FlexSEA-Execute: Advanced Motion Controller for Wearable Robotic Applications

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***Abstract*—Wearable robots, such as powered prostheses and active exoskeletons, often rely on electric motors for actuation. Emulating biological joint angle and torque profiles requires special sensors, high peak power and advanced real-time controls. Safety is paramount and fail-safe circuits are required to detect and correct problematic situations. A smaller, lighter circuit can lead to a more efficient and affordable robot. Few commercial motor drivers accommodate all of these requirements. In this paper we present FlexSEA-Execute (Figure 1), the advanced motion controller part of FlexSEA, the FLEXible, Scalable Electronics Architecture designed for wearable robotic applications. At 36cm³ and 34.8g, this PSoC-based design integrates a 8A/25A (continuous/pulse) brushed/brushless motor driver, a safety co-processor, multi-drop RS-485, a strain gauge amplifier, a 6-axis inertial motion unit (IMU), USB, and a programmable expansion connector.**

Index Terms – embedded system, control, power electronics, brushless motor, wearable robotics

I. INTRODUCTION

Wearable robots can be used to replace limbs in subjects with pathologies [1], or they can be used to augment able-bodied subjects [4]. The fundamental goal of most prostheses is to reproduce the functionality of the biological limb they replace; their mass, volume and “behavior” have to be similar to their biological counterpart [3]. Exoskeletons used for rehabilitation, assistance, or augmentation, tend to apply power in a biomimetic way [5]. Precise motion control is fundamental in achieving these goals.

Wearable robots can be passive (no batteries, elastic and dissipative elements), quasi-passive (no net work from a power source, active elements such as clutches can be used) or active (can apply positive power with actuators). Passive or quasi-passive exoskeletons can be lighter than active devices. They can lower metabolic cost for specific actions such as walking [7] or hopping [8]. However, it is challenging to offset the penalty of added mass without adding positive power [5]; many devices include power storage and actuators. This works focuses on active devices and, more specifically, on motor control challenges.

Mass and volume are important constraints in wearable robots. More than the mass of the motor driver itself, its physical dimensions have a significant impact on the total system mass; a large circuit will require a larger enclosure. Added distal mass on extremities requires more metabolic energy than proximal mass [9], and according to the Augmentation Factor equation, the power to weight ratio of wearable robots is especially important for augmentation projects [5]. One strategy used by researchers to avoid power to mass ratio issues that can slow-down the development process and require more complex devices is to use off-board (i.e. external, bench-top) motors and electronics [6][11]. This generally confines the experiments to a fixed laboratory setting.

Autonomous, active wearable robots mostly use batteries for energy storage, and electric motors are the principal source of mechanical power. They can be brushed [2][10][12] or brushless direct current (BLDC) [1][3][5]. The higher power to weight ratio of the latter is beneficial, but it comes at the cost of more complicated power electronics. Electric motors with high torque constants can be used to reduce the transmission ratio required to obtain desired joint torque and speed. One brushless motor commonly used in research is the Maxon EC-30 (30501x, Maxon Motor, Sachseln, CH) [1][3][5]. Its low inductance, 16.3µH for the 24V version (model 305013), can be an issue for motor drivers and certain models require external inductors. They add mass, volume and inefficiency to the system.

The control algorithms used tend to emulate natural joint motion and they have to adapt to changing environmental conditions. The robot state and the environmental parameters are measured by sensors. Series-elastic actuators (SEA) [13], commonly used in wearable robotics [1][5], can require more sensors than electric motors alone. Force and torque can be measured with force-sensitive resistors [3], potentiometers or encoders linked to springs [2][4][9] and strain gauges [3][4][6][10]. Joint angles are measured by optical encoders [6] and potentiometers [10]. Accelerometers and gyroscopes (sometimes integrated in IMUs) are also used to estimate

