Software Requirements Specification for Mechatronics: **Formula Electric Vehicle Control System**

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Contents

Revision History

Date	Version	Notes
Oct 5th, 2022	1.0	Initial Revision

1 Project Drivers

1.1 The Purpose of the Project

The purpose of this project will be to design, simulate, implement, and test a fully functioning vehicle control system for a quarter-scale Formula 1 style electric vehicle. Currently, the McMaster Formula Electric team is in the process of preparing their vehicle for the FSAE competition taking place in Michigan next summer. During the 2020 Fall - 2021 Winter term of the school year, the team went through a full redesign of the electrical and embedded system architecture. The new architecture included a switch from Atmel to STM32F7 microprocessors, enabling the team to develop, test, and integrate in-house vehicle software for their ECUs. This change allows us to implement our own custom vehicle controls software.

1.2 Scope

The control system will be responsible for managing the following vehicle subsystems: battery management, vehicle mode selection, tractive motor, and vehicle dynamics.

1.3 Typical Operations Overview

A student on the McMaster Formula Electric team, who is familiar with the basics of Matlab, can push the finished vehicle controls model to the respective ECU's that exist in the vehicle. In terms of adjust things like sensitivity, a student can enter the model and change values that are presented to them. This can adjust things like brake & accelerator sensitivity, how aggressive the cooling system will run, and even maximum torque & horsepower output from the motors.

1.4 The Client, the Customer, and Other Stakeholders

For our Capstone, our stakeholder will be the McMaster Formula Electric team. They will be able to take our model and utilize it for this year's EV4 vehicle, which is slated to be ready for competition in summer 2023.

1.5 Users of the Product

The individuals on the embedded software & vehicle controls sub-team will be the main user of the product. They'll be able to push our model onto their new custom ECU's (Electronic Control Unit) to control the vital subsystems required for vehicle propulsion.

2 Project Constraints

2.1 Mandated Constraints

The following constraints must be adhered to during the design of the system:

MD1	Total expenses mustn't exceed \$750.
Rationale	The project must stay within the budget given by the CAS department.

MD2	Project must be completed before the end of the academic year.
Rationale	Deadline is a project-requirement set by the CAS department.

MD3	The control system must adhere to the 2022 Formula SAE Rules.
Rationale	Rules must be followed to ensure vehicle is eligible for competition.

2.2 Naming Conventions and Definitions

Abbreviations & Acronyms used throughout project documentation:

MFE	Mac Formula Electric
ECU	Electronic Control Unit
BMS	Battery Management System
CAN	Controller Area Network
EV	Electric Vehicle
SAE	Society of Automotive Engineers
PCB	Printed Circuit Board
SoC	State of Charge
TMS	Thermal Monitoring System
AMK	Arnold Müller Kirchheim GmbH; supplier of the vehicle's motor, inverter, controller kit
APPS	Accelerator Pedal Position Sensor
AMS	Accumulator Management System - FSAE lingo, alias for BMS
IMD	Insulation Monitoring Device, installed in the Tractive system.
BSPD	Brake System Plausibility Device, nonprogrammable circuit to check for simultaneous braking and high power output.
PWM	Pulse Width Modulation
MSR	Mode Selection Ring
CCR	Cooling Control Ring
ACR	Accumulator Management Ring
TMR	Tractive Motor Ring
VDR	Vehicle Dynamics Ring

2.3 Relevant Facts and Assumptions

The following are facts relevant to the project:

RF1	The Motors we will be interfacing with, are AMK's "Formula Student Electric" 2 Wheel Drive Racing Kit.
Rationale	This kit contains the necessary motors and motor drivers required to propel the vehicle. Our control system will be interfacing with these through the use of contactors for enable/disable, as well as communication with the motor drivers to send torque requests.

RF2	For battery management, we will be interfacing with an Orion BMS system.
Rationale	This kit has built in functions for things like current & voltage protection, thermal management, cell balancing, and cell health monitoring. The system even has the capability to output digital and analog signals, to control chargers, motor controllers, and other external devices. For our use case, we will be controlling the BMS based on feedback given back to us for things like cell temperature to control our fan curve.

