	
43	IMU-Counter_Left_Ankle(7downto0)	
44	IMU-Acc_Z_Left_Ankle(15downto8)	
45	IMU-Acc_Z_Left_Ankle(7downto0)	
46	IMU-Acc_Y_Left_Ankle(15downto8)	
47	IMU-Acc_Y_Left_Ankle(7downto0)	
48	IMU-Acc_X_Left_Ankle(15downto8)	
49	IMU-Acc_X_Left_Ankle(7downto0)	
50	IMU-Gyro_Z_Left_Ankle(15downto8)	
51	IMU-Gyro_Z_Left_Ankle(7downto0)	
52	IMU-Gyro_Y_Left_Ankle(15downto8)	

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53	IMU-Gyro_Y_Left_Ankle(7downto0)	
54	IMU-Gyro_X_Left_Ankle(15downto8)	
55	IMU-Gyro_X_Left_Ankle(7downto0)	
56	IMU_rhall_Left_Ankle(15downto8)	
57	IMU_rhall_Left_Ankle(7downto0)	
58	IMU_Temperature_Left_Ankle(15downto8)	
59	IMU_Temperature_Left_Ankle(7downto0)	
60	IMU-Counter_RIGHT_Ankle(23downto16)	
61	IMU-Counter_RIGHT_Ankle(15downto8)	
62	IMU-Counter_RIGHT_Ankle(7downto0)	
63	IMU-Acc_Z_RIGHT_Ankle(15downto8)	
64	IMU-Acc_Z_RIGHT_Ankle(7downto0)	
65	IMU-Acc_Y_RIGHT_Ankle(15downto8)	
66	IMU-Acc_Y_RIGHT_Ankle(7downto0)	
67	IMU-Acc_X_RIGHT_Ankle(15downto8)	
68	IMU-Acc_X_RIGHT_Ankle(7downto0)	
69	IMU-Gyro_Z_RIGHT_Ankle(15downto8)	
70	IMU-Gyro_Z_RIGHT_Ankle(7downto0)	
71	IMU-Gyro_Y_RIGHT_Ankle(15downto8)	
72	IMU-Gyro_Y_RIGHT_Ankle(7downto0)	
73	IMU-Gyro_X_RIGHT_Ankle(15downto8)	
74	IMU-Gyro_X_RIGHT_Ankle(7downto0)	
75	IMU_rhall_RIGHT_Ankle(15downto8)	
76	IMU_rhall_RIGHT_Ankle(7downto0)	
77	IMU_Temperature_RIGHT_Ankle(15downto8)	
78	IMU_Temperature_RIGHT_Ankle(7downto0)	
79	IMU-Counter_Left_Knee(23downto16)	
80	IMU-Counter_Left_Knee(15downto8)	
81	IMU-Counter_Left_Knee(7downto0)	
82	IMU-Acc_Z_Left_Knee(15downto8)	
83	IMU-Acc_Z_Left_Knee(7downto0)	