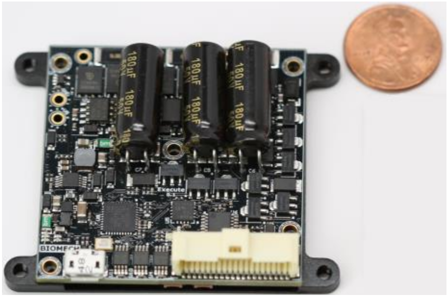

Figure 1 FlexSEA-Execute 0.1 mounted on its optional heatsink

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angles or gait cycle periods [3][5][14]. The control algorithms used in wearable robotics differ from what is used in industrial applications. As a consequence, control loops are not always closed on the motor driver [3][12]. Integrating more peripherals, computing power and sensors on the motion controller can reduce the number of circuit boards required for an application. It helps with performance by removing the delays of inter-circuit communication, and with reliability by reducing the number of connectors [15].

For wearable robots being attached to humans, safety and reliability are primary functional requirements [12]. This is especially true for medical devices. Faults need to be detected and corrective actions taken to place the system in a safe operating mode.

Through a careful analysis of wearable robotic requirements across sensor, actuator and computational modalities, it will be demonstrated that a motion controller design can be achieved that is applicable to a plethora of wearable robotic research programs, and that it can reduce design time and improve device functionality.

II. REQUIREMENTS

Based on the specificities of motor control for wearable robots and currently available electric motors, we compiled a list of requirements:

- Motor type: brushed and brushless DC
- Four quadrant (4Q) operation, supports regenerative currents
- Voltage (min.): 24V DC
- Power (min.): 100W average, 300W peak
- Current (min.): 5A average, 20-30A peak[1]
- Fast (2Mbps min.) multi-drop serial interface
- High pulse-width modulation (PWM) frequency, supports low-inductance motors without additional components
- Precise, high-bandwidth current control with min. 10kHz sampling frequency.
- Integrated strain gauge/load cell interface
- Integrated 6-axis IMU
- Expansion port to support additional inputs and outputs: analog inputs (min. 12bits), digital inputs and outputs, serial communication (UART/SPI/I^2C)
- Built-in safety detection and correction circuitry (brownouts, disconnected battery, software fault, over/under-voltage, over-temperature, etc.)
- Volume inferior to 50cm^3, longest dimension inferior to 60mm, weight under 50g
- No external circuitry or components required
- Passive cooling only, no fan required

Table 1 compares the major commercial motor controller mentioned in academic literature, and other comparable circuits currently available on the market. All the controllers listed support brushless motors, four-quadrant operation and sensor-based commutation. This work presents FlexSEA-Execute 0.1, an advanced motion controller that fulfills all the criteria listed above.

