

PROJECT REPORT
(Project Semester January-June 2017)

Automotive Electronic Integration (Vehicle Tracking System)

Submitted By

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January to June 2017

Declaration

I hereby declare that the project work entitled "**Vehicle Tracking System**" is an authentic record of my own work carried out at STMicroelectronics, Greater Noida, UP, India as requirements of six months project semester for the award degree of B.E. Electronics and Communication Engineering, PEC University of Technology, Chandigarh, under the guidance of **Mr. Bipin Chandra Pande** and **Dr. Jyoti Kedia**, during the period, January to June, 2017.

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Acknowledgment

I would like to thank STMicroelectronics AMG and Automotive team for providing me an opportunity to work with them. I am also highly indebted to all team members who helped me throughout the internship semester.

I am highly indebted to my manager and mentor Mr. Bipin Chandra Pande for providing me an opportunity to work under him. I sincerely thank him for his support and guidance. I would also like to thank Mr. Subodh Vikram Shukla for his guidance in BLDC and ACIM Motor Drive Systems.

I would also like to express my sincere gratitude to my college mentor Dr. Jyoti Kedia for her support and encouragement throughout my internship. I would like to thank PEC Administration for providing me an internship opportunity.

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List of Abbreviations

- **ACIM** : AC Induction Motor
- **AMG** : Analog and MEMS Group
- **ASIC** : Application Specific Integrated Circuit
- **BCM** : Body Control Module
- **BLDC** : Brush-less DC
- **BLE** : Bluetooth Low Energy
- **BSP** : Board Support Packages
- **CAN** : Controller Area Network
- **CMSIS** : Cortex Micro-controller Software Interface Standard
- **ECM** : Electronic Commutation Motor
- **ECU** : Engine Control Unit
- **FOC** : Field-Oriented Control
- **HAL** : Hardware Abstraction Layer
- **IoT** : Internet of Things
- **ISP** : Internet Service Provider
- **LIN** : Local Interconnect Network
- **MITM** : Man-in-the-Middle Attack
- **OOP** : Object-Oriented Programming
- **P2P** : Peer-to-Peer
- **PMSM** : Permanent Magnet Synchronous Motor
- **RSSI** : Received Signal Status Indicator
- **RTOS** : Real-Time Operating System
- **SFR** : Special Function Register
- **SIG** : Specific Interest Group
- **SoC** : System on Chip
- **SWD** : Single Wire Debug
- **TCP** : Transmission Control Protocol
- **UDP** : User Datagram Protocol
- **VLE** : Variable Length Encoding

Chapter 1

Summary

During the internship period at STMicroelectronics, Greater Noida, India, several projects were done as a part of the AMG¹ Systems Lab Department and the Automotive Department. The AMG Systems Lab, also called the Central Lab, is involved with the design, development and implementation of various proof-of-concept systems revolving around fields like IoT, LED lighting, efficient power supplies, wireless communication systems and various motor control applications. As part of the automotive Department and AMG Systems Lab, various opportunities to work on many realms of the industry, from application software development and firmware development to circuit design and testing were provided. A brief categorization of the projects is depicted in figure 1.1. A short summary of each project is also mentioned in section 1.1.

1.1 Summary of projects

A summary of the broad fields and the corresponding projects are as follows

1.1.1 BLDC² and ACIM³ Drives and Speed Controllers

Electrical motors are one of the most used actuators that can convert electrical energy to mechanical energy. Many other mechanical actuators like the Hydraulic Cylinder is a linear actuator, which has , electrical motors deliver mechanical energy in the form of rotation.

¹Analog and MEMS Group

²Brush-less DC

³AC Induction Motor

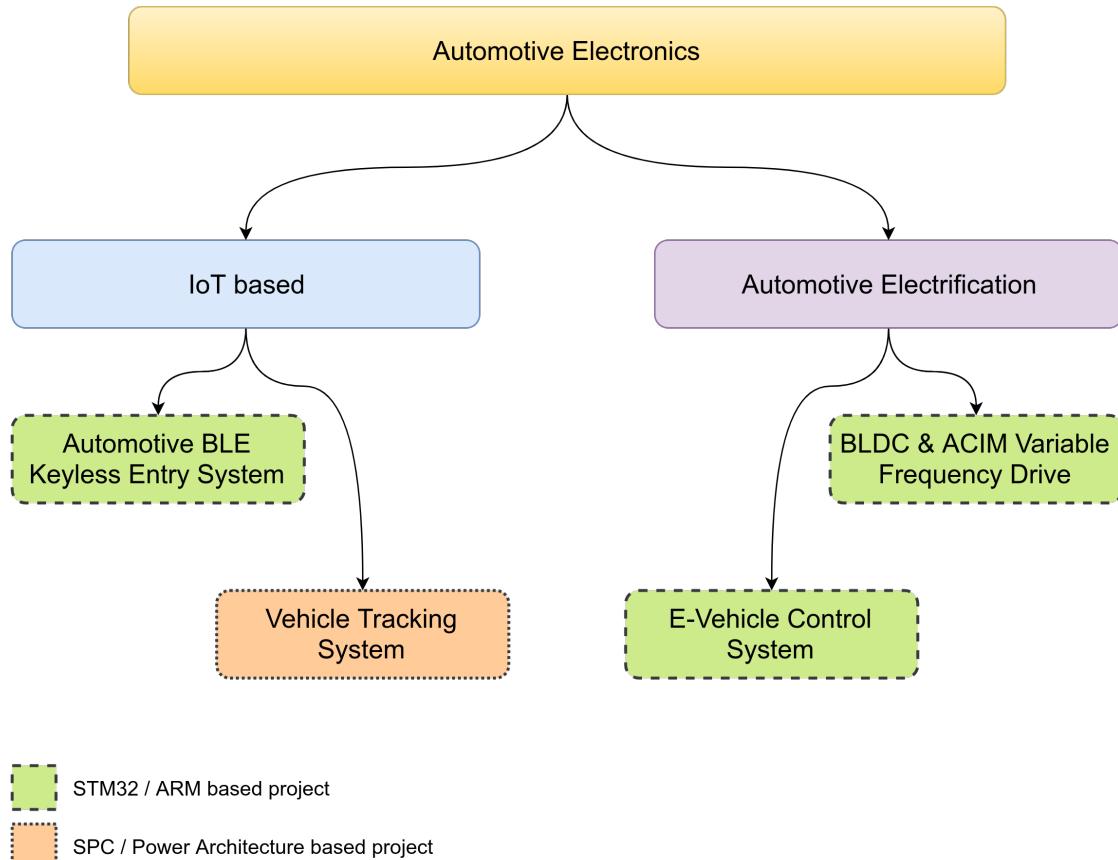


Figure 1.1: Categorization of projects done in the Internship period.

PMSM,⁴ are synchronous motors that use permanent magnets for magnetic field generation instead of a separate set of windings called the field windings. BLDC motors are a special kind of PMSM, also called the ECM or Electronic Commutation Motor. These are called so, because, instead of having a mechanical commutator⁵, a specifically conditioned signal is provided to the windings directly⁶. The electronic device which is responsible for the generation of such a conditioned signal, for the BLDC motor is called a *BLDC Motor Drive*.

