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System Integration in a Through-the-Road, In-Wheel Motor Hybrid Electric Vehicle Using FPGA-Based *CompactRIO* and *LabVIEW*

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Abstract –*A through-the-road (TTR) hybrid electric vehicle (HEV) is a sub-type of the parallel hybrid, in which the internal combustion engine (ICE) and electric motor provide propulsion power to different axles. TTR architecture allows for hybrid conversion of an existing vehicle using in-wheel motors (IWM), as alternative to on-board motor. Operation requires different types of signals to be acquired and processed: hardwire low-voltage analog signals, digital pulse-train and CAN-bus signals. This work discusses system integration in a TTR hybrid: motor controller, engine control unit (ECU) and energy management system (EMS), using FPGA-based CompactRIO controller. The EMS needs to generate an enhanced throttle signal to the ECU - bypassing the original signal from the throttle position sensor - to gain control of the internal combustion engine for proper hybrid operation.*

Keywords: HEV, split-parallel hybrid, TTR hybrid vehicle, in-wheel motors, energy management system, system integration, throttle emulation

1.0 INTRODUCTION

A split-parallel hybrid electric vehicle (HEV) is a sub-type of parallel HEV, in which the internal combustion engine and electric motor provide propulsion power to different axles of the vehicle. The term ‘through-the-road’ (TTR) hybrid is also used to refer to this architecture, since power coupling between the engine and electric motor is not through some mechanical device but through the vehicle itself, its wheels and the road on which it moves. TTR drive-train allows for the possibility of hybridizing existing vehicle with in-wheel motors (or hub motors) - as an alternative to on-board motor - for retrofit hybrid conversion. The front driveshaft is powered by the engine, while the rear wheels are fitted with in-wheel motors, resulting in a through-the-road, in-wheel motor hybrid vehicle (TTR-IWM) (Figure 1).

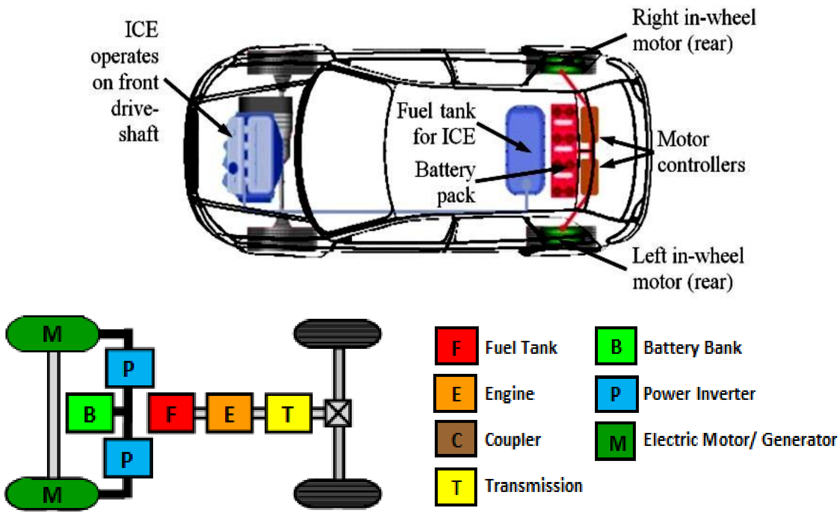

Figure 1: Split-parallel through-the-road hybrid electric vehicle with in-wheel motors

For comparison, Figure 2 presents two other configurations of a single-axle, device-coupled parallel hybrid drive-train: post-transmission and pre-transmission coupled.

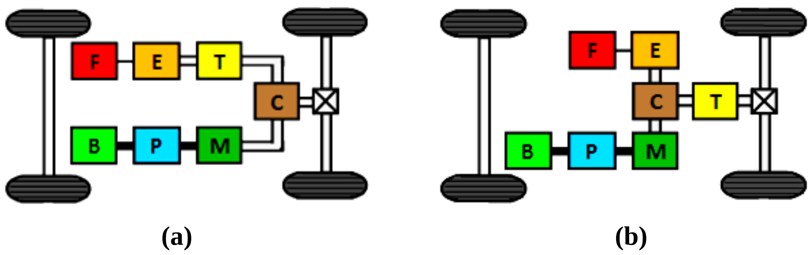

Figure 2: Single-axle, device-coupled parallel HEV configurations:
(a) post-transmission, (b) pre-transmission

A TTR-IWM system consists of motor drives to control the in-wheel motors, energy storage (battery pack) and an energy management system (EMS) to control the vehicle's energy flow. Reduction of fuel consumption is the main target of having a hybrid power-train, along with these other objectives (Chan et al., 2010; Ehsani et al., 2010):

i) To fulfill power request from the driver (acceleration, gradeability and peak speed)
ii) To minimize emissions
iii) To sustain a reasonable level of state-of-charge (SOC) of the on-board energy storage device for self-sustaining operation, and
iv) To recover as much of braking energy as possible.