TABLE 1 COMMERCIAL MOTOR CONTROLLER COMPARISON

Manufacturer	**Advanced Motion Controls**		**Copley Controls**		**Elmo Motion Control Ltd.**	**Maxon**		**Roboteq, Inc.**		**Technosoft**
Model #	AZBDC20A8	DZRALTE-040L080	Accelnet Module (ACM-090-24)	Accelnet Plus Module (APM-090-30)	"Gold Whistle" G-WHI 15/100SE	EPOS4 Module 50/8 (504384)	EPOS4 Compact 50/8 CAN (520885)	SBL1330	SBL1360	iPOS4808 VX-CAN
Voltage (V)	10 - 80		20-90	14-90	12 - 100	10 - 50		9 - 30	9 - 60	11 - 50
Current (cont./pulse (A), time)	12/20, ?	20/40, 2s every 10s	12/24, 1s	15/30, 1s	15/21.2, ?	8/30, TBD		20/30, 30s		8/20, 2.5s
PWM f (kHz)	31	20	15/30		22	50		10 - 20		20 - 100
Controllers	Current	Current, Hall Velocity, Position, Velocity	Position, Velocity, Torque, Trajectory		Current, Velocity, Trajectory, Motion Controller	Position, Velocity, Torque, Trajectory		Speed, Position		Current, Speed, Position, Trajectory
Protections	Over current, over temperature, over/under-voltage, short circuit	40+ configurable functions, over current, over temperature (drive & motor), over/under-voltage, short circuit	Over/under-voltage, temperature, short-circuit, I^2t		Software error, short-circuit, temperature, over/under voltage, internal errors, etc.	Current limit, overcurrent, temperature, over/under-voltage, voltage transients, short-circuit, firmware		Short circuit, stall, over/under-voltage		Short-circuit, over/under-voltage, temperature, I^2t
Interface(s)	PWM & DIR	RS-232, RS-485, analog, PWM, etc.	RS-232, CAN, analog		RS-232, USB, CAN & EtherCAT optional	CAN, RS-232, USB, Optional EtherCAT		RS232, 0-5V Analog, or Pulse (RC radio), optional CAN, USB		RS-232, CAN w/ selectable address
Addressable	No	Yes	Yes		Yes	Yes		Yes		Yes
Expansion	None	8 digital (5 in, 3 out), 1 analog	10 digital in, 2 digital out	11 digital in, 6 digital out, 1 analog in	2 digital in, 2 isolated digital out, 2 non-isol. digital out, 2 analog in	4 digital in, 2 digital out 500mA, 2analog in, 2 analog out		2x 40V 1.5A outputs, 6 IOs		2 analog in, 8 digital in, 5 digital out 500mA
Min. Inductance (µH)	100	150 at 48V, 75 at 25V	200	200	100	100-200		Unspecified		8 at 100kHz (>60 recommended)
Commutation	Trapezoidal	Sinusoidal, Trapezoidal	Sinusoidal	Sinusoidal, field-oriented control	Vector control sinusoidal	Field-oriented Control (FOC)		Trapezoidal		Sinusoidal, Trapezoidal
Physical (X/Y/Z, V, W (mm, cm^3, g))	63.5/50.8/22.9, 74, 94.5	76.2/50.8/22.9, 89, 123.9	102.7/66.5/24.9, 170, 160	76.3/58.2/20.5, 91, 120	55/46/15, 38, 55	59.5/46/14.1, 39, TBD	59.5/58.5/33, 115, TBD	70/70/25.6, 125, 60		56/48.1/8.9, 24, 16
Comments	Designed to be integrated in your PCB. Certified.	Addressable, Designed to be integrated in your PCB. Certified.	Many voltage and current options in the same family. Certified. Optional heatsink.		Many voltage and current options in the same family. Fully programmable	New product, coming soon. Pin headers for PCB mounting.	New product, coming soon. Comes with connectors. Built-in motor chokes (2.2µH)	Basic scripting, prog. current limit, 115k RS-232		Weight excludes connector and capacitors. Volume excludes capacitors. Programmable motion sequences.
Referenced	[3]		Brushed eq. in [4][12]					[5]		[14]

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[1] Power and current peaks can happen at different times in the gait cycle, hence voltage times peak current doesn't not equal peak power.

III. HARDWARE DESIGN

At its core, the FlexSEA-Execute board is a BLDC motor driver specialized for robotic and prosthetic applications. The high level hardware design goals were to maximize the system integration (small physical dimensions, large number of integrated peripherals and interfaces, support for external input and output devices), allow fast communication and networkability via the use of a fast multi-drop communication interface, and have built-in safety features. Figure 2 presents the logical organization of the FlexSEA-Execute 0.1 board. In orange are the schematic sheets and in grey are the sub-circuits present on certain sheets. Figure 3 highlights the safety features. These circuits, subcircuits, and additional features are discussed in sections A-H below.

A. *Microcontroller and safety co-processor*

A Cypress Semiconductor Programmable System on Chip (CY8C5888AXI-LP096, Cypress Semiconductor, San Jose, CA) was selected as the main controller. Unlike most of the ICs used for this application, it is not a microcontroller optimized for motor control or a DSP [19], but a hybrid solution comprising of a 80MHz ARM Cortex-M3 microcontroller, and analog and digital reconfigurable blocks integrated in one chip. It allows a tighter integration of analog peripherals, high performance control loops with minimal CPU intervention, and more flexibility for the expansion IOs than conventional microcontrollers.