3 Context Diagrams

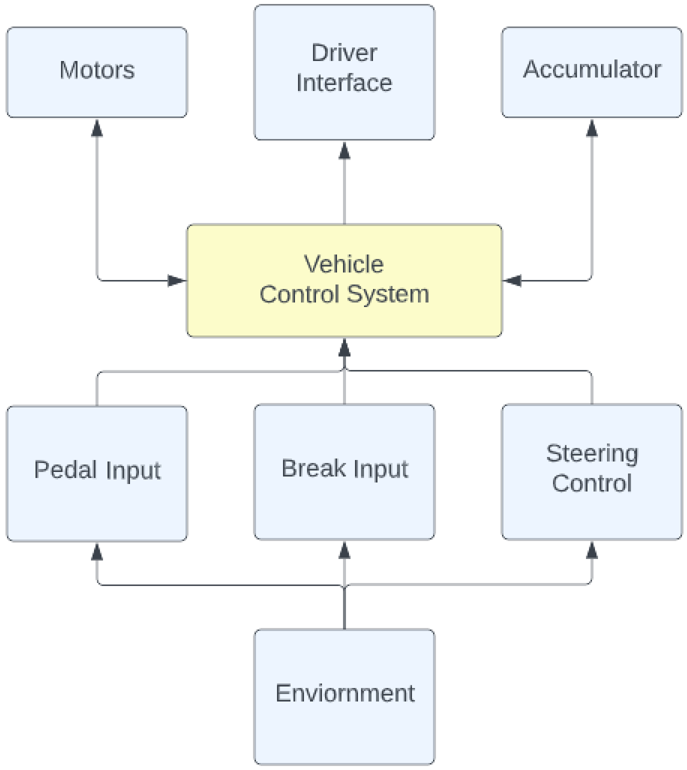

Figure 1: Control System Context Diagram

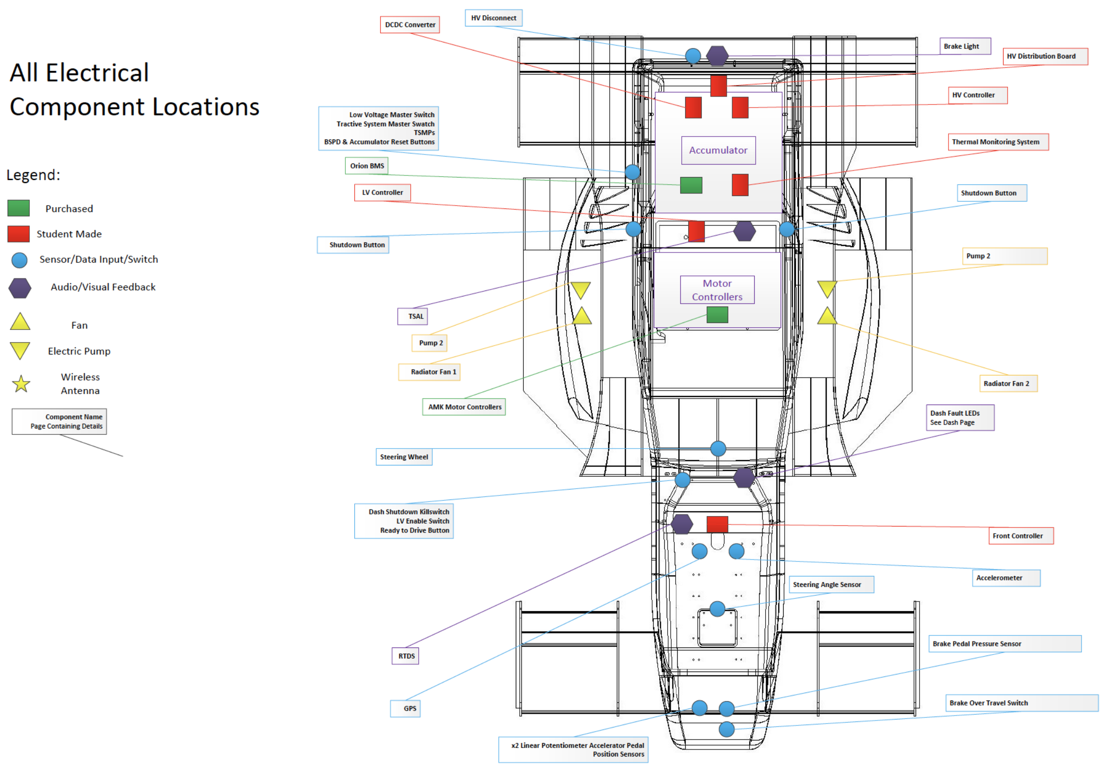

Figure 2: Electrical Component Context Diagram

4 Functional Decomposition Diagrams

The following diagrams show monitor (input) and control (output) variables for each of the control system's subsystems. "Ring" is a common automotive industry term for model-based control program. As such, the MFE team refers to their vehicle control subsystems as Rings.