Optimized design and sizing of the HEV components are critical in achieving the above objectives (Young et al., 2007; Anbaran et al., 2014). The EMS control strategy is equally significant - to control operational status and power distribution between the two propulsion sources, in order to optimize fuel consumption and have a self-sustaining energy storage, since the vehicle is a non-plug-in hybrid (no external charging). The EMS receives inputs of throttle position and brake pedal request directly from the respective sensors (analog signal), engine rpm and vehicle speed from the instrument panel (digital pulse-train), fuel consumption from the fuel flowmeter (digital pulse), battery state of charge (SOC) and various motor parameters from the motor controllers (CAN bus) (Zulkifli et al., 2015).

2.0 SYSTEM ARCHITECTURE AND PARAMETERS

Figure 3 shows a generalized system architecture of the TTR-IWM hybrid, applicable to new purpose-built and conversion vehicles. The EMS is connected to the ECU and motor controllers. The in-wheel motors are driven by dedicated controllers which operate in torque control, to vary current fed to the motors. In addition, the EMS generates throttle command signals, which represents power demand, to both the ECU and motor controllers.

Power request from the driver comes from the throttle position sensor (TPS). Along with other inputs, the TPS signal is used in the ECU of a conventional vehicle to determine fuel injection and ignition parameters, which directly affect engine power output. In a hybrid power-train, the same TPS signal will be processed by the EMS to produce power commands to both the ECU and motor controllers (Zulkifli et al., 2015).

During vehicle braking, a brake pedal position signal (BPP) is sent to the EMS, which then instructs the motor controller to reverse current flow to allow the in-wheel motors to operate as generators, to charge the on-board battery bank - a process called re-generative braking, or simply 're-gen'. Thus, an important function of the EMS is to determine the amount of power to be derived from the generators for battery charging and self-sustaining operation.

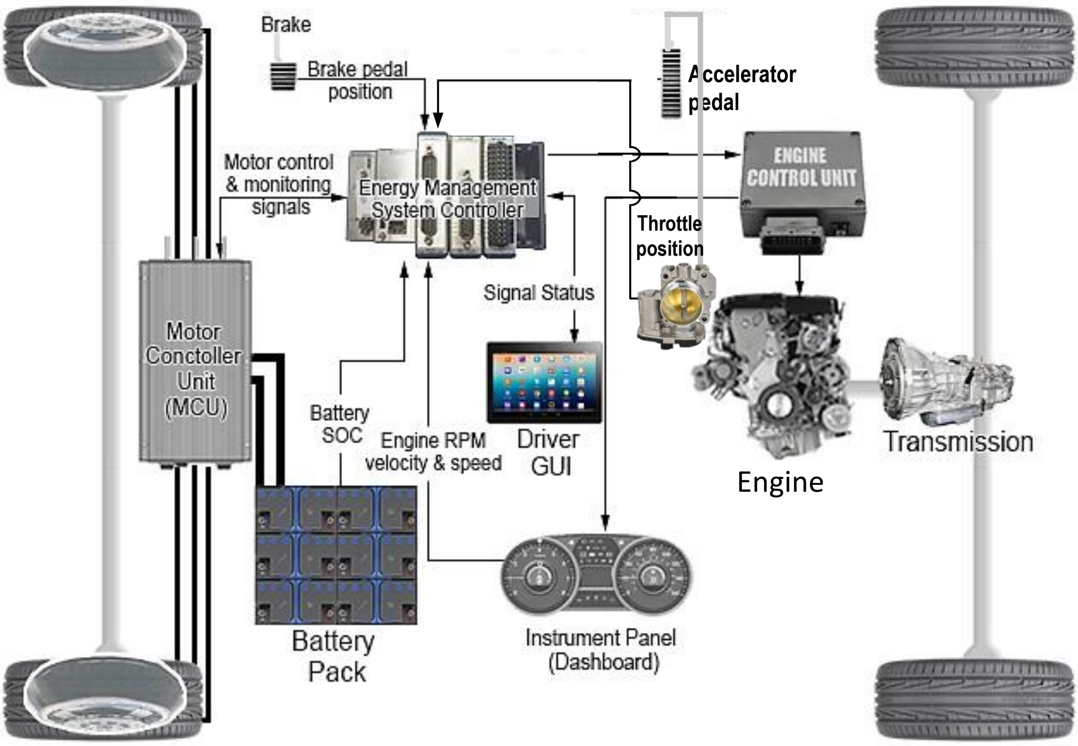

Figure 3: System architecture of split-parallel TTR-IWM hybrid vehicle

Figure 4 and Figure 5 show block diagram and control parameters of a TTR-IWM hybrid system, highlighting the EMS in a dashed rectangle. In a basic hybrid conversion, there is no signal going from the EMS to the ECU; thus, engine operation cannot be controlled. This leads to a serious drawback since the original look-up maps in the ECU are designed for single-source propulsion only (engine only) and the pre-tuned engine parameters may not yield optimum performance when electric propulsion is added to the system. Shifting of the engine operating point – which is a critical strategy of hybrid operation to reduce fuel consumption and achieve higher efficiency – cannot be directly controlled without a signal from the EMS to the ECU.