To prevent user errors from creating dangerous situations, or to recover from a failure, a second controller (CY8C4245LQI-483, Cypress Semiconductor, San Jose, CA), is used as a safety co-processor. Figure 3 shows the PWM lines going through the second processor. It has total control over the power bridge and it can place the system in a fail-safe mode. A Watchdog Clock (WDCLK) line is used to notify the co-processor of problems with the main microcontroller. I²C is used to exchange information and sensor values.

B. *Power bridge and current sensing*

Three half-bridges are present on the circuit, with two MOSFETs and one gate driver each. The BSC014N06NS MOSFETs (Infineon Technologies, Neubiberg, DE) were selected for their small, industry standard package (QFN 5x6), availability, price, low drain to source resistance ($R_{DS(ON)}$) and low gate capacitance. As a safety margin, MOSFETs rated for at least twice the bus voltage (28V Max) were selected. At 60V, the BSC014N06NS are protected in case of major inductive spikes. The IRS21867 (International Rectifier, Leominster, MA) gate drivers were selected because of their robustness, especially for their tolerance to negative transient voltages. The gate resistor values were experimentally chosen, via simulation and in-circuit measurements. 6.8Ω and 3.3Ω (respectively high- and low-side) offer a good compromise between fast transitions and minimum ringing.[2] The programmed deadtime of 13 cycles gives us an effective 100ns between transitions of complementary MOSFETs (calculated from the gate threshold voltage) and a negative undershoot below 2V. Placement and routing have been carefully optimized to minimize parasitic inductance and improve thermal dissipation.

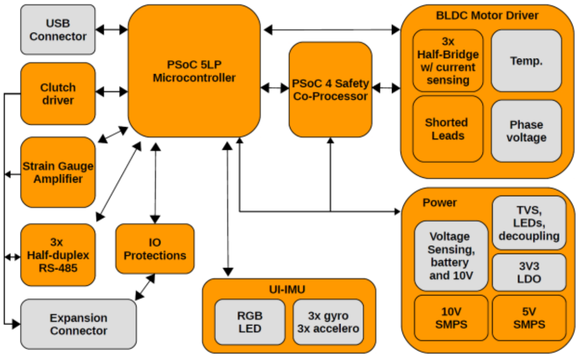

Figure 2 System diagram - overall

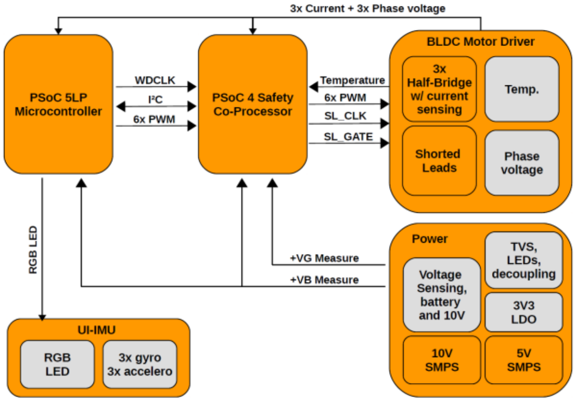

Figure 3 System diagram - safety features

Each half-bridge has a 5mΩ low-side current sensing resistor. Programmable analog blocks inside the PSoC 5 are used to create a ±20A current sensor with only 3 external components (amplifier feedback resistors and low-pass filtering capacitor).

C. *Communication*

Controller Area Network (CAN) [18] and Ethernet for Control Automation Technology (EtherCAT) are commonly used in robotics. CAN is inexpensive, robust and safe, but its 1Mbps bandwidth can be an important limitation for application with multiple motor drivers and fast refresh rates. EtherCAT offers 100Mbps but it requires a master, special cables, connectors, and application-specific integrated circuits (ASICs). They add to the cost, volume and complexity of the system. RS-485 is often associated with old technology [17] but its simplicity, low cost, robustness and speed (theoretically up to 100Mbps; 4Mbps achievable in our application[3]) made it an interesting option for FlexSEA, especially in multi-drop configuration. Three transceivers are used to allow different communication strategies. From one

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[2] The schematic shows 47Ω gate resistors. They were used as a safe value before the optimization could be done.

[3] Single twisted pair asynchronous communication; limited by the PSoC UART component.

to 3 twisted pairs can be used to achieve asynchronous half-duplex (default), synchronous half-duplex, asynchronous full-duplex or synchronous full-duplex data exchanges.