Following is a brief list about the projects involving BLDC and ACIM motor drives.

- **BLDC Motor Drive on SPC platform :** The project involved testing of a BLDC drive library already implemented by STMicroelectronics. An exhaustive testing and verification of the firmware library was done.
- **BLDC Motor Drive on STM8 platform:** This involved design and tuning of the motor drive using the six-step commutation algorithm. Although, the Motor Drive power stage (MB459) was designed for both low voltage (<35V) and high voltage(>35V) operations but the end objective was to drive a high power BLDC motor at 48V. The peak power rating of the motor drive was around 300W. The motor drive features Over current protection, over voltage protection, BEMF sampling, Configurable one or three shunt Current Sensing, Configurable UI and user input options and regenerative braking ability. The Motor Drive controls speed through a PI controller and can perform torque regulation in closed loop operation.
- **ACIM drive on STM32 (STM32F303RE) :** This involved porting of an already implemented firmware from one Hardware Abstraction Layer (STM32-ARM Standard Peripheral Lib) to another (STM32 Cube HAL).

1.1.2 Automotive Keyless Entry System using BLE

The Keyless Entry System is a security system in automobiles to unlock it without the physical key. The objective of this project was to implement a communication system between a mobile phone app and a BlueNRG1 hardware module to transmit character messages. The BlueNRG1 is a dedicated SoC⁶ for Bluetooth applications. This project was designed for an automotive application in which the mobile app is used to unlock or lock an automobile's central locking system.

⁴Permanent Magnet Synchronous Motor

⁵Mechanical commutators are common in electrical machines like the permanent magnet DC motor.

⁶System on Chip

1.1.3 Vehicle Tracking System

IoT is a fast expanding field for electronics devices. Many technologies and protocols have been developed and rigorously tested to expand the notion of internet onto devices like LED lighting systems, household security and surveillance systems. Technologies such as 6LoWPAN⁷ are aimed at connecting even the smallest of electronic devices like discrete sensor units and household objects. The idea of IoT in household objects is quite interesting. One such application was the use of RFID technology to detect the location of small household objects like keys. The Vehicle Tracking System is an attempt to bring IoT technology to automobiles. The Vehicle Tracking System involves a hardware module incorporated in an automobile and a central server system, designed to transmit and store data in the cloud(central server), which can be accessed by the user via an Android app. The objective was to design and implement a hardware module. The hardware module comprised of a micro-controller (SPC560D40L1) and a GSM module (Quectel M66). The hardware module uses the GSM communication band to transmit vital automobile statistics to the central server via the TCP/IP data packeting protocol. HTTP was used at the application layer.

1.1.4 E-Vehicle Control System (e-rickshaw)

Now-a-days with the decline of non-renewable energy sources, the automotive market has been seeing a shift to hybrid and clean vehicles. These vehicles rely on battery technology and sophisticated high power motors for locomotion. An E-vehicle Control System is a set of hardware and software components that are designed so as to provide a safe and easy way to operate an E-vehicle. E-vehicle here refers to an automobile which relies on electricity for its power needs and does not use any fossil fuels. The E-vehicle system project was made specifically for e-rickshaws, which are gaining popularity in many parts of India. E-rickshaw components in the present market are supplied by Chinese vendors who manufacture unreliable hardware components susceptible to failure and charge a lot of money due to their monopoly in the market. The e-rickshaw project is an attempt to enter this new market with good quality and reliable hardware, which is comparably cheaper than the Chinese counterparts.

The E-vehicle Control System is discussed in section 6.3.3

⁷6LowPan is an abbreviation for IPv6 over Low power Wireless Personal Area Networks. It is a technology that was originally intended to extend internet connectivity to smaller low power devices that may not have any dedicated TCP/IP stack. Now-a-days, it is used for creating pico-nets or micro-networks of devices, Peer-to-Peer device communication.

Chapter 2

Introduction

2.1 Automotive Electronics

Automotive electronics are electronic systems used in road vehicles, such as: engine management, ignition, radio, carputers, telematics, in-car entertainment systems and others. Electronic systems have become an increasingly large component of the cost of an automobile, from only around 1% of its value in 1950 to around 30% in 2010.

2.2 Battery technology in Automotive Industry

The automotive industry is expanding at a rapid pace. Automobiles are now-a-days more “smarter” and react to environment changes more rapidly. Contrast todays vehicles with the first ever automobiles, which had no logical processing units or sensors. Everything needed to done manually. Today, automotive industry is highly dependent on the electronics industry for providing efficient systems. This may be called **Automotive Electrification**. With the introduction of high-efficiency high-density LiPo¹ batteries in the market, the automotive market has taken a turn towards electrification of vehicles. Corporations like Tesla Motors are the pioneers of this technology. With an increase in the production of various kinds of cells and batteries, the market has been flooded with these components. As a consequence, the prices for batteries has dropped sharply in the last decade. This has also impacted the automotive industry, with big companies like Tesla Motors to take the initiative for making “clean” and pollution-free vehicles.

¹LiPo is an abbreviation for Lithium-Polymer ion batteries. These are a variety of battery which uses a polymer electrolyte composed of Li ions instead of a traditional liquid electrolyte. These are extremely light weight and pack a relatively larger amount of energy per volume than other types available.

2.3 Internet of Things

Internet of Things refers to a network of physical objects, like household articles, vehicles, tools, buildings, worn-items, etc. embedded with suitable software and hardware. This software and hardware may enable these objects to communicate with each other or with devices on another network like the Internet. IoT² is also a rapidly growing field. Wireless IoT devices are now-a-days available in any shape or size, starting from smart household appliances like TV, AC, Refrigerators, etc. to small beacons the size of a coin and wearable devices. IoT enabled devices may enable the user to interact with the devices in a number of ways, which include:

- Controlling the device with the help of another device like a mobile phone or a computer.
- Controlling the device with help of HID (Human Interface Device).
- Controlling the device with the help of ones body, using suitable sensors. For example, a smart-watch may be used to turn on an appliance when it detects motion in a certain direction. Sensors such as accelerometers and gyroscopes may be used to detect linear or radial motion.
- Device controlling another appliance.

The uses of IoT are limitless and it is just a matter of time, when the market will be flooded with IoT based devices.

2.4 Combining Automotive Electrification and IoT

With the development of dedicated sensors and low cost IoT devices, it is now possible to efficiently integrate IoT into automobiles. Various kinds of electronic integration is already existent in present automobiles, such as

- **Automotive ECU :** ECU stands for Engine Control Unit. It is a logical control system, which takes some input data from the automobile engine sensors like temperature, acceleration, rate of fuel flow, etc. The ECU is responsible for the efficient combustion of fuel and maintaining the engine conditions well within its operation limits.
- **Body Control Devices :** Body Control Units are responsible for various body control functions of the automobile like central locking system, power windows, various lights like the headlights, tail-lights and indicator lights.
- **Automotive Audio Equipment :** Audio Equipments in automobiles are composed of various electronic devices like audio amplifiers, radio-frequency sys-

²Internet of Things

tems, audio decoders and effects-processors(DSP), low noise amplifiers, speaker systems.