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84	IMU-Acc_Y_Left_Knee(15downto8)	
85	IMU-Acc_Y_Left_Knee(7downto0)	
86	IMU-Acc_X_Left_Knee(15downto8)	
87	IMU-Acc_X_Left_Knee(7downto0)	
88	IMU-Gyro_Z_Left_Knee(15downto8)	
89	IMU-Gyro_Z_Left_Knee(7downto0)	
90	IMU-Gyro_Y_Left_Knee(15downto8)	
91	IMU-Gyro_Y_Left_Knee(7downto0)	
92	IMU-Gyro_X_Left_Knee(15downto8)	
93	IMU-Gyro_X_Left_Knee(7downto0)	
94	IMU_rhall_Left_Knee(15downto8)	
95	IMU_rhall_Left_Knee(7downto0)	
96	IMU_Temperature_Left_Knee(15downto8)	
97	IMU_Temperature_Left_Knee(7downto0)	
98	IMU-Counter_RIGHT_Knee(23downto16)	
99	IMU-Counter_RIGHT_Knee(15downto8)	
100	IMU-Counter_RIGHT_Knee(7downto0)	
101	IMU-Acc_Z_RIGHT_Knee(15downto8)	
102	IMU-Acc_Z_RIGHT_Knee(7downto0)	
103	IMU-Acc_Y_RIGHT_Knee(15downto8)	
104	IMU-Acc_Y_RIGHT_Knee(7downto0)	
105	IMU-Acc_X_RIGHT_Knee(15downto8)	
106	IMU-Acc_X_RIGHT_Knee(7downto0)	
107	IMU-Gyro_Z_RIGHT_Knee(15downto8)	
108	IMU-Gyro_Z_RIGHT_Knee(7downto0)	
109	IMU-Gyro_Y_RIGHT_Knee(15downto8)	
110	IMU-Gyro_Y_RIGHT_Knee(7downto0)	
111	IMU-Gyro_X_RIGHT_Knee(15downto8)	
112	IMU-Gyro_X_RIGHT_Knee(7downto0)	
113	IMU_rhall_RIGHT_Knee(15downto8)	
114	IMU_rhall_RIGHT_Knee(7downto0)	

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115	IMU_Temperature_RIGHT_Knee(15downto8)	
116	IMU_Temperature_RIGHT_Knee(7downto0)	
117	IMU-Counter_CENTER(23downto16)	
118	IMU-Counter_CENTER(15downto8)	
119	IMU-Counter_CENTER(7downto0)	
120	IMU-Acc_Z_CENTER(15downto8)	
121	IMU-Acc_Z_CENTER7downto0)	
122	IMU-Acc_Y_CENTER(15downto8)	
123	IMU-Acc_Y_CENTER(7downto0)	
124	IMU-Acc_X_CENTER(15downto8)	
125	IMU-Acc_X_CENTER(7downto0)	
126	IMU-Gyro_Z_CENTER(15downto8)	
127	IMU-Gyro_Z_CENTER(7downto0)	
128	IMU-Gyro_Y_CENTER(15downto8)	
129	IMU-Gyro_Y_CENTER(7downto0)	
130	IMU-Gyro_X_CENTER(15downto8)	
131	IMU-Gyro_X_CENTER(7downto0)	
132	IMU_rhall_CENTER(15downto8)	
133	IMU_rhall_CENTER(7downto0)	
134	IMU_Temperature_CENTER(15downto8)	
135	IMU_Temperature_CENTER(7downto0)	
136	POT_Left_Ankle(12downto5)	
137	POT_Left_Ankle(4dowto0&"0000")	"0000"
138	POT_Right_Ankle(12downto5)	
139	POT_Right_Ankle(4dowto0&"0001")	"0001"
140	POT_Left_Knee(12downto5)	
141	POT_Left_Knee(4dowto0&"0010")	"0010"
142	POT_Right_Knee(12downto5)	
143	POT_Right_Knee(4dowto0&"011")	"0011"
144	POT_Left_Hip(12downto5)	
145	POT_Left_Hip(4dowto0&"0100")	"0100"

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146	POT_Right_Hip(12downto5)	
147	POT_Right_Hip(4dowto0&"0101")	"0101"
148	FSR1_Right(12downto5)	
149	FSR1_Right(4dowto0&"0110")	"0110"
150	FSR2_Right(12downto5)	
151	FSR2_Right(4dowto0&"0111")	"0111"
152	FSR3_Right(12downto5)	
153	FSR3_Right(4dowto0&"1000")	"1000"
154	FSR1_Left(12downto5)	
155	FSR1_Left(4dowto0&"1001")	"1001"
156	FSR2_Left(12downto5)	
157	FSR2_Left(4dowto0&"1010")	"1010"
158	FSR3_Left(12downto5)	
159	FSR3_Left(4dowto0&"1011")	"1011"
160	Left_Hip_Encoder(15downto8)	
161	Left_Hip_Encoder(7downto0)	
162	Right_Hip_Encoder(15downto8)	
163	Right_Hip_Encoder(7downto0)	