D. Connectors

The two power input signals (battery voltage and ground) and the three motor phases use through-hole pads on the circuit board. They can accommodate wires up to AWG16. Inline connectors, such as bullets or Anderson Powerpoles, can be used. This design choice gives the robot designer maximal flexibility regarding mechanical integration, and it keeps the circuit size small.

A 40 position Molex PicoClasp (501571-4007, Molex, Lisle, IL) connector is used for all other signals: RS-485 differential pairs, strain-gauge input, Hall effect sensors, encoder, and 12 expansion signals. Up to 8 of them can be analog inputs (Analog to Digital Converter (ADC): 12-bit SAR, 8-20-bits Sigma Delta). Serial communication interfaces such as UART, I²C, and SPI can be software-linked to the connector, allowing the connection of external circuitry.

E. Sensors

Many control strategies rely on force/torque sensing [14]. In electric motors torque is proportional to current, but it is an indirect measurement when a transmission is involved. The torque constant can also change with temperature. Strain gauges and load cells can be used for accurate, direct force measurement. Their output signals are typically in the order of millivolts. A high amplification is needed, and electromagnetic noise from the motor and the power electronics can become an issue. FlexSEA-Execute has a built-in two stage differential amplifier. Offset and gains are digitally programmable (half-supply ±20%, $500 < \text{Gain} < 10000$). A low-pass common mode filter with 44dB of attenuation at 20kHz filters commutation noise, allowing the sensor to be used near motors. Spring deflection force sensors (or any other analog sensor) can be accommodated via the analog inputs on the expansion connector.

Accelerometers and gyroscope can be used to measure the robot's position in the gate cycle, heel strike or joint angle. A 6-axis IMU (MPU-6500, InvenSense, Boston, MA) (±2 to ±16g, ±250 to ±2000°/s) is built-in. Bus voltages, phase voltages, microcontroller temperature and power bridge temperature are measured to detect abnormal situations.

F. Protection circuits

In case of major problem, such as a disconnected battery, a prosthesis has to be placed in a fail-safe mode to protect its wearer. Brownout protection circuits (capacitors isolated by a diode) keep the microcontrollers powered a few milliseconds after the bus drops, allowing them to place the system in a safe state. Shorting the leads of the motor provides damping, a safer scenario than a free moving joint. Depletion-mode MOSFETs are used to short the motor leads together in the absence of power or control signal. The safety co-processor has to actively generate a negative voltage to disable that protection, making the system inherently safe.

All the signals going to the external world via the expansion connector have clamp diodes and series resistors to protect the board in case of Electro-Static Discharge (ESD). A unidirectional Transient Voltage Suppressor (TVS) is used to protect the +VB bus in case of over-voltage or reverse polarity.

G. Printed circuit board (PCB) and heatsinking

Integrating all of the required circuits in a small volume required careful component placement and layout. Leadless surface-mount packages with fine pitches and connection density demand small trace width and spacing of 5 mils. This prevented the use of 2Oz (or more) copper for the power electronics[4]. A 6-layer PCB with blind-vias was designed, with up to 3-layers used per power path. Dual-sided assembly was used. Mixing high-power electronics and sensitive analog amplification on the same circuit required special attention to signal integrity. Multiple vias are used to extract heat from the PCB traces and planes and bring it to the bottom layer. A flat, unpopulated surface is used to get a low thermal resistance connection with a heatsink. Isolating phase-change thermal transfer material is used between the PCB and the heatsink (Laird Technologies A15372-02, 0.02°C/W, 127µm).

H. Miscellaneous

Other features of the design include a clutch driver on an 8-bit 20kHz output, and a RGB LED to indicate board status. Two switch-mode power supplies (SMPS) are used to generate 10V for the gate drivers and 5V for the microcontroller and peripherals.

IV. SOFTWARE DESIGN

The PSoC has programmable analog and digital blocks. They can be configured graphically (schematic and drop-down menus) or via their C API. Programmable hardware and the direct memory access (DMA) controller are used to reduce CPU load.