- **CAN Bus :** CAN stands for Controller Area Network. It is a automotive bus specification designed for high speed data transfer. The CAN bus enables several micro-controllers to share data with each other without the presence of a host or central system. It is used for integrating various electronic automotive components like the ECU, Body control unit, sensors, etc. with each other so that they can function in harmony. The CAN bus is discussed in more detail later.

2.4.1 The need for IoT in automobiles

- Integration of more and more Silicon³ into automobiles.
- Smarter and more efficient automobiles.
- Larger economic benefit. Smarter automobiles are more desirable in the current market and hence provide more economic value than its counterparts.

³Silicon, here refers to electronic logic components. These may refer to logic gates, ASICs, sensors or micro-controller units.

Chapter 3

Software Tools and Hardware Components

Table 3.1: A brief summary of the tools used

S.No.	Specifications	Title	Description
1.	Operating System	Windows 7	Base OS
2.	IDE	IAR Workbench	IDE for ARM embedded software development
3.	IDE	SPC5Studio	IDE for SPC embedded software development
4.	Software	UDE Debugger	A debugger software that supports debugging of micro-controllers with the IEEE compliant JTAG specifications
5.	Software	STM32CubeMX	Firmware Code Generator for the STM32 ARM hardware platform devices
6.	API and Stack	BlueNRG-DK	A comprehensive software development kit for the BlueNRG family of SoCs
7.	Programming Language	C	Default language interface for IAR and ppc-gcc-vle compilers used in code production
8.	Hardware Device	STM32 Nucleo	Evaluation boards for STM32 ARM hardware platform
9.	Hardware Device	SPC Discovery	Evaluation boards for SPC hardware platform
10.	Hardware Device	BlueNRG-1	BLE SOC based on ARM Cortex-M0 core
11.	Hardware Device	Telit GL865	SoC for GSM Communication
12.	Hardware Device	Quectel M66	SoC for GSM Communication
13.	Management Tools	Git	Code Version Management and Repository System

3.1 IAR Workbench (also called EWARM, Embedded Workbench for ARM)

IAR Embedded Workbench is the preferred platform for embedded software development at STMicroelectronics, India. IAR offers a fast and easy way to write code, compile, upload and flash onto the hardware with minimal effort. It provides an integrated solution for rapid software development. IAR employs its own compiler

tool-chain for compiling C code to the ARM Cortex-M core based hardware platforms. There are several other IDEs as well like Keil, AC6 Studio, etc. but they do not provide as much streamlined development cycle as IAR does.

3.1.1 In-built debugger system

IAR workbench has an in-built debugger system, that supports several hardware specifications like JTAG, J-LINK, STLINK, SWD¹, SWIM, etc. The debugger supports functions such as

- Breakpoints
- Run or pause execution control
- C-SPY single command execution
- Custom scatter file or linker file configuration
- Live-watch of variables
- Real time view of memory, SFRs and CPU registers
- Injecting values in registers and memory location in real time.

3.2 SPC5Studio

It is the official IDE for embedded firmware development for the SPC hardware platform (discussed in section 4.4.2.1). It supports three compiler toolchains:

- FreeGCC compiler toolchain with VLE (GNU)
- Hightec Compiler Collection (Proprietary)
- GHS Compiler Toolchain (Proprietary)

The IDE is based on the Eclipse IDE, a popular open-source IDE for C development. The low level-firmware packages are part of the SPC5Studio itself. The low-level drivers are made in the Freemarker templating language. A GUI interface is provided for manual configuration of the low-level drivers. The configuration can also be done directly to the low-level header files. This kind of configuration is kept persistent using the Patch Architecture of SPC5Studio. It is discussed in section 3.2.1.

3.2.1 Patch architecture

The common code for the low-level drivers is embedded in the SPC5Studio itself and included in the project automatically. This is in contrast to other IDEs, where

¹Single Wire Debug

the user has to download the relevant low-level drivers and include them manually in the project. The advantage of SPC5Studio's method is that, in case of a new version of the low-level drivers is released the IDE will automatically update the project according to the new version, while in other IDEs the user has to do so manually.

3.2.2 Powerful code-completion and management platform

SPC5Studio is built on Eclipse IDE, which is a very popular IDE for Java and C programming. It has borrowed excellent code completion and management features from Eclipse. This enhances productivity and speed of the developer.

3.2.3 Pre-built project templates and configuration

To increase the speed of development, several pre-built project templates are already included in the IDE. These project templates contain code for general configuration and operation of each peripheral of the device.

3.3 UDE Debugger Toolkit

Since SPC5Studio does not have any built-in debugging framework or tools, an external toolkit is necessary for operation and debugging. For SPC platform, UDE Debugging toolkit is the standard and default software for debugging. It has built in support for many CPU architectures and several debugging specifications. It also has support for assembly language mixed-breakpoints, i.e. it will show the code in assembly language and the user can run the code one line at a time.

3.4 STM32CubeMX

STM32CubeMX is part of the STMCube project by STMicroelectronics, whose objective is to ease and shorten the development efforts and time. The STM32CubeMX is targeted for the STM32 ARM-based platform. Similar software kit exists for the STM8 and SPC platforms also. In simple words, STM32CubeMX is a initialization code generator. It provides an easy to use and interactive GUI to configure and generate firmware code for a platform. Its general flow of use is

- Select a suitable micro-controller platform, based on the features and number of peripherals. STM32CubeMX provides a comprehensive database so that the user can easily choose a platform, according to his/her needs.
- Configure which peripherals to use. It automatically disables the clock source for the peripherals selected not to be used.
- Configure the clock frequency to each peripheral by adjusting the clock prescalers for each of them.
- Generate the initialization code and open it in the IDE of choice.
- Add the application code in the code thus generated.

3.5 BlueNRG-1 DK

It stands for BlueNRG-1 Application Development Kit. It is a set of tools and low-level drivers for the BlueNRG-1 platform. The parts of the Development kit are

- **BlueNRG-1 Flasher** : It is tool for flashing compiled hex code to a BlueNRG-1 device.
- **BlueNRG-1 ST-LINK Utility** : It is a utility software for core level configuration of the BlueNRG-1 platform.
- **Documentation** : A comprehensive set of documentation for using the low-level drivers and APIs for the platform.
- **Example Firmwares** : A few examples that demonstrate typical uses of the Development Kit.
- **C Libraries** : Some C libraries needed by the Development Kit like, peripheral drivers, CMSIS², HAL³ libraries and BSPs⁴.

3.6 Toolchains

A toolchain is a set of tools and software used to perform complex software development tasks. A toolchain may include compilers and debuggers for a platform and even version control systems. A Version Control System is a tool that allows easy management of code across many versions and changes.