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3.2.2 Wiring of Sensors

note: this is just sensing at present

FROM			SIGNAL	TO	
	PIN	TYPE		LOCATION	IC
CONNECTOR J1	A14	I2C-SDA	IMU1	Left Knee	BMI160
	A13	I2C-SCL			
	A16	I2C-SDA	IMU2	Left Ankle	BMI160
	A15	I2C-SCL			
	A18	I2C-SDA	IMU3	Left Foot	BMI160
	A17	I2C-SCL			
		I2C	~~IMU4~~		~~BMI160~~ ~~INTERNAL TO BOARD~~
		I2C			
		I2C			
	B14	I2C-SCL	Distance Sensor	Left Foot	GP2Y0E03
	B13	I2C-SDA			
	B1	ADC	POT	Left Hip	PDF241-S425F-103B0
	B5	ADC	POT	Left Knee	PDF241-S425F-103B0
	B9	ADC	POT	Left Ankle	PDF241-S425F-103B0
	B3	ADC	FSR	Left FSR1	FSR03CE
	B7	ADC	FSR	Left FSR2	FSR03CE
	B11	ADC	FSR	Left FSR3	FSR03CE
	A9	Encoder	Decoder	Left_En_A+	453234
	A10	Encoder	Decoder	Left_En_A-	453234
	A11	Encoder	Decoder	Left_En_B+	453234
	A12	Encoder	Decoder	Left_En_B-	453234
CONNECTOR J2	A14	I2C	IMU5	Right Knee	BMI160
	A13	I2C			
	A16	I2C	IMU6	Right Ankle	BMI160
	A15	I2C			
	A18	I2C	IMU7	Right Foot	BMI160
	A17	I2C			
	B14	I2C	Distance Sensor	Right Foot	GP2Y0E03
	B13	I2C			
	B1	ADC	POT	Right Hip	PDF241-S425F-103B0
	B5	ADC	POT	Right Knee	PDF241-S425F-103B0
	B9	ADC	POT	Right Ankle	PDF241-S425F-103B0
	B3	ADC	FSR	Right FSR1	FSR03CE
	B7	ADC	FSR	Right FSR2	FSR03CE
	B11	ADC	FSR	Right FSR3	FSR03CE
	A9	Encoder	Decoder	Right_En_A+	453234
	A10	Encoder	Decoder	Right_En_A-	453234
	A11	Encoder	Decoder	Right_En_B+	453234
	A12	Encoder	Decoder	Right_En_B-	453234

Sets of Inertial Measurement Units (IMU), Proximity Sensors, Potentiometers (POT), and Force Sensing Resistors (FSR) are connected as listed in above chart and located external to the control circuit card, they are interfaced per Inter-Integrated Circuit (I2C) serial interface or Analog to Digital Converter (ADC) to logic within the FPGA.