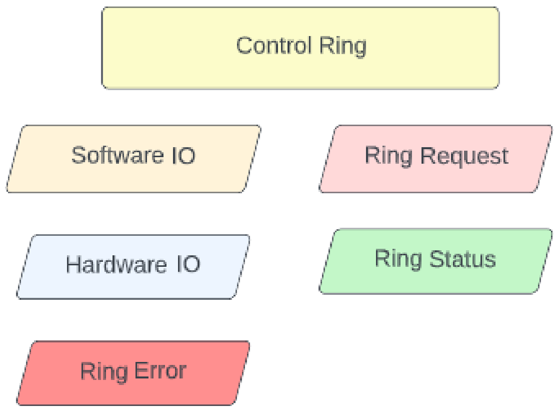

Figure 3: UML Color Coding Legend

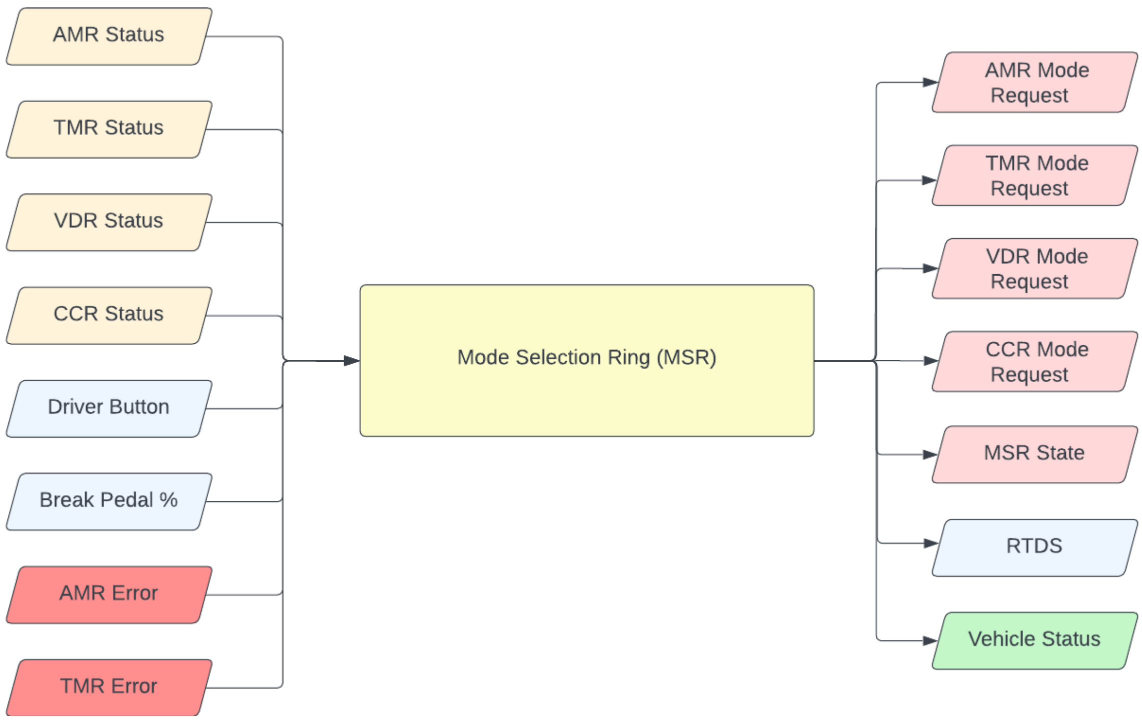

Figure 4: Mode Selection Ring UML

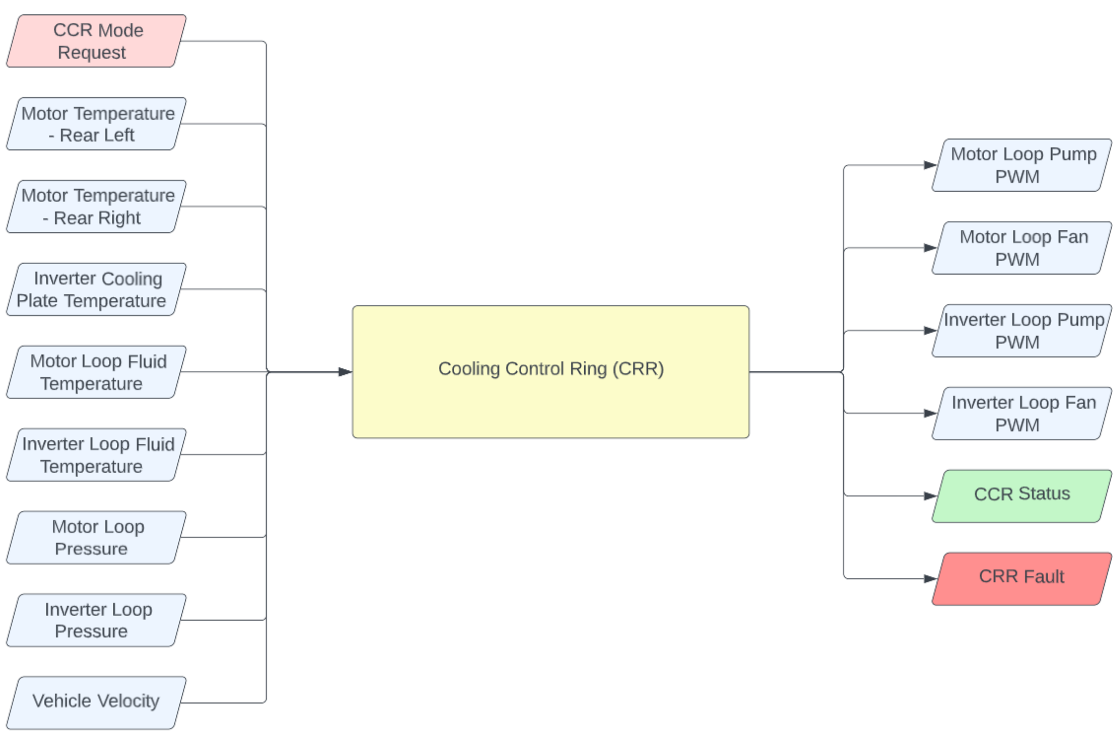

Figure 5: Cooling Control Ring UML

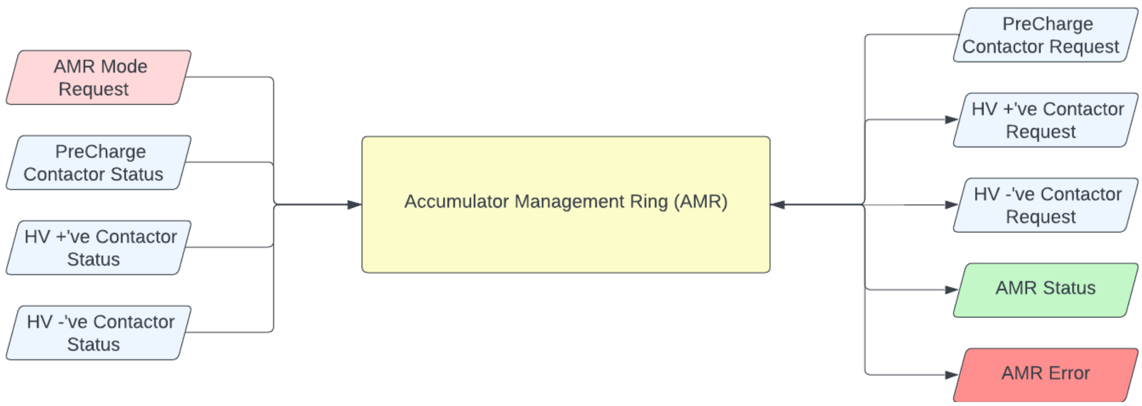

Figure 6: Accumulator Management Ring UML

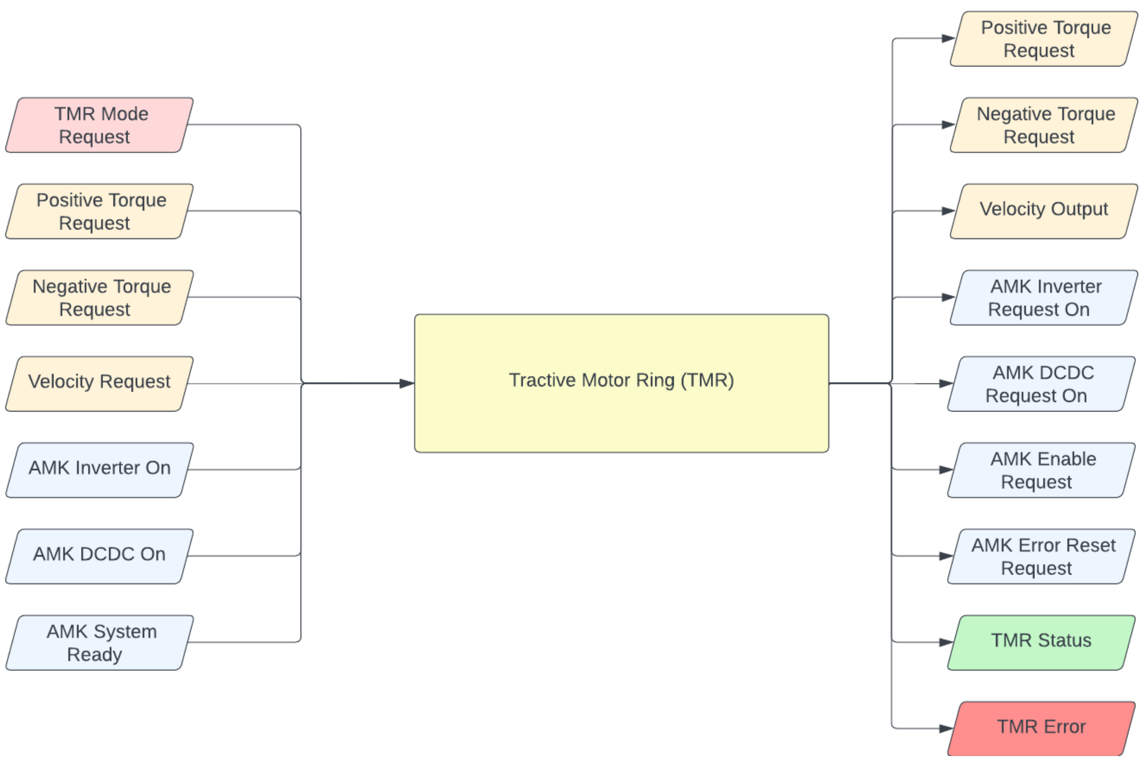

Figure 7: Tractive Motor Ring UML

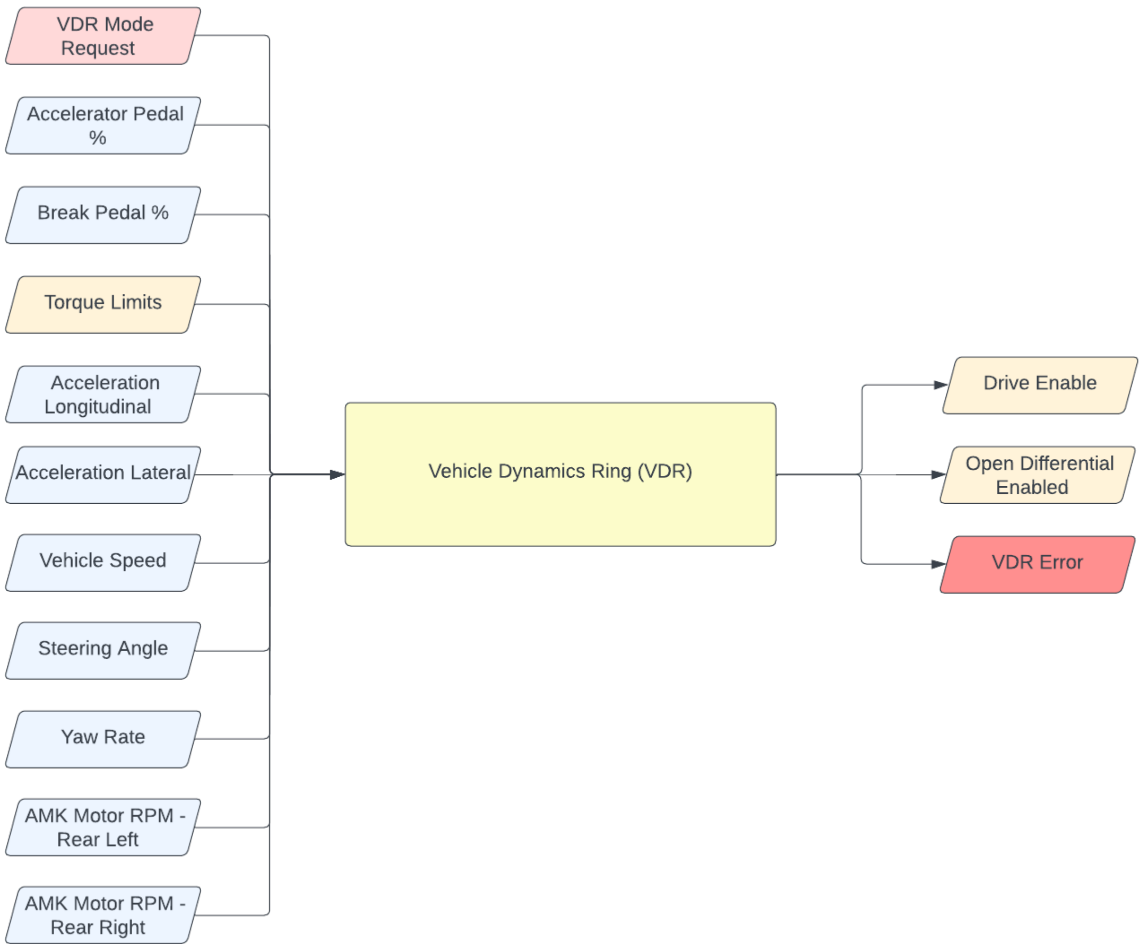

Figure 8: Vehicle Dynamics Ring UML

5 Functional Requirements

5.1 Accumulator Management Ring

AMR1	Accumulator Management control shall monitor the following inputs: AMR Mode Request, PreCharge Contactor Status, HV Positive Contactor Status, HV Negative Contactor Status.
Rationale	These inputs determine the state and control domain of the battery.