For almost all of the period of internship, the C programming was used. As there were a number of different platforms it was necessary to use a wide variety of toolchains. Some toolchains that were used

²Cortex Microcontroller Software Interface Standard

³Hardware Abstraction Layer

⁴Board Support Packages

- IAR ARM toolchain
- GNU CCC ARM toolchain
- GNU CCC PPC toolchain (with VLE support)
- COSMIC STM8 toolchain

3.7 STM32 Nucleo

The STM32 Nucleo is a family of development boards based on the STM32 microcontroller platform. The STM32 Nucleo come in three variants, the Nucleo-32, Nucleo-64 and Nucleo-144. The boards are categorized on the package of the STM32 integrated on the board. Thus the Nucleo-32 has TQFP-32, Nucleo-64 has TQFP-64 and Nucleo-144 has TQFP-144 integrated in them respectively. The STM32 Nucleo boards have morpho connectors which allow them to be easily integrated with Arduino shields. A shield is a stackable board which extends the functionality of the existing system. For example, Sensor shields, Ethernet Shields and Wireless connectivity Shields.

3.8 SPC Discovery Boards

Similar to the Nucleo boards, Discovery boards provide a fast and reliable platform for prototyping. The boards provide common interfaces like SPI, UART and USB right away and also provide easy integration with debuggers like JTAG. The Discovery boards are manufactured according to the end application, for example a discovery board targetted for motor control applications will provide dedicated 84-pin motor control connectors and dedicated connectors for motor feedback inputs from hall sensors and other sensors. Most Discovery boards also provide an onboard debugger unit. The debugger units are based on two-channel FTDI UART modules, which support the JTAG debugging specifications through a process called bit-banging. Bit-Banging is basically a process of packet transmission by piggybacking it onto a different protocol. So the micro-controllers Debug Control Unit is communicated using the UART protocol.

3.9 BlueNRG-1 Bluetooth SoC platform [1]

The BlueNRG-1 is a very low power Bluetooth low energy (BLE) single-mode system-on-chip, compliant with Bluetooth specification. The BlueNRG-1 extends the features of award-winning BlueNRG network processor, enabling the usage of the em-

bedded Cortex M0 for running the user application code. The BlueNRG-1 includes 160 KB of programming Flash memory, 24 KB of static RAM memory with retention (two 12 KB banks) and SPI, UART, I²C standard communication interface peripherals. It also features multifunction timers, watchdog, RTC and DMA controller. An ADC is available for interfacing with analog sensors, and for reading the measurement of the integrated battery monitor. A digital filter is available for processing a PDM stream. The BlueNRG-1 offers the same excellent RF performance of the BlueNRG radio, and the integrated high efficiency DC/DC converter keeps the same ultra-low power characteristics, but the BlueNRG-1 improves the BlueNRG sleep mode current consumption allowing a further increase in the battery lifetime of the applications.

3.10 Telit GL865 and Quectel M66

The Telit GL865 and Quectel M66 are integrated network processor SoCs. These are designed for GSM communication. They support the dual GSM frequency bands. Both of the modules can be easily interfaced to a master device or micro-controller using UART or SPI, but can also function as standalone network processors. The Telit GL865 features an in-built hardware python interpreter. This interpreter allows it to decode python statements that can be written to the modules flash memory to perform standalone tasks. The M66, on the other hand, is designed as a cheap and rugged SoC with the smallest footprint and size in the industry. Both of the processors are extremely efficient and operate at 1.6V CMOS technology.

3.11 Git Version Control and Management System

Git is a software tool used for version control and management. It essentially keeps track of the changes and additions made in the project files and maintains a history for each of the selected files in a project directory. This helps the programmer to quickly revert back to a working version if an addition to the code breaks its functionality or to develop new features in complete isolation to the main branch, so that they don't break the main branch if something goes wrong. Git is also an extremely useful tool for team coordination and collaboration. A central source code repository can be maintained, and a large team can contribute to the repository by "pushing" their code to this central repository.

Chapter 4

Vehicle Tracking System (VTS)

4.1 Introduction

The product is a smart solution for keeping track of a vehicles location and its vital statistics. The Vehicle Tracking System is an integrated solution with built-in GSM and GPS functionality for data acquisition and connectivity.

4.2 Existing Solution(s) (Hardware and Software)

A fair number of such solutions already exist in the market. One of the solutions that was analyzed was based on a MediaTek controller unit (ARM core) with ublox GPS and SIM-900 GSM modules. A piezo-electric MEMS sensor IC, ADXL345 was also integrated to collect velocity and acceleration data. The problem with this very implementation is that it is not composed of automotive grade components. Automotive grade components are designed to be more rugged and temperature resistant. As no automotive grade components were used in the analyzed design, it is more susceptible to failure. The design was made to be as cheap as possible, so a lot of components were used after lots of cost-cutting.

4.3 Objectives

After a preliminary analysis of the given product, a set objectives were formulated. The primary objective was to design and implement a Vehicle Tracking solution which is rugged enough to meet automotive needs and can be used with minimal human intervention. Additionally, the following objectives were laid out.

- To showcase the abilities of the Teseo III range of geolocation devices, developed at ST. Teseo is a family of ASICs developed primarily for geolocation, and has several peripherals like SPI, UART, in-built flash, etc. The Teseo range has had three iterations over the years and the latest iteration supports geolocation protocols such as NMEA, GNSS, GPS, Galileo, Beidou, etc. It is a moderately priced highly powerful system, designed for automotive applications in mind.
- To use the SPC series of micro-controllers. The SPC series is based on the e200hz core which is based on the Power Architecture. It is based on the Book-E specification for PowerPC which defines some specifications for embedded applications. More details about the SPC platform is given at section [4.4.2.1](#).
- The solution should collect the following vehicle statistics:
 - Longitude
 - Latitude
 - Speed
 - GSM and GPS RSSI¹
 - Engine Ignition status
 - Central Locking status
 - Air-Conditioner status
 - Timestamp of data acquisition
- The solution should send the acquired data using GPRS through TCP transport layer or using HTTP GET in the application layer.

4.4 Project Details

The hardware and software sections of the project were taken care of separately. Following are the details of the hardware and software implementations of the project.

4.4.1 System Model

The system follows a client-server model. A flow diagram of the general system model is shown in figure [4.1](#). As shown in the figure the system consists of the following key components.