The BLDC commutation is handled in hardware. Look-up tables orient the complementary PWM signals to the half bridges according to Hall sensors. A 12-bits 1MSPS SAR ADC samples the appropriate current sensor in the middle of the active PWM cycle and a DMA interrupt is generated every 5 samples (20kHz when using 100kHz PWM). It calls the software PI current controller. Other than the current controller, the software stack includes a PID position controller, a trapezoidal trajectory generator and an impedance controller. Custom controllers can easily be added by users.

A master timer generates a 1ms timebase, divided in 10 100µs slots. This time-sharing mechanism allows code to be executed at a constant period, with a fixed phase between functions. This mechanism adds determinism, stabilizes the

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[4] Technically possible, but cost prohibitive.

behavior of the code, and simplifies the integration of new routines. More details about the software are available in [20][21] and by consulting the sources.

V. RESULTS

Table 1 summarizes the specifications of FlexSEA-Execute 0.1. Many of the experimental procedures are extensively described in [20].

FlexSEA-Execute's board temperature was measured in continuous during 3 trials (33 minutes each, with a cooldown period between each trial). The experimental parameters used were: 100kHz PWM, 7Ω/4Ω gate resistors, 20 cycles deadtime[5], 540W power supply (9152, B&K Precision, Yorba Linda, CA), 120µH 400mΩ load, circuit mounted on its 5 cm^3 minimalist aluminum heatsink (see Figure 1) and suspended 15cm above the test bench, no forced air. Conservative continuous current values of 5 and 8A have been used to obtain the static current rating. To emulate a typical biological profile, a pulse experiment was done with 100 millisecond long 25A pulses every second (10% duty cycle) and "off" duty-cycle current of 3.5A (average current of 5.65A). Figure 4 shows the results of the three experiments. The thermal time constant is approximately 4 minutes.

A strain-gauge (MLC700-10KG, Manyyear Technology Inc., Shenzen, China) force calibration experiment, in the presence of 20kHz motor commutation noise, gave a coefficient of determination (R^2) of 0.9928. Motor current can also be used to control force. The 20 kHz PI current controller was tested with a fixed static load (120µH 400mΩ), and a set point ramping from 1.64A to 13.71A in increments of 610mA. The current measured (A622, Tektronix, Beaverton, OR) confirmed the theoretical gain of 12.2mA/bit. The coefficient of determination of the transfer function is $R^2=0.99$.

The two 500mA SMPS (10V for the gate voltage and pre-regulation, 5V for the logic circuits) were tested up to 600mA. The protection circuits (PTC) introduce load regulations of respectively 9.38 and 12.69%. This can affect analog measurements when significant current is drawn. The list of safety features tested includes the watchdog clock, over-temperature, battery voltage range and disconnected battery. The test procedures and details results are available in [20]. The appropriate reaction to a specific fault being application dependent, the errors are flagged but no corrective actions are taken in the current software release.

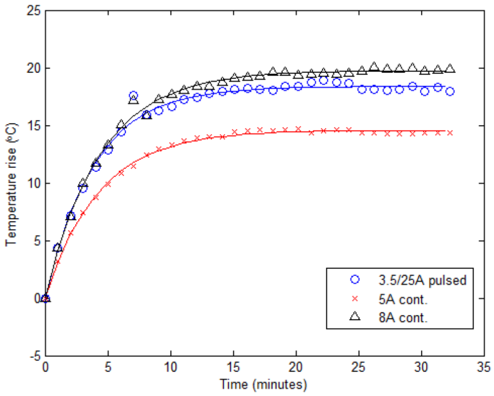

Figure 4 Thermal step response

The RS-485 communication was tested with one twisted pair (asynchronous half-duplex) at 2Mbps with three circuits on the same bus (1x Manage, 2x Execute). Future experiments will include the other two transceivers and faster data rates.