The figures below show an additional parameter: an enhanced throttle signal which bypasses the original TPS, which will allow the hybrid system to gain control of the engine, as in a production hybrid vehicle. This enhanced TPS is generated by the EMS based on the original TPS and a certain control strategy to achieve optimal power distribution and fuel economy (Zulkifli et al., 2014).

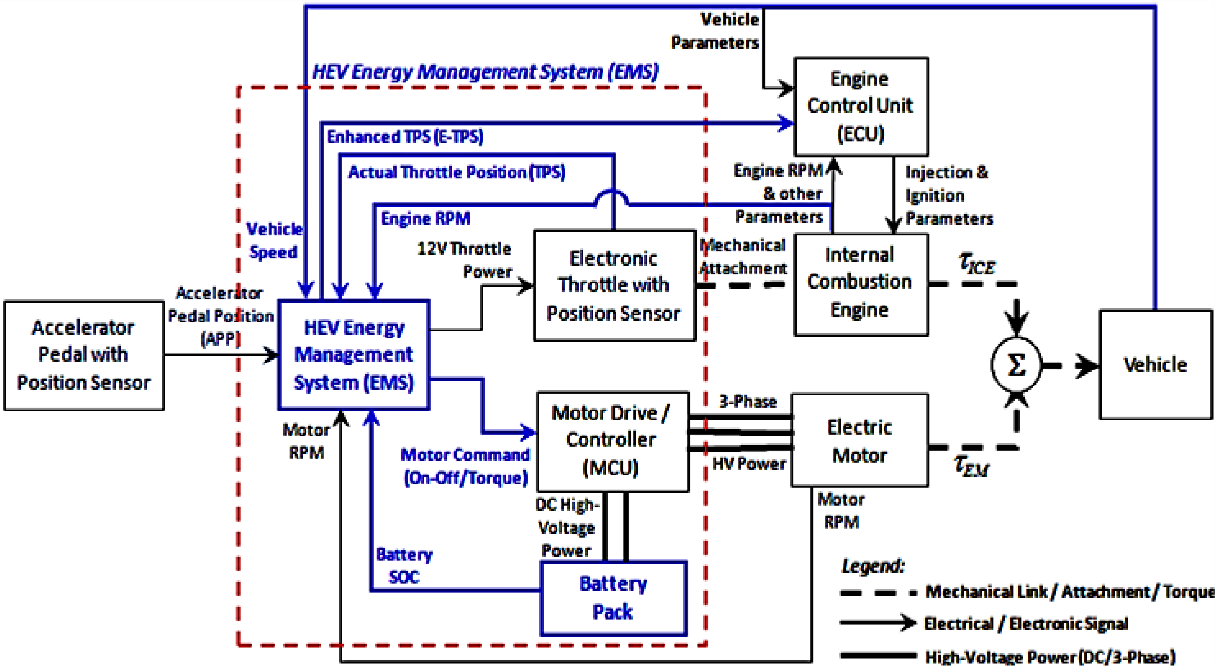

Figure 4: Block diagram of TTR-IWM hybrid system with enhanced throttle signal (TPS)

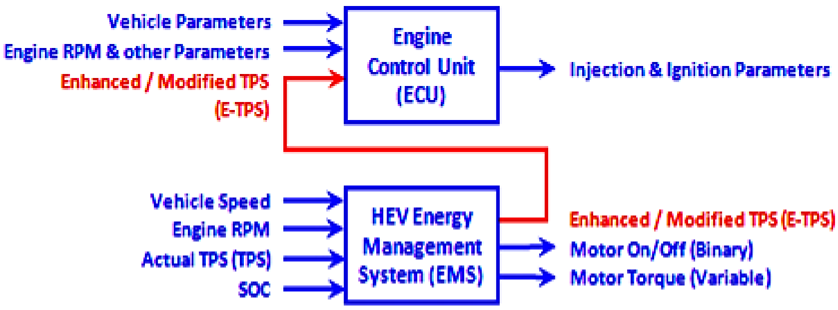

Figure 5: Control parameters with enhanced throttle signal from EMS to ECU

3.0 EMS IMPLEMENTATION

Figure 6 shows in-wheel motor installation and motor controllers located in the trunk of the vehicle, along with a DC-DC converter to obtain supply power for the motor controller from the car's 12V battery at the front. The different types of signals – analog, digital and CAN – requires a mixed-signal controller hardware for the EMS. In the present conversion hybrid program, a *National Instruments' CompactRIO* FPGA-based embedded controller (Figure 7) is employed, programmed with *LabVIEW* software.

A graphical driver interface (GUI) is implemented on a tablet PC (Figure 7) with a cabled TCP-IP or wireless connection to the EMS. The interface appears on a dynamically-controllable HTML page hosted by the web server function of the *CompactRIO*, enabling the driver to monitor and control the hybrid drive-train. In-vehicle data logging of EMS parameters is also possible. Table 1 lists the respective parameters monitored and controlled by the EMS, while Figure 8 shows vehicle layout and connectivity of the TTR-IWM system, along with EMS *CompactRIO* controller installation in the vehicle. Figure 9 shows the complete system connectivity and cabling diagram for the TTR-IWM hybrid electric vehicle.