- Central Server
- NodeJS
- Database Back-end Server
- Internet Gateway (ISP)
- GSM Mobile Tower (GSM antenna)

¹Received Signal Status Indicator

- GSM communication link
- VTS equipped vehicles

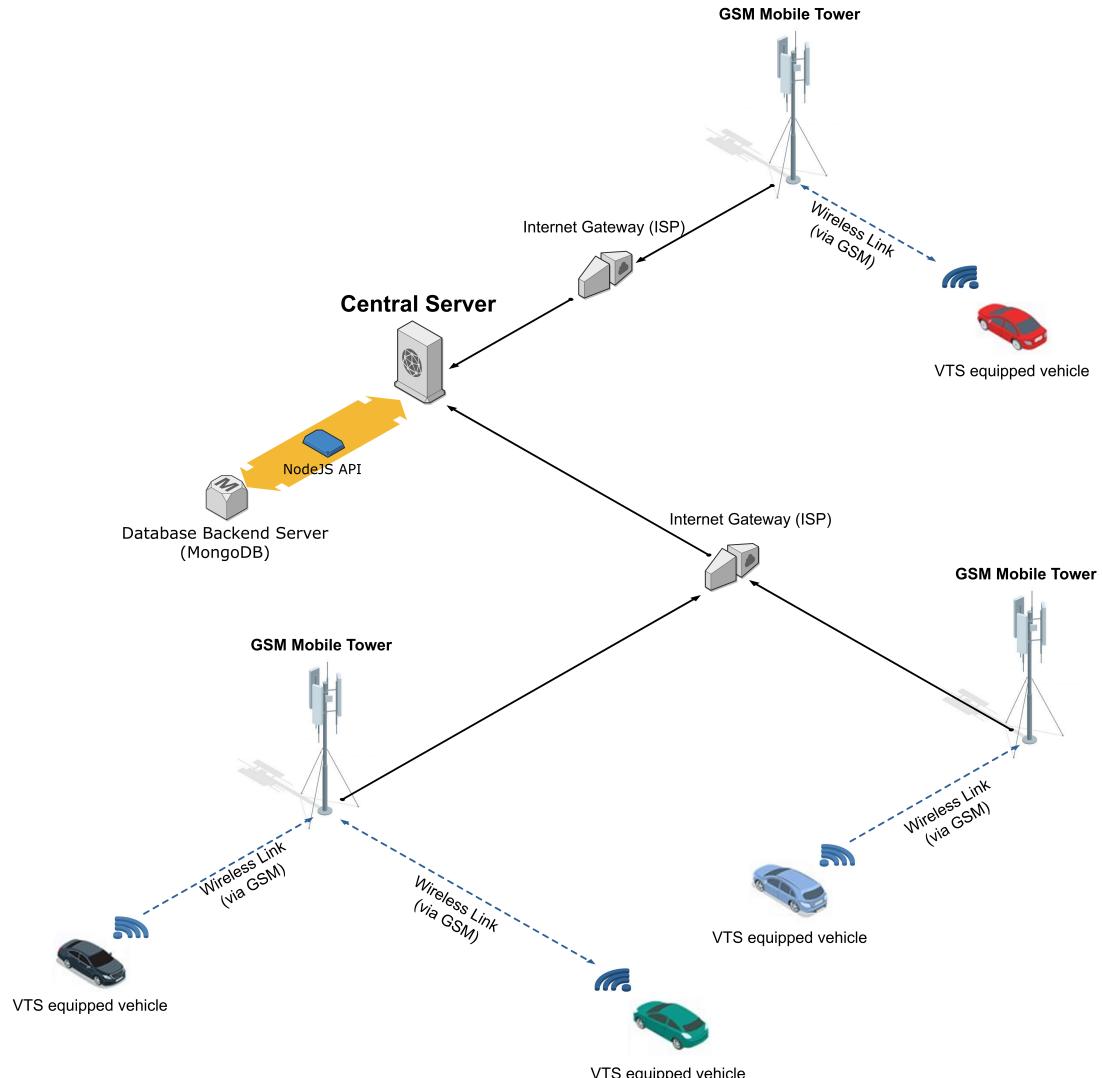


Figure 4.1: System Model of the Vehicle Tracking System

A brief explanation of each component is as follows:

1. Central Server

The Central Server is responsible for maintaining connectivity to each of the individual VTS-equipped vehicles and receive the geolocation and vehicle data. The communication is done either via the TCP protocol in transport layer or via HTTP protocol in the application layer of the TCP/IP stack.

- Using TCP protocol

Communication using TCP protocol needs an open socket or port at the

server end. As soon as the authentication handshake is complete between the client and the server, the client can transmit and receive data from the server. The created link is full duplex i.e. it supports simultaneous transmission and reception at both ends.

- Using HTTP protocol

Communication using HTTP protocol uses the underlying TCP layer but the communication link itself is not full duplex. The server on its own cannot initiate transmission on its end to the client. The server can only send data after the client has connected and transmitted some data. This is a drawback in HTTP protocol, that there is no always-alive link as there was in TCP. Thus the client has to repeatedly establish and break its connection whenever it wants to send some data.

2. NodeJS

NodeJS was the preferred server-side programming language due to its speed and flexibility. Several APIs were available in NodeJS that facilitated and reduced the server-side development time.

3. Database Back-end Server

This is the back-end server responsible for managing the database of all the tracked data. A database application known as MongoDB was used for this purpose. MongoDB is known for being light-weight and readily integrable with NodeJS. This database can further be queried from an android application that can display the information at the user-end.

4. Internet Gateway

The Internet Gateway is responsible for routing the data packets from the VTS to the central server. The gateway is managed by ISPs². A dedicated channel was secured with Airtel, for testing purposes.

5. GSM Communication link

The GSM communication link is managed between the GSM base station of a particular cell and the GSM module in the VTS. The data communication is done through GPRS (General Radio Packeting Service).

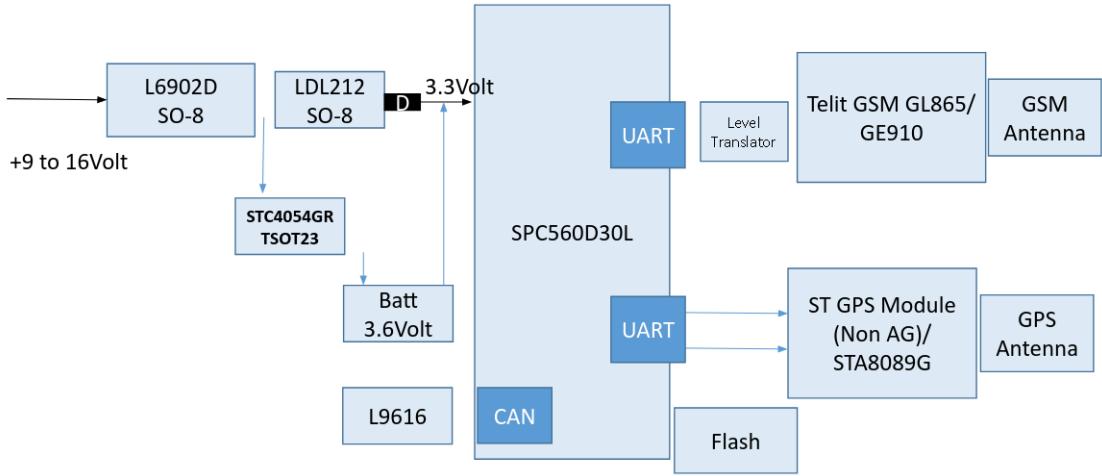


Figure 4.2: A hardware block diagram of VTS

4.4.2 Hardware

4.4.2.1 The SPC series of micro-controllers

The SPC series of micro-controllers is based on the Power Architecture Book E specification, developed by Freescale (now NXP) and Motorola. The Book E specification is designed for embedded applications of low to medium range processing needs. The SPC series was formerly called the MPC series and was being developed at NXP. A deal was struck between NXP and ST, wherein both parties agreed to develop the MPC series further to use it in the automotive domain. Thus, NXP provided their hardware and ST developed the low-level peripheral drivers required to write software for this device. The low-level peripheral drivers are now a part of the SPC5Studio suite, previously discussed in section 3.2.