Likelihood of Change	Likely - More inputs may be needed as module complexity grows.

AMR2	Accumulator Management control shall compute the following output parameters: PreCharge Contactor Request, HV Positive Contactor Request, HV Negative Contactor Request, AMR Status, AMR Error.
Rationale	Essential command signals and state reporting to other control system modules.
Likelihood of Change	Likely - More outputs may be needed as module complexity grows.

AMR3	Accumulator Management control shall not issue a contactor-close command during any fuse condition.
Rationale	Fusing refers to a contactor ”welding” shut due to an electrical current spike, and can occur during high-load conditions.
Likelihood of Change	Very unlikely - Key functionality

AMR4	Accumulator Management control shall adhere to FSAE EV.4.1.1 - ”The maximum power drawn from the Accumulator [battery] must not exceed 80 kW.”
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

AMR5	Accumulator Management control shall adhere to FSAE EV.4.1.2 - ”The maximum permitted voltage that may occur between any two points must not exceed 600 V DC”
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

AMR6	Accumulator Management control shall adhere to FSAE EV.4.1.3 - ”The powertrain must not regenerate energy when vehicle speed is between 0 and 5 km/hr”
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

AMR7	Accumulator Management control shall adhere to FSAE EV.4.2.1 - ”Supplying power to the motor to drive the vehicle in reverse is prohibited”
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