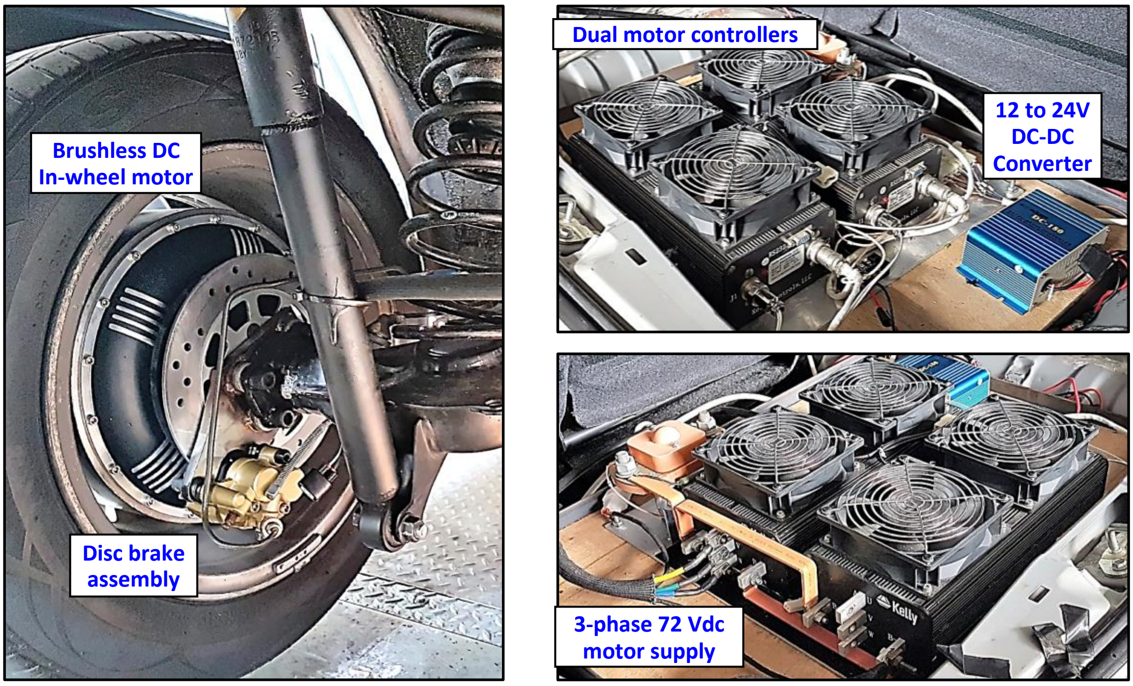

Figure 6: In-wheel motor installation and motor controllers with DC-DC converter

Figure 7: *National Instruments CompactRIO* and tab-based graphical driver interface

Table 1: EMS control/monitoring parameters

	I/O Parameter	Cable Type	Signal Type
A	Fuel Flow	2-core shielded pair	Digital pulse
B	Throttle Position Signal (TPS)	2-core shielded pair	Analog
C	Enhanced Throttle Position Signal	2-core shielded pair	Analog
D	ECU Parameters	4-core shielded pair	Digital pulse-train
E	Brake Pedal Position	3-core shielded pair	Analog
F	Motor Parameters	4-core shielded pair	CAN bus
G	Battery State-of-Charge (SoC)	2-core shielded pair	Analog
H	Motor Torque Command	4-core shielded pair	Analog