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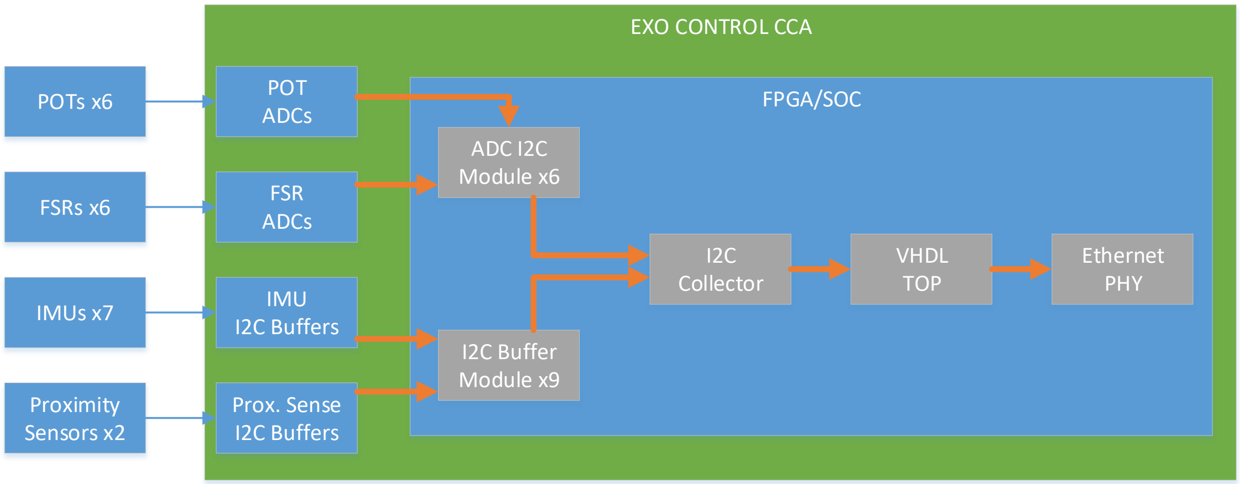
3.3 FIRMWARE ARCHITECTURE

One top level VHSIC Hardware Description Language (VHDL) module will control all aspects of the required logic architecture for this Test application of Exoskeleton