The low-level peripheral drivers have also seen a few iterations. The first iteration was called the **HAL**, or the *Hardware Abstraction Layer*. It used a set of C functions to interact with the peripheral hardware. As it turned out, it was not scalable and could not be ported to the large range of SPC micro-controllers that were made. So a newer and scalable iteration was made, which was called the **RLA**, or the *Register Level Access* layer. Instead of using functions, the RLA uses C unions and structs to map the peripheral registers and some higher level functions to interact with them. This way only the union and structs needed to be varied for each hardware, while the higher level functions could be reused. Thus RLA, is the preferred and supported driver for SPC and was used in the project.

²Internet Service Provider

4.4.2.2 Power Supply section

The device was designed to take its power supply from the automobiles +12V power rail directly. Additionally a large number of onboard components require different voltages for their functioning, like the GPS module runs on +1.8V while the GSM module runs on +3.3V. So several voltage regulators were used.

In scenarios like theft, the thief removes the car battery so as to not trigger off any alarms. The device was designed to function in such a case also. For this an onboard power supply from a Lithium polymer battery was used.

A block diagram of the power supply section of the device is shown in figure 4.3.

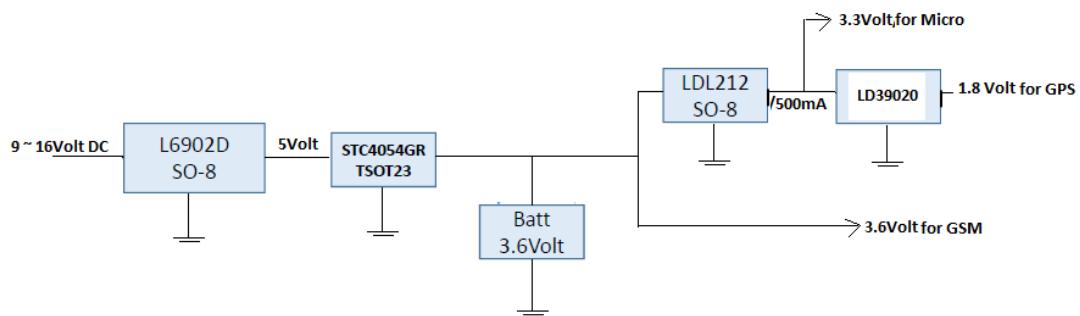


Figure 4.3: Power Supply Section of the Vehicle Tracking System

Device Description

- **L6902D**

The input section is composed of L6902D. This is a low-voltage LDO (Low Dropout voltage regulator). The input to this IC is from the automobiles power supply rail of +12V. A safe margin of +9V to +16V has been assumed. This device gives an output of +5V.

- **STC4054GR**

The +5V output is then given to the input of a Battery Management IC, STC4054GR. This IC produces a regulated current flow for safe charging of the Lithium Polymer battery. The output voltage varies from +3.6V to +4.5V DC, according to the charging region the battery is currently in. The Li-Po battery used is of 3.6V rating.

The +3.6V nominal output of the battery was given to the GSM module, as it required a voltage of +3.3V to +4.2V for proper functioning. Also, the GSM

module needs current upto 2A, and the PCB tracks were designed according to this.

- **LDL212**

The +3.6V output of the battery is not suitable for devices functioning at +3.3V, thus a voltage regulator was introduced in the chain. The LDL212 produces regulated +3.3V to supply for micro-controller.

- **LD39020**

Further a +1.8V supply was required for the GPS module. The LD39020 is a fixed-mode voltage regulator used for this purpose.

4.4.2.3 Device Integration

The project features a number of co-dependent devices. The micro-controller is the central entity in the system, while all the other devices follow and obey the commands the are sent by the micro-controller. The devices need a medium to communicate with the controller. This is done using communication busses. There are several kinds of bus technologies like the SPI, I2C, CAN, etc. In this project two kinds of bus technologies are used.

1. UART or LIN bus

UART stands for *Universal Asynchronous Receiver and Transmitter*. It is a protocol for serial data communication and uses two physical wires, one for data transmission and one for reception. The UART protocol is widely used due to its availability and simplicity. The UART protocol sends data in the form of byte-sized packets that have a starting and a stop bit. The packet may contain 7-bits or 8-bits of data. Thus for textual data, one character is sent at a time. The simplicity of UART lies in the fact that very minimal physical level hardware is required. As the communication mode is asynchronous, no clock synchronization is required. The two communicating devices just have to know the signal rate at which transmission is occurring, beforehand. This is called the baud rate and is measured in bps (*bits per second*).

In this project UART is being used for communication with the GSM and GPS module. A baud rate of 115200 bps was used for communication with both the devices.

2. CAN bus

The CAN bus stands for *Controller Area Network*. It is a differential bus, multi-master protocol, which is designed for high-speed data communication, gen-

erally in automotive systems. A CAN bus is multi-master, which means that it can support more than two communicating devices simultaneously. A CAN bus is composed of two components:

- The CAN peripheral

$$f_{Tq} = \frac{f_{CANCLK}}{\text{(Prescaler value)}}$$

$$\text{Bit Rate} = \frac{f_{Tq}}{(\text{number of Time Quanta})}$$

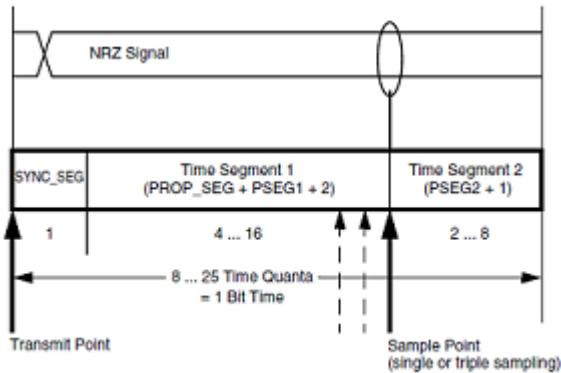


Figure 4.4: CAN bus configuration

The CAN peripheral is the integrated peripheral present inside the microcontroller system, which encodes the data to digital signals. The NRZ protocol is most widely used for this. The CAN peripheral outputs the digital signals via two GPIOs named the **CAN_rx** and **CAN_tx**, for reception and transmission, respectively. The CAN protocol is also asynchronous in nature, so no clock synchronization is necessary. The signal rate or the bit rate of transmission is pre-negotiated between the devices. The signal is received by sub-sampling the received waveform, at a frequency of f_{Tq} , where $f_{Tq} = \text{bit_rate} * \text{number_of_time_quanta}$. The bit rate and the number of time quanta are pre-negotiated within the devices.

The multi-master approach of the CAN bus allows it to have a large number of devices connected and transmitting data simultaneously. This is done by using a data identifier with each set of transmitted data.