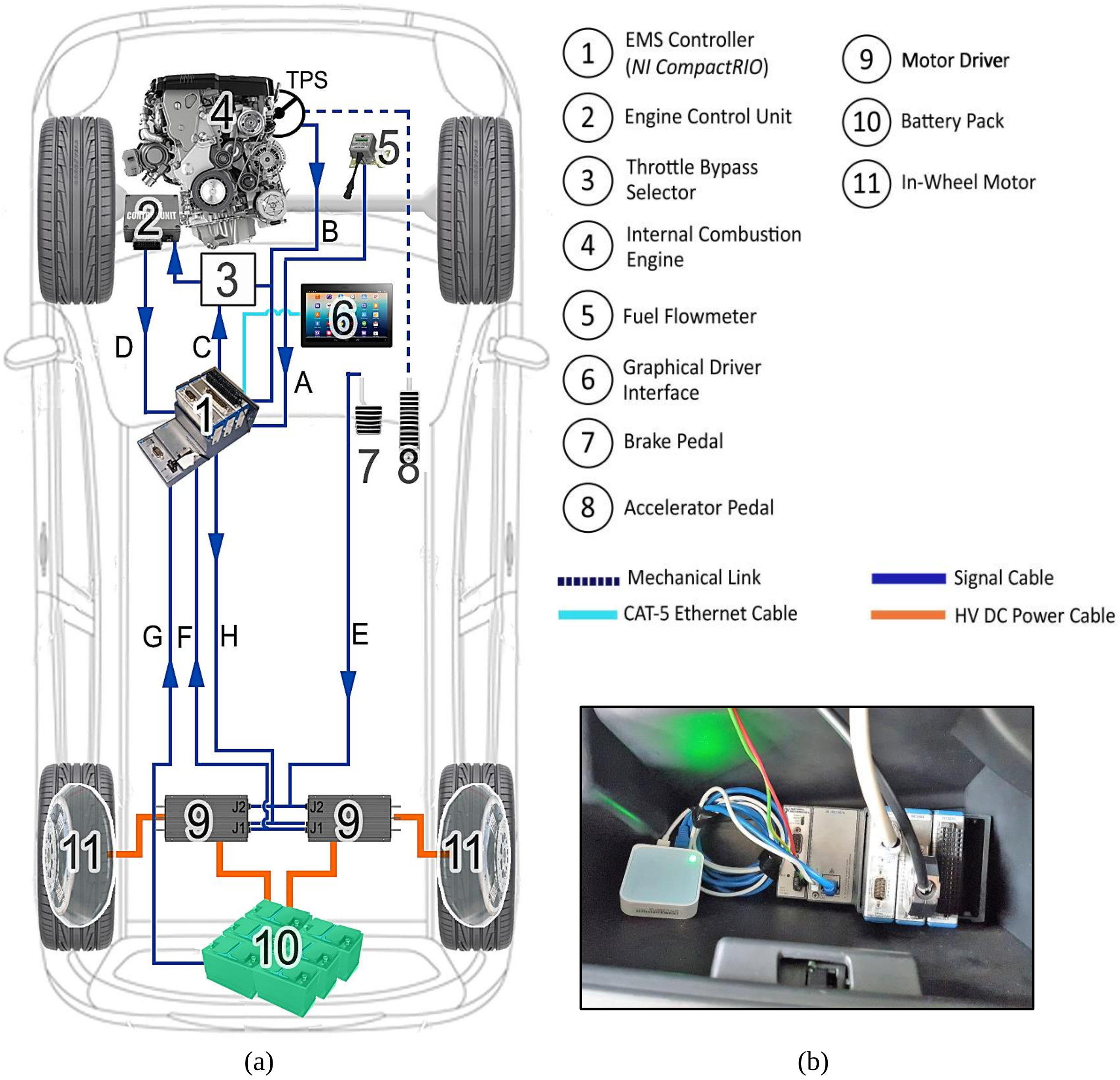

Figure 8: (a) Vehicle layout and system connectivity; (b) EMS controller (*NI CompactRIO*) with wireless router in the passenger glove compartment