VI. DISCUSSION

Table 1 and Table 2 compare FlexSEA-Execute with commercial alternatives. The only commercial solution that is smaller and lighter than FlexSEA-Execute is the Technosoft iPOS drive, however it requires a female connector and capacitors, making a true comparison hard. No product integrates an IMU or a strain gauge amplifier. The main hardware limitation of the design we advance in this paper is the limited input voltage (24V). Some competitors provide more safety features than FlexSEA-Execute. All the hardware required by these functions is present on the circuit, but the supporting software has yet to be developed.

TABLE 2 FLEXSEA-EXECUTE 0.1 SPECIFICATIONS

Elect.	Supply voltage	15-24V
	Motor current	8A Continuous, 25A pulsed (100ms every s)
	Intermediate	10V 500mA SMPS
	Logic supply	5V 500mA SMPS
Motor	Type	3-phase brushless (BLDC)
	Sensor(s)	Hall effect, optical encoder
	Commutation	Block (Sinusoidal & FOC HW supp.*)
	PWM	12 bits 20kHz, 9.65 bits 100kHz
	Inductance	Unspecified, min. value tested 63µH
CPU	Reference	PSoC 5LP - CY8C5888AXI-LP096
	Special features	Programmable analog and digital blocks
	CPU/RAM/IOs	80MHz ARM Cortex-M3, 256KB RAM, 62
	Software / IDE	PSoC Creator 3.1, C (GCC 4.7.3) and
	Co-processor(s)	PSoC 4 - CY8C4245LQI-483
Serial interface	Type	3x Half-Duplex RS-485
	Bandwidth	Up to 4Mbps with 1TP, 2Mbps tested
USB		Full-Speed (FS) 12 Mbps
Current control	Hardware	5mΩ resistor
	Software /	20kHz PI controller, 12.2mA/bit
Safety features	Overvoltage	TVS clamps at 36V
	Overcurrent	Software protection
	Locked rotor	Hardware - lead shorting circuit
	Board	CPU + bridge temperature reading
Clutch		Variable voltage, 8-bits PWM, 400mA
Strain		Dual stage, 500 < G < 10000, high CMRR
External periph.	Connector	Molex PicoClasp 40 positions, SMD 1mm
	IOs available	12
	Digital IOs	Up to 12
	Analog inputs	Up to 8 (12-bit SAR, 8-20-bits Sigma Delta)
	Serial	I^2C, SPI, UART
	Other	1 optical encoder (A/B/I), 1 Hall effect
Physical	X (mm)	49
	Y (mm)	49
	Z (mm)	From 12 to 15mm depending on capacitors
	Weight	20.1g barebone, 34.8g with heatsink
PCB tech.	Layers	6
	Copper	1 Oz
	Trace/space/via	5/5 mils trace/space, 8/20 mils blind vias
	Assembly	Double-sided
Other		6-axis IMU, RGB LED

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[5] The optimal values of 6.8 and 3.3Ω were not available at the lab when the experiment was conducted. The deadtime was lengthened from 13 to 20 cycles to accommodate the slower transitions.

A. Future work and open source

At the time of this publication FlexSEA is an active project and FlexSEA-Execute 0.2 is currently being tested. The main modifications are:

- Wider input voltage: 18 to 48V
- Supports peak current of 30A
- On-board memory (data logging)
- Improved voltage regulators
- Easier to use programming connectors
- Minor bug corrections listed in [20]
- Better safety detection and limits: I²t calculation, safe shutdown when problems are detected
- Graphical user interface (GUI) to simplify debugging and tuning
- Faster data transfer using the 3 twisted pairs

All the FlexSEA design files and sources are open-source and can be used as-is, or modified, in your future project[6]. Sharing a common design allows the exchange of software among researchers worldwide, promoting collaboration and quickening the advancement of science.

B. Conclusion

In this paper we present FlexSEA-Execute, an advanced motion controller optimized for wearable robotic applications, part of the open source flexible, scalable electronics architecture (FlexSEA). It has been used to prototype a knee prosthesis, autonomous ankle exoskeletons and a bilateral ankle exoskeleton with neuro-inspired controls. We humbly hope that FlexSEA-Execute will become a widely adopted motor driver in the field of wearable robotics, paving the way for revolutionary artificial limbs and human augmentation machines.

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