AMR8	Accumulator Management control shall adhere to FSAE EV.4.2.1 - ”Supplying power to the motor to drive the vehicle in reverse is prohibited”
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

AMR9	Accumulator Management control shall issue any other BMS commands in accordance with procedures outlined in the Orion BMS documentation.
Rationale	To ensure correct operation of the BMS kit.
Likelihood of Change	Very unlikely - Key functionality

5.2 Cooling Control Ring

CCR1	Cooling Control shall monitor the following inputs: CCR Mode Request, Motor Temp Rear Left, Motor Temp Rear Right, Inverter Cooling Plate Temp, Motor Loop Fluid Temp, Inverter Loop Fliud Temp, Motor Loop Pressure, Inverter Loop Pressure, Vehicle Velocity.
Rationale	These aspects of the vehicle & battery state must be known in order to send suitable commands to the cooling system.
Likelihood of Change	Likely - More inputs may be needed as module complexity grows.

CCR2	Cooling Control shall compute the following output parameters: Motor Loop Pump PWM, Motor Loop Fan PWM, Inverter Loop Pump PWM, Inverter Loop PWM, CCR Status, CCR Fault.”
Rationale	Essential command signals and state reporting to other control system modules.
Likelihood of Change	Likely - More outputs may be needed as module complexity grows.

CCR3	Cooling Control shall compute duty factors for each cooling loop such that temperatures remain within tractive system operation range.
Rationale	Hardware operation limits
Likelihood of Change	Very unlikely - Hardware operation limit

5.3 Mode Selection Ring

MSR1	Mode Selection shall monitor the following inputs: AMR Status, TMR Status, VDR Status, CCR Status, Driver Button, Brake Pedal %, AMR Error, TMR Error
Rationale	These aspects of the vehicle state must be known in order to send suitable commands to the rest of the control system.
Likelihood of Change	Likely - More inputs may be needed as module complexity grows.

MSR2	Mode Selection shall compute the following output parameters: AMR Mode Request, TMR Mode Request, VDR Mode Request, CCR Mode Request, MSR State, RTDS, Vehicle Status”
Rationale	Essential command signals and state reporting to other control system modules.
Likelihood of Change	Likely - More outputs may be needed as module complexity grows.

MSR3	Mode Selection shall adhere to Activation Sequence rule FSAE EV.10.4.1 [”Low Voltage (GLV) System”] - The Shutdown Circuit may be Closed when or after the GLV System is energized
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

MSR4	Mode Selection shall adhere to Activation Sequence rule FSAE EV.10.4.2 ["Traction System Active"] • Definition – High Voltage is present outside of the Accumulator Container • Tractive System Active must not be possible until both: (1) GLV System is Energized; (2) Shutdown Circuit is Closed
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

MSR5	Mode Selection shall adhere to Activation Sequence rule FSAE EV.10.4.3 ["Ready to Drive"] • Definition – the Motor(s) will respond to the input of the APPS • Ready to Drive must not be possible until: (1) Tractive System Active; (2) The brake pedal is pressed and held to engage the mechanical brakes; (3) The driver performs a manual action to initiate Ready to Drive such as pressing a specific button in the cockpit
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

MSR6	Mode Selection shall adhere to Shutdown Circuit Operation rule FSAE EV.8.2.1 - The Shutdown Circuit must Open when any of the following exist: • Operation of, or detection from any of the components listed in EV.8.1.1 • Any shutdown of the GLV System
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

MSR7	Mode Selection shall adhere to Shutdown Circuit Operation rule FSAE EV.8.2.2 - When the Shutdown Circuit Opens: • The Tractive System must Shutdown • All Accumulator current flow must stop immediately • The voltage in the Tractive System must be Low Voltage T.9.1.2 in five seconds or less • The Motor(s) must spin free. Torque must not be applied to the Motor(s)
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

MSR8	Mode Selection shall adhere to Shutdown Circuit Operation rule FSAE EV.8.2.3 - When the AMS, IMD or BSPD Open the Shutdown Circuit: • The Tractive System must remain disabled until manually reset • The driver must not be able to reactivate the Tractive System from inside the vehicle • Operation of the Shutdown Buttons or TSMS must not reset the Shutdown Circuit • The Tractive System must be reset only by manual action of a person directly at the vehicle
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

VSM9	Mode Selection shall adhere to Shutdown Circuit Operation rule FSAE EV.8.2.4 - The driver may reset the Shutdown Circuit from the cockpit, subject to EV.8.2.3
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

5.4 Tractive Motor Ring

TMR1	Tractive Motor control shall monitor feedback signals from the AMK motor controller: AMK Inverter On, AMK DCDC On, AMK System Ready.
Rationale	The current motor state must be known in order to send suitable commands to the motor controller.
Likelihood of Change	Very unlikely - Key functionality

TMR2	Tractive Motor control shall also monitor the following inputs: TMR Mode Request, Positive Torque Request, Negative Torque Request, Velocity Request.
Rationale	Certain aspects of the vehicle state must be known in order to send suitable commands to the motor controller.
Likelihood of Change	Very unlikely - Key functionality

TMR3	Tractive Motor control shall issue motor commands in accordance with procedures outlined in the AMK documentation.
Rationale	To ensure correct operation of the motor kit.
Likelihood of Change	Very unlikely - Key functionality

TMR4	Tractive Motor control shall compute the following output parameters: Positive Torque Request, Negative Torque Request, Velocity Output, AMK Inverter Request On, AMK DCDC Request On, AMK Enable Request, AMK Error Reset Request, TMR Status, TMR Error."
Rationale	Essential command signals and state reporting to other control system modules.
Likelihood of Change	Likely - More outputs may be needed as module complexity grows.