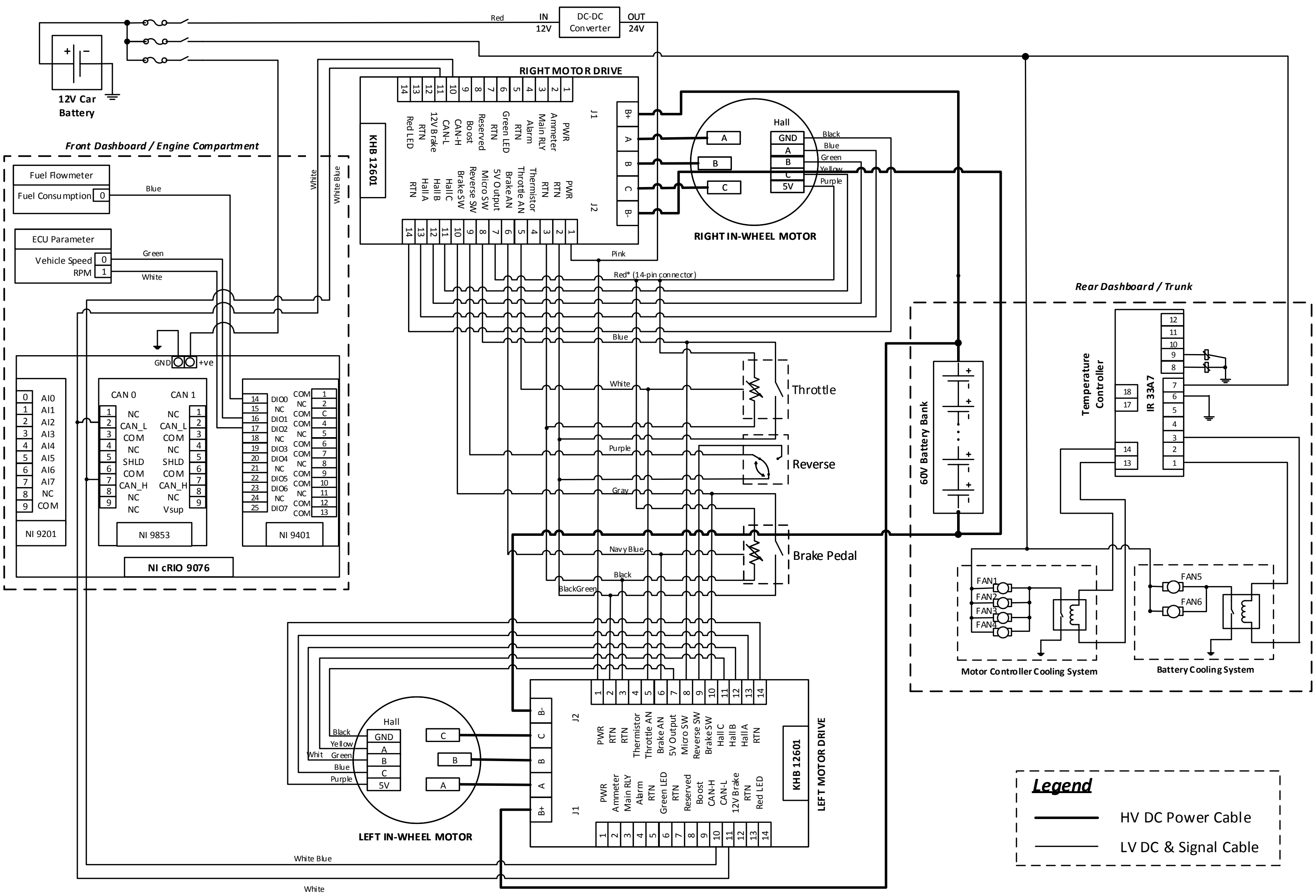

Figure 9: System connectivity and cabling diagram of TTR-IWM hybrid electric vehicle

4.0 FUEL CONSUMPTION AND ECU PARAMETERS

4.1 Fuel Flow Measurement (Digital Pulse)

An instantaneous fuel flow transducer (installed in vehicle hood) generates a pulsed signal output where each pulse represents 5 ml of fuel consumption. A *CompactRIO* digital input/output module NI 9401 is used for the fuel measurement (Figure 10). However, since the flowmeter sends a 12-V pulse train while the NI 9401 only accepts digital TTL signals (below 5.25 V), a diode clipper circuit is used to condition the signal before entering the NI module.

A screenshot of the graphical driver interface is also shown in Figure 10, for continuous real-time monitoring of vehicle parameters and in-vehicle data logging. The red rectangle shows fuel flow reading updated with every new pulse received from the flowmeter, while the blue box shows logging of both instantaneous fuel flow and accumulated consumption. The two graphs in the green rectangle show instantaneous flow and total consumption. Figure 10 also shows the *LabVIEW* program code for fuel measurement.