- The CAN physical layer

The CAN physical layer is composed of an interface IC, the actual physical layer link and two terminating resistors. For this project, a CAN physical layer IC named, L9616 was used. A block diagram is shown in figure 4.5,

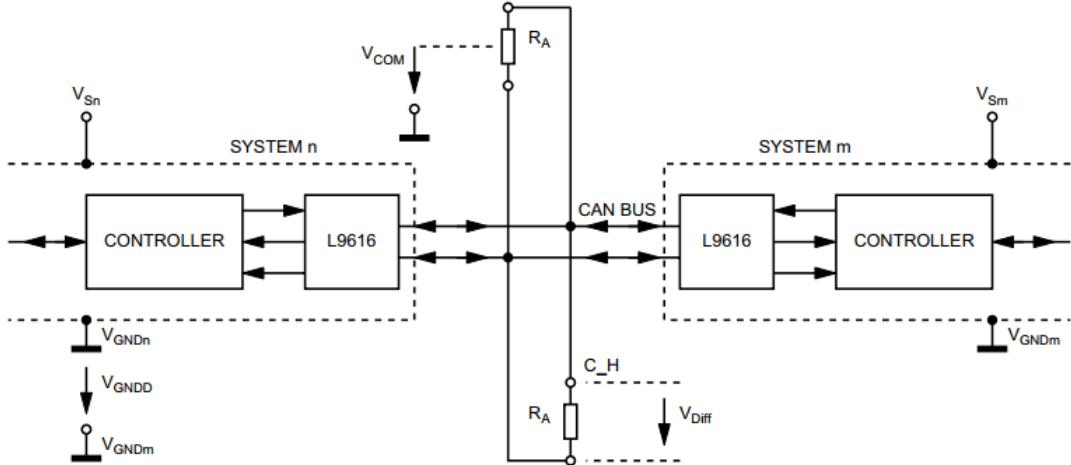


Figure 4.5: CAN bus physical layer

CAN physical layer is composed of two wires called the **CAN_HI** and **CAN_LOW**. CAN_HI wire achieves a higher potential than CAN_LOW when a dominant bit (0) is to be transmitted, and both CAN_HI and CAN_LOW achieve a floating potential when a recessive bit (1) is to be transmitted. The difference between the higher potential of CAN_HI and lower potential of CAN_LOW is nominally +1V. Thus the receiver samples the potential difference between the CAN_HI and CAN_LOW wires to detect if recessive or dominant bit is being transmitted. The advantage of such a system is that no GND wire is required between the systems. Each system may have different operating voltage, they only have to maintain the nominal differential voltage between CAN_HI and CAN_LOW.

The CAN bus wires are generally terminated with two terminating resistors on both ends as shown in the figure 4.5. The value of each terminating resistor is generally 120 ohms. The terminating resistors provide an impedance matching for the system. Thus value of the terminating resistors is chosen to match the characteristic impedance of the CAN transmission line.

Table 4.1: Comparison between LIN and CAN bus systems

S.No.	Local Interconnect Network	Controller Area Network
1.	LIN is a low-speed system	CAN is a high reliability and high-speed system
2.	LIN is closely related to the UART protocol	CAN is not related to the UART protocol

S.No.	Local Interconnect Network	Controller Area Network
3.	LIN has a typical bandwidth of 20kBps for a bus length of 40m	CAN specification ensures a bandwidth of 125kBps for a bus length of upto 40m.
4.	LIN is a master-slave protocol, with one master and as many as 15 slaves	CAN is a multi-master protocol
5.	LIN does not ensure fault-tolerant data transmission on its own	CAN ensures fault-tolerance in data transmission
6.	LIN is not a full replacement of the CAN bus. But the LIN bus is a good alternative wherever low costs are essential and speed/bandwidth is not important. Typically, it is used within sub-systems that are not critical to vehicle performance or safety	CAN bus is preferred for safety critical applications in automobiles like ECU communication and interacting with the braking system

4.4.2.4 Serial Flash Device

A Flash memory device was also integrated into the system. The flash memory device is used to store acquired data when it can not be sent to the central server. The device used was M25P16 which is a 16 megabit flash memory with a clock frequency of 75MHz. It is interfaced using SPI bus protocol. The device follows master-slave architecture where the micro-controller is the master and the flash memory is the slave. The flash memory device receives specific commands, for example data write or read at address, and it responds with the appropriate data.

4.4.3 Software

The firmware for the device is written for the SPC series of micro-controllers, but is fairly portable to other systems as well. While writing the firmware the following points were kept in mind:

- The firmware should be able to perform several tasks in real time. The system needs to track the GPS coordinates in real time as well as communicate to

the GSM network and monitor the vitals of the vehicle. The tasks should not interfere with each other.

- The firmware should be as compact as possible. Although, the SPC microcontrollers used had an abundant amount of flash memory available for code storage, it was decided to keep the size as low as possible so that it could be ported to other cheaper systems with lower amount of memory.
- The firmware should be easy to understand and debug.

4.4.3.1 Available options and trade-offs

- For keeping the code easily understandable and debuggable, the structure of the code was chosen in the form of a Finite State Machine. Several states based, on the functioning of the system were selected, such as
 - Reset State
 - Init State
 - Idle State
 - Data Acquire State
 - GSM Send State
 - Wait State

An explanation and description of each state is given in section 4.4.3.3. The advantage of this architecture is that the current state is easily visible in the UDE Debugger. Thus, a real time monitoring of the system can be done.

- For keeping the code asynchronous or non-blocking, one option was to use an RTOS. RTOS stands for Real-time Operating System. It is an operating system for embedded systems. It supports preemptive multi-tasking, which means that every process is run for a certain amount of time, not necessarily to its completion and a context-switch is made. A context-switch refers to the saving of current contents of stack, CPU registers and the program counter to a memory location and fill them with the contents of a new process. In this way a periodic context switch is made by the RTOS and a number of processes can run simultaneously. The latency is a measure of the delay the RTOS introduces as an overhead in this process. On an average CPU with a 16 MHz clock frequency, FreeRTOS, an implementation of RTOS, introduces a maximum latency of about 7ms.

The RTOS is an extremely efficient solution to this problem but it comes at a cost. An implementation of RTOS known as ChibiOS is available and well supported on the SPC platform but even a minimal integration of ChibiOS takes about 50kB of flash memory which is way too much for some smaller

cost-efficient systems.

Thus a non-blocking architecture based on *co-operative preemption* was employed. So, instead of employing a separate RTOS, the firmware was written in such a way that it mimics the behaviour of RTOS. This in-turn introduced a larger latency than RTOS but it was cost-efficient and the whole code was compiled to a size of just 29kB.

The non-blocking architecture is discussed in section 4.4.3.2

4.4.3.2 Non-Blocking State Architecture

As one of the requirements of the system was to perform several tasks in parallel, the state machine alone can't take up all the CPU time. An example of this scenario is evident with the *Input Sensing* functionality of the system. According to this functionality the vital statistics of the vehicle like Door Central Locking status, Air Conditioner status, Engine Ignition status and Battery Power status can be accessed by tapping into the Electronic Control Unit of the vehicle and routing it to the GPIO pins of the micro-controller. In this way, no new hardware will be required to sense the vital statistics.