Control Circuitry. It will control submodules as seen in the following logic diagram, and described in subsequent subsections.



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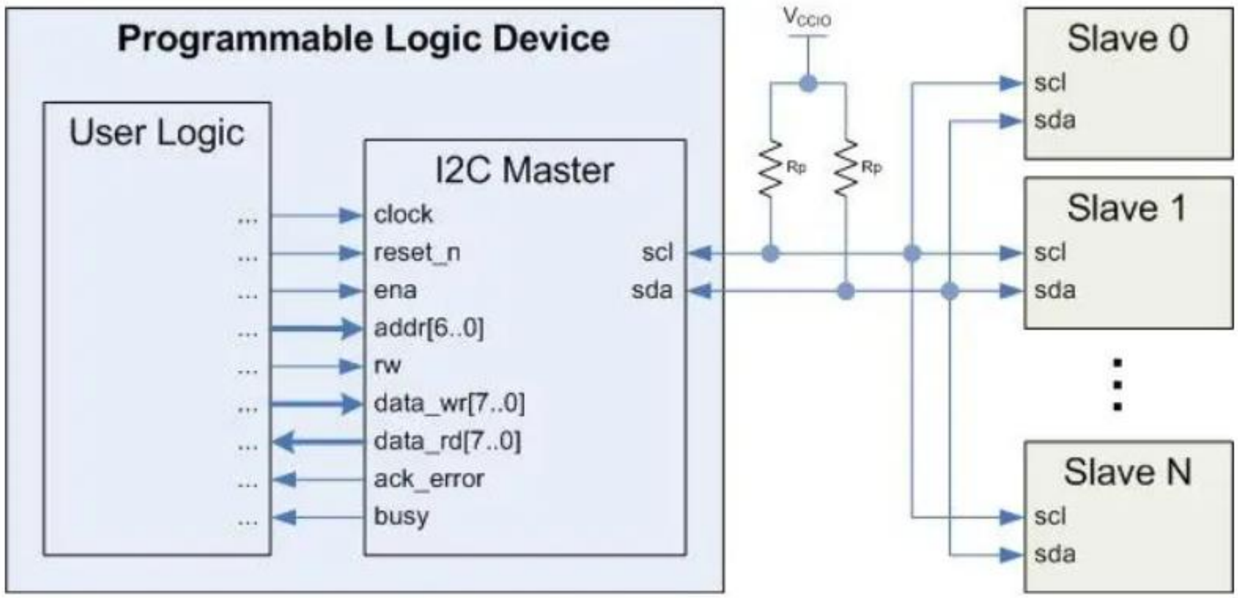
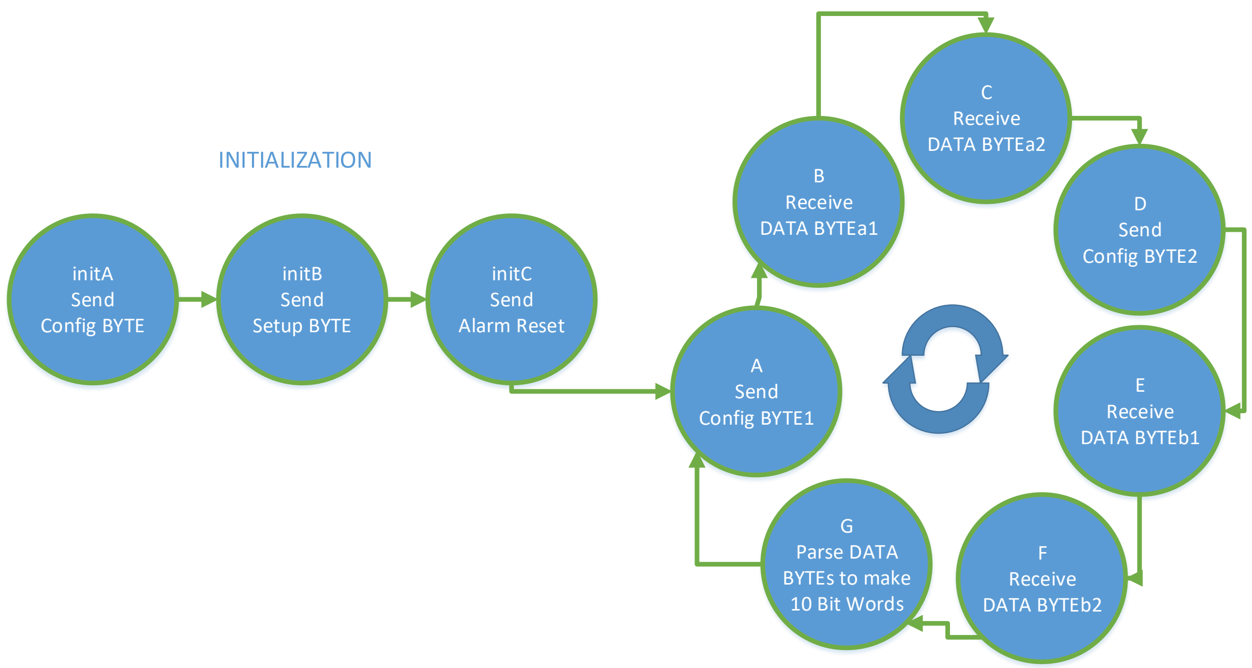
3.3.1 I2C Conversion