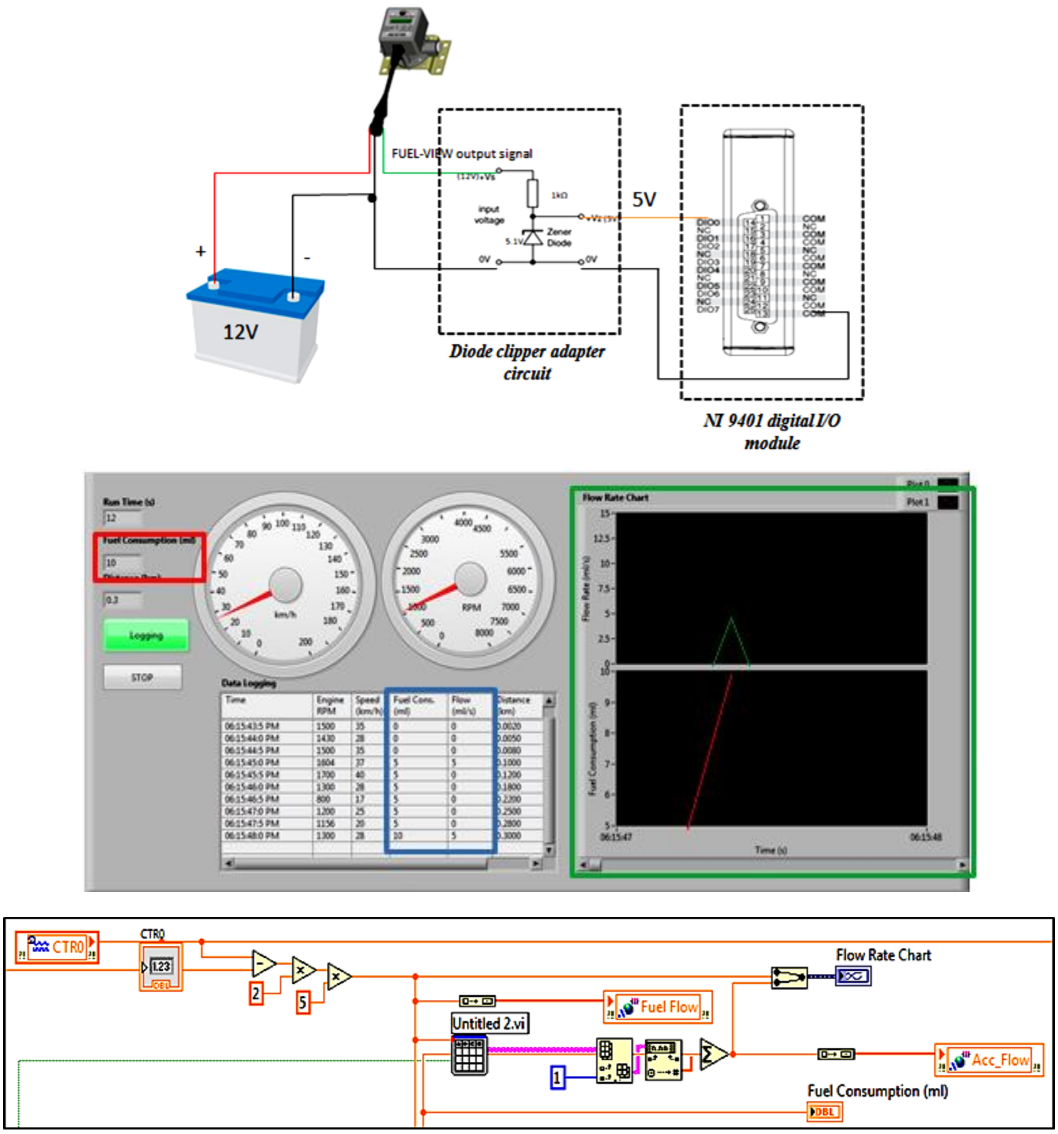

Figure 10: Fuel flow measurement

To measure engine rpm and vehicle speed, the EMS is connected directly to the ECU signals. A simple wiretap is implemented and two cables going to the driver's instrument panel (dashboard) that carry these signals are identified. From initial testing, it is observed that the digital-pulse signals are frequency-modulated - when speed is changed, only the signal's frequency varies, while the signals' duty cycle and voltage level remain constant.

The square wave signals have an amplitude of about 14V, which reflects the car's battery voltage. Further tests are performed to obtain the relation between the signals' frequency and actual engine rpm and vehicle speed. The following simple relationships (1), (2) are obtained via linear regression:

$$\text{Engine rpm} = 30.078*(\text{frequency of rpm signal}) + 160.02 \quad (1)$$

$$\text{Vehicle speed} = 1.487*(\text{frequency of speed signal}) + 1.768 \quad (2)$$

Figure 11 shows hardware configuration and *LabVIEW* program code for engine rpm and vehicle speed measurements.

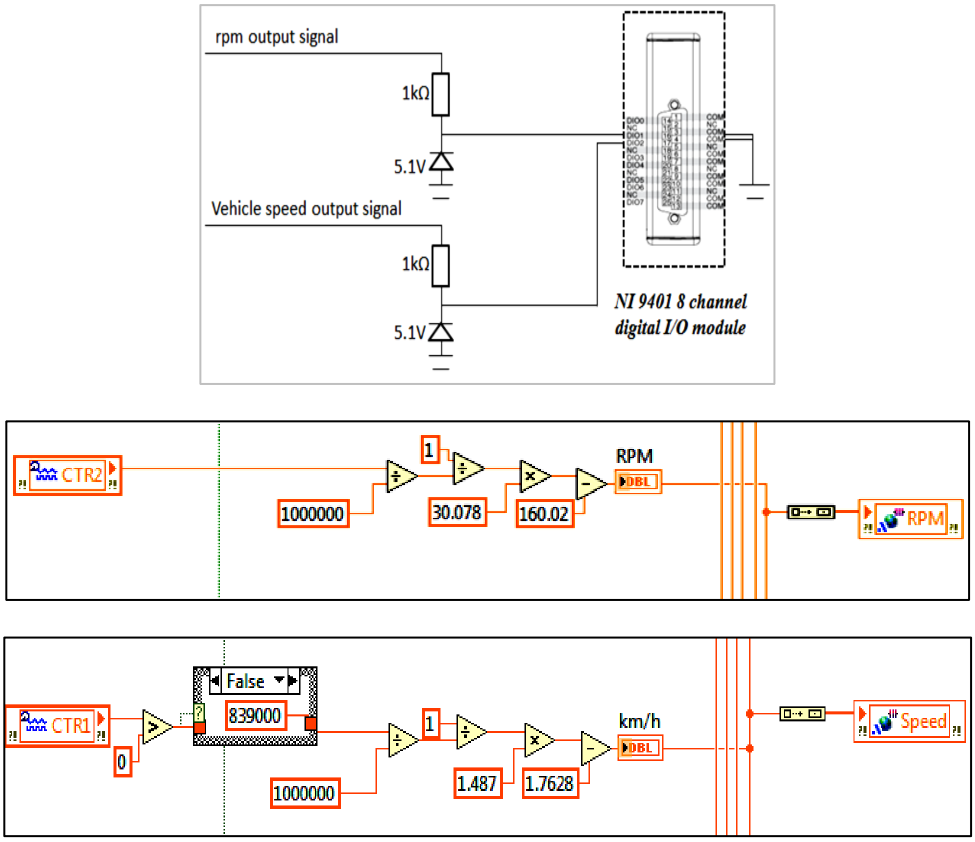

Figure 11: Hardware configuration and *LabVIEW* code for engine rpm and vehicle speed

4.3 Motor Parameters (CAN Bus)

The dual brushless DC motor drive/controller provide various motor and controller parameters for real-time and continuous monitoring of the in-wheel motors, via CAN bus. This function is critical for efficient and safe operation of the hybrid vehicle. A *CompactRIO* high-speed CAN module NI-9853 is used to connect to the J1 port of the motor controller (*Kelly Controls*), as shown in Figure 12, with a transfer rate of 1 Mbit/s. Parameters provided by the motor drive are listed in Table 2. Based on the signal type, the EMS software is programmed to acquire the respective parameters at different sampling/update rates, for optimum use of software resource.