TMR5	Tractive Motor control shall adhere to FSAE EV.4.2.3 - "Any algorithm or electronic control unit that can adjust the requested wheel torque may only lower the total driver requested torque and must not increase it"
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

TMR6	Tactive Motor control shall adhere to FSAE EV.5.7.1 - ”The power to the Motor(s) must be immediately and completely shut down when the two of these exist at the same time: (1) The mechanical brakes are engaged; (2) The APPS signals more than 25% pedal travel”
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

TMR7	Tractive Motor control shall adhere to FSAE EV.5.7.2 - ”The Motor shut down must remain active until the APPS signals less than 5% pedal travel, with or without brake operation.”
Rationale	Competition rule
Likelihood of Change	Very unlikely - Competition rule

5.5 Vehicle Dynamics Ring

VDR1	Vehicle Dynamics control shall monitor the following inputs: VDR Mode Request, Accelerator Pedal %, Brake Pedal %, Torque Limits, Longitudinal Acceleration, Lateral Acceleration, Vehicle Speed, Steering Angle, Yaw Rate, AMK Motor RPM Rear Left/Right
Rationale	These aspects of the vehicle state must be known in order to send suitable commands to the rest of the control system.
Likelihood of Change	Likely - More inputs may be needed as module complexity grows.

VDR2	Vehicle Dynamics control shall compute the following output parameters: Drive Enable, Open Differential Enable, VDR Error”
Rationale	Essential command signals and state reporting to other control system modules.
Likelihood of Change	Likely - More outputs may be needed as module complexity grows.

6 Non-Functional Requirements

6.1 Look and Feel Requirements

The control system has no ”front-end” that would drive user-facing look and feel requirements.

NFR1	The control system Simulink models shall follow a standardized format that facilitates readability and encapsulation.
Rationale	Future FSAE students should be able to understand control logic while consulting as little documentation as possible.

6.2 Usability Requirements

The control system will not be directly interacted with by a user.

NFR2	The control system build target shall be the team-selected microcontroller platform, STM32F7
Rationale	Software compatibility with the end-use hardware.

6.3 Performance Requirements

NFR3	Running the control system on the embedded controller shall not exceed the computational throughput of the controller.
Rationale	To ensure vehicle safety expectations and competition rules are met, and to ensure vehicle performance is as desired.

6.4 Maintainability and Support Requirements

NFR4	The control system shall make use of hardware abstraction modules, that have consistent outputs to our system regardless of changing the underlying hardware.
Rationale	Future hardware changes can be accommodated within their own encapsulated modules rather than requiring control logic models.

NFR5	The control system modules shall incorporate modularization principles, including encapsulation and information hiding.
Rationale	Having modules and sub-modules interact through well-defined inputs/outputs, while hiding their implementation, facilitates maintainability by allowing module implementation updates to not drive downstream changes.

NFR6	The control system modules shall be documented according to a standardized, team-approved format.
Rationale	Facilitate effective knowledge transfer to future FSAE students.

6.5 Security Requirements

Code-level security is not within the scope of the project. However, access to source code and high-level control logic is.

NFR7	The control system repository shall be public for the duration of the capstone project.
Rationale	Open visiblity for marking and accountability.

NFR8	The control system repository shall be made private upon completion of the project.
Rationale	To prevent our team's work being copied by a rival team, as this can cause issues in terms of plagiarism as per the FSAE rules, while also in practise reducing our competitive advantage.

6.6 Cultural and Political Requirements

As this is a competition-only vehicle with strict guidelines from SAE, there are no relevant requirements reflecting on societal politics and culture.

6.7 Legal Requirements

As this is a competition-only vehicle with strict guidelines from SAE, there are no relevant legal requirements from governing bodies (that would not already been implicitly required with the SAE guidelines).

6.8 Health and Safety Requirements

NFR9	The control system shall follow FSAE guidelines for safe energizing sequences.
Rationale	Most electric-related vehicle safety features (eg. emergency stops, fuses) are handled on the hardware level.

NFR10	If the vehicle is in motion while an unsafe condition occurs, the control system shall zero the motor torque commands until a system reset.
Rationale	The vehicle's "safe state" should be to allow the driver to coast or brake to a safe location, without issuing any positive/negative torque command from the motors.

7 Project Issues

7.1 Open Issues

Issues that have been raised and do not yet have a conclusion.