There are 15 I2C slaves being translated into 8bit bytes that will fully be addressed and data inputs buffered by the I2C collector module. Each I2C conversion module is a separate entity and instantiated on the TOP VHDL Module. Each I2C has a separate SCL and SDA line and can be collected in parallel, thus the SDA and SCL lines being interconnected is not real and should just be considered as shown for ease of depiction.



3.3.2 I2C Collector

3.3.2.1 Read 6 POTs



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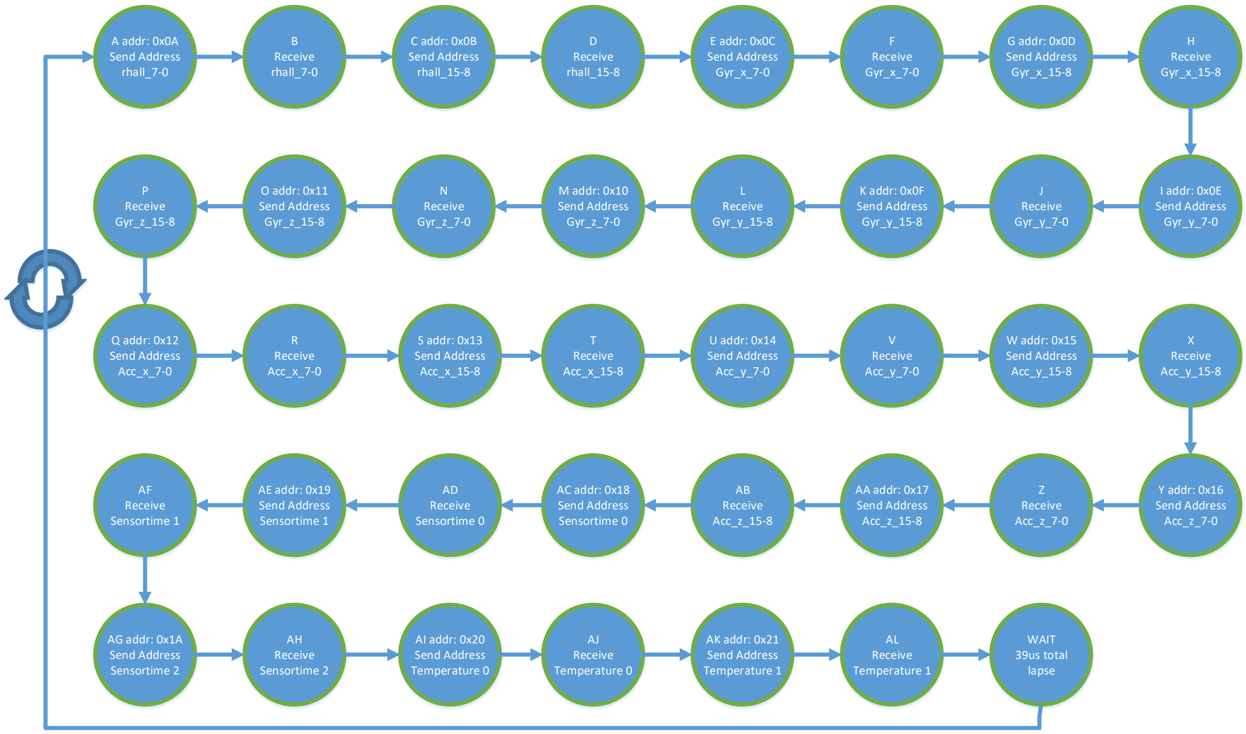
At startup, ADCs are initialized, then they are continuously cycled every 6 BYTE read/write cycles and packaged into 10 bit words to be sent to the Ethernet PHY. I2C clock frequency of 750khz

3.3.2.2 I2C IMU Buffer



The IMUs are continuously read in 39 microsecond intervals with an I2C clock frequency of 750khz. All bytes are read synchronously as shown in the above logic diagram. Each time one full read of this logic is performed, it also takes the buffered bytes from the ADCs and proximity sensors and sends packet through Ethernet.

3.3.2.3 I2C Proximity Sensor Buffer

This is to be determined, and not currently implemented with hardware not in place. All data associated with these sensors will carry bits of ‘0’ for corresponding words with this module not in place.

3.3.3 Ethernet PHY

The contents of this module is proprietary to XILINX. The contents will be delivered per 3.3.1 externally through 10/100 baseT Ethernet over industry standard CAT5 cable with a reconfigurable IP to be determined per the Kernel/Driver of the Host system receiving this data.

3.4 SECURITY ARCHITECTURE

Not required for initial prototype of this design

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3.5 COMMUNICATION ARCHITECTURE

Communication will be provided through user interface devices, USB, Bluetooth and Ethernet. The confines of control and feedback provided per these interfaces will be provided per the detail design of this system.

3.6 PERFORMANCE

Electronic Products that are also Medical Devices are subject to the device provisions of the Federal Food, Drug, and Cosmetic Act. This system **shall** adhere to all FDA, ISO, and IEEE standards relevant to its use and hardware. These cases will be evaluated by Internal Review Board (IRB) prior to utilization on human subject.

CAUTION—INVESTIGATIONAL DEVICE, LIMITED BY FEDERAL LAW TO INVESTIGATIONAL USE.