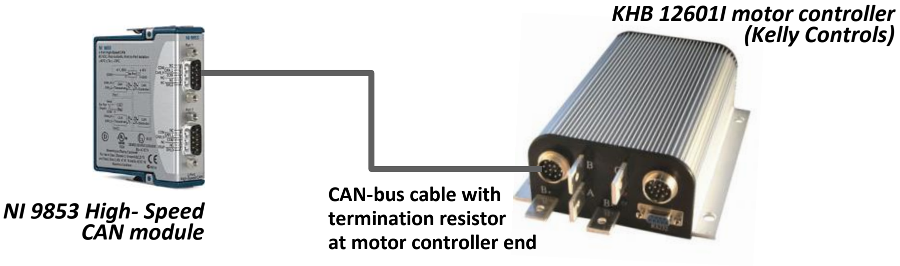

Figure 12: System connectivity for monitoring of motor & motor controller parameters

Table 2: Monitoring parameters of motor & controller via CAN bus

Acquisition Frequency	**Single Read Only**
Parameter Name	***Controller model***
CAN command	CCP_FLASH_READ
CAN data [0]	0xF2
CAN data [1]	INFO_MODULE_NAME
CAN data [2]	8
Parameter Name	***Software version***
CAN command	CCP_FLASH_READ
CAN data [0]	0xF2
CAN data [1]	INFO_SOFTWARE_VER
CAN data [2]	2
Parameter Name	***Min. throttle***
CAN command	CCP_FLASH_READ
CAN data [0]	0xF2
CAN data [1]	CAL_TPS_DEAD_ZONE_LOW
CAN data [2]	1

Acquisition Frequency	**Single Read Only**
Parameter Name	***Max. throttle***
CAN command	CCP_FLASH_READ
CAN data [0]	0xF2
CAN data [1]	CAL_TPS_DEAD_ZONE_HIGH
CAN data [2]	1
Parameter Name	***Min. brake***
CAN command	CCP_FLASH_READ
CAN data [0]	0xF2
CAN data [1]	CAL_BRAKE_DEAD_ZONE_LOW
CAN data [2]	1
Parameter Name	***Max. brake***
CAN command	CCP_FLASH_READ
CAN data [0]	0xF2
CAN data [1]	CAL_BRAKE_DEAD_ZONE_HIGH
CAN data [2]	1

Table 2: Monitoring parameters of motor & controller via CAN bus (cont'd)

Acquisition Frequency	High Update Rate (CAN Bus Streaming)
Parameter Names	*Brake command*
	Torque command
	Operation voltage
	Supply voltage
	Battery voltage
CAN command	CCP_A2D_BATCH_READ1
CAN data [0]	0x1b
Parameter Names	*Current – Phase A*
	Current – Phase B
	Current – Phase C
	Voltage – Phase A
	Voltage – Phase B
	Voltage – Phase C
CAN command	CCP_A2D_BATCH_READ2
CAN data [0]	0x1a

Acquisition Frequency	Low Update Rate (CAN Bus Streaming)
Parameter Names	*PWM*
	Motor rotation enable
	Motor temperature
	Controller temperature
	Inverter heat sink (high side) temp
	Inverter heat sink (low side) temp
CAN command	CCP_MONITOR1
CAN data [0]	0x33
Parameter Names	*Motor speed (MSB of RPM)*
	Motor speed (LSB of RPM)
	% of rated current
	MSB of error code
	LSB of error code
CAN command	CCP_MONITOR2
CAN data [0]	0x37

Acquisition Frequency	Very Low Update Rate
Parameter Name	*Throttle Switch Status (On/Off)*
CAN command	COM_SW_ACC
CAN data [0]	0x42
CAN data [1]	COM_READING
Parameter Name	*Brake Switch Status (On/Off)*
CAN command	COM_SW_BRK
CAN data [0]	0x43
CAN data [1]	COM_READING
Parameter Name	*Reverse Switch Status (On/Off)*
CAN command	COM_SW_REV
CAN data [0]	0x44
CAN data [1]	COM_READING

5.0 CONCLUSIONS

An energy management and supervisory system (EMS) is an essential component of a through-the-road hybrid vehicle with in-wheel motors (TTR-IWM). The EMS controls power distribution between the propulsion sources and charging of the energy storage, to achieve optimum fuel economy and self-sustaining storage. Proper operation requires different types of signals to be acquired and processed by the EMS: hardwire low-voltage analog signals from throttle position and brake pedal sensors, digital pulse signals from fuel flowmeter and vehicle instrument panel (engine rpm and vehicle speed) and finally CAN-bus signals from the motor controllers (motor parameters). It is found that hybrid operation requires the EMS to generate an enhanced throttle signal to the ECU, bypassing the original signal from throttle position sensor, to gain control of the internal combustion engine. In the immediate future, lab testing will be implemented on the TTR-IWM hybrid prototype to ascertain effectiveness of the system integration, in stationary mode. Finally, road tests will be carried out, to validate simulation results of energy management and control of the TTR hybrid vehicle.

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