- Version control mechanism needs to be instantiated for Simulink model development.
- Sourcing and/or development of plant models to use in Model-in-loop testing is an open issue.

7.2 Off-the-Shelf Solutions

As this competition follows strict requirements from FSAE, a unique control system must be developed by each team. Systems provided by Mathworks and/or hardware manufacturers cannot be used beyond acting as a broad inspiration or syntax reference. Purchasing vehicle control software from a automotive supplier (eg. Bosch) would still require customization in order to meet FSAE competition requirements.

7.3 Risks

- The FSAE vehicle may not be ready by end-of-project to do vehicle level integration.
- The embedded hardware may not be ready by end-of-project to do hardware-level integration.
- Hardware-level testing introduces some health and safety risk.
- The team-selected microcontroller (STM32F7) may not have computational capacity required for a functional control system.
- Roadblocks caused by MFE that are out of the team's control

7.4 Costs

Listed below are the costs associated with any hardware required to help design our product.

Item	Price
NUCLEO-F767ZI Debugger	$25

7.5 Waiting Room

The following are the additions to the project that would be tackled after initial release of the product.

(i) Vehicle Stability Control Program

(ii) Torque Vectoring

(iii) Over-the-air Data Acquisition

Appendix — Reflection

This project requires a team-wide understanding of developing embedded software that is functionally complete, robust, maintainable and documented, as well as working within a continuous-improvement framework. Other mechatronics-specific knowledge includes model-based design, signal conditioning, V-model development, requirements-based testing, software-simulation and physical modelling environments and state machine design. Broader technical knowledge will be developed in electric vehicles and automotive standards. Team members will need to be adept with various industry tools including Git, MATLAB/Simulink and LaTeX. Transferable skills are numerous, but notably include experience in compliance-driven design, design communication and collaborative project management.

Team Member	Knowledge/Skills to develop
Dharak	Software simulation & physical system modelling, project management, integration testing, software design documentation
Abhishek	Embedded software development, design communication, model-based design, V-model, control system theory
Jason	Embedded software development, design communication, Simulink algorithms, predictive and intelligent control, real time applications with controls
Laura	Embedded software development, design communication, Simulink, knowledge of electric vehicles and their subsystems
Derek	Embedded software development, design communication, signal conditioning, state machine design, LaTeX, Git

Approaches and rationale are as follows.

Team Member	Knowledge/Skills to develop
Dharak	To acquire knowledge and master the aforementioned skills, I could begin by (1) documenting my work and experience I have gained over my 6 years on MFE in order to easily transfer it down to my team members, (2) consult the expansive catalog of resources provided by decorated FSAE Teams online, and (3) take a leading role in managing both the technical and admin work of the capstone group. Of the listed methods, I will be pursuing method (1) to build my knowledge and skill set. As I have prior experience with embedded software, vehicle controls, and project management due to my past and current involvement with MFE, the best way for me to be able to reinforce the skills I have gained and applied is to reflect back upon them by documenting and teaching others. I strongly believe the best way to test ones knowledge on a topic is by explaining it to someone else, so by explaining the topics related to my goals to my team members, I will be reinforcing my own understanding and be able to find any holes in my own knowledge.
Abhishek	To enhance the skills I've listed above, I can (1) make use of great professors that are available to us, like Professor Lawford, that have a deep understanding of vehicle control systems (2) put into practice what I've learned in multiple courses during my time at McMaster eg. Real Time Applications and Intelligent Control, and finally (3) make use of the great FSAE Formula Electric community to fill any gaps in understanding I may have. Having previous co-ops in the controls space, I will be using what I've learned from practical experience and theoretical experience to become a great asset to this project's development and final outcome.
Jason	Build on course work I have done based around software development and control theory. Additionally, being able to actually develop a control algorithm for on a vehicle is a very unique opportunity and so being able to grasp skills in all areas of it is important to me. Working on simulink for the model driven design pacemaker project provided a great introduction into simulink and I want to build on this skill set through this project. Through conducting research on vehicle controls algorithms, or through consulting professors, I will aim to complete my goal. From the above approaches, I will be pursuing the approach of working with professors, such as Dr. Martin v. Mohrenschildt as he is an expert in the control systems area.

Laura	To ensure that I acquire the skills and knowledge listed above, I will thoroughly review the documentation provided by the MFE team. I will also do research on other electric vehicles, especially ones that are available commercially, to keep up with the ongoing demands and trends of the industry. This will help me to make sure I am on track with my team and that I fully understand the scope of the project and can make meaning contributions to the team. As I have previous experience with software development and design communication, I will be focusing on continuing to learn about electrical vehicles and their subsystems.
Derek	Though I have some experience in state-machine design, formal documentation in LaTeX, and in Git, these have been for smaller-scale projects where I could get by with just the basics. This project provides the opportunity to deepen by knowledge by applying these skills to a larger (in module count) and more complex system. I can enhance these skills by (1) taking advantage of the talent-base of the FSAE team by consulting team members for their knowledge and design advice, and (2) taking advantage of the support from the Capstone instruction team, by consulting with the instructors/TAs for their best-use practices.