As GSM communication and acquiring geolocation data from GPS satellites is a time-consuming task for the system. In a blocking architecture it may take a relatively large amount of time for the system to wait for these tasks. Inherently in a blocking architecture, the system will have to halt all of its processes and wait for completion of the task at hand. Such an architecture is not feasible to be used in this case. This may result in over looking of input data. For example, the system takes 10 seconds to establish a GSM connection to the nearest cell tower and register itself, the system will have to halt for those 10 seconds, so any change in the vehicle vital statistics will go unnoticed.

To counter this scenario, the firmware was designed to be non-blocking in nature. This is evident from the main function of the firmware.

```
int main(void) {
    while(1){
        state_machine_exec();
        gps_state_machine();
        input_sense();
    }
}
```

Thus inside the main while loop, three *re-entrant* functions are present, `state_machine_exec()`,

`gps_state_machine()` and `input_sense()`. Re-entrant functions are designed such that they are able to remember their progress and resume the process when called again. Thus, each function in the main while loop is designed such that it executes partially, remembers its progress and exits, thus transferring the control to the next function. The next function similarly executes in this form and the while loop takes care that each function runs periodically.

4.4.3.3 The Finite State Machine

A flow diagram of the state machine is provided in the figure 4.6.

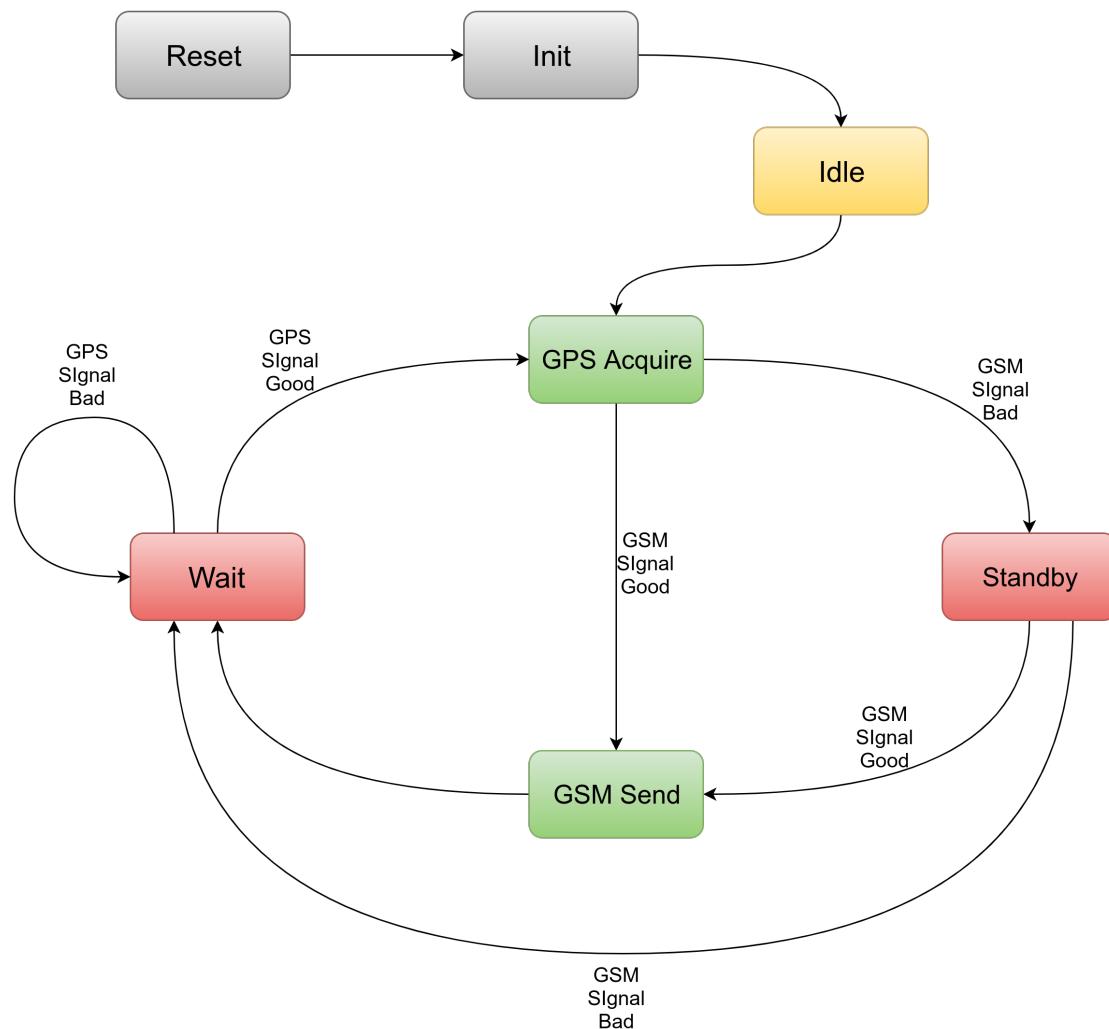


Figure 4.6: The Finite State Machine Flow Diagram

The FSM has been implemented in C using switch-case statements, as follows

```

static state_return_t ret;

switch (current_state) {

case RESET:
    ret = state_reset();
    if (ret==SUCCESS) {
        next_state = INIT;
    } else if (ret==STATE_REMAIN) {

    } else {
        next_state = INIT;
    }
    break;

case WAIT:
    ret = state_wait();
    if (ret==GPS_SIGNAL_GOOD) {
        next_state = DATA_ACQUIRE;
    } else if (ret==GPS_SIGNAL_BAD) {
        next_state = WAIT;
    } else if (ret==WAIT_TIME_NOT_OVER) {
        next_state = WAIT;
    } else if (ret==STATE_REMAIN) {

    } else {
        next_state = DATA_ACQUIRE;
    }
    break;
}

```

As evident from the code snippet above, each state has been encapsulated inside a function of appropriate name, for example `state_reset()`, `state_init()` and `state_idle()`.

An example of such a state function `state_idle()` is given below as a code snippet.

```

/**
 * @brief Idle state function
 *
 * Entry point to the state machine loop.
 * Default entry point after recovery from fault.

```

```

* Wait for both GPS and GSM module to acquire
* a good signal strength.
*
* @return state_return_t
*/
state_return_t state_idle() {

    state_return_t ret;

    /* Check GSM module SIM registration status */
    if (state_idle_status_var == STATE_IDLE_ENTRY) {
        /* wait for SIM registration */
        _SM_WRAPPER(is_sim_registered(NON_BLOCKING), SIM_REGISTRATION_FAIL);
        state_idle_status_var = SIM_REGISTERED;
    }

    if (state_idle_status_var == SIM_REGISTERED) {
        /* enable GPRS */
        _SM_WRAPPER(enable_GPRS(NON_BLOCKING), GPRS_ENABLE_FAULT);
        state_init_status_var = GPRS_EN_DONE;
    }

    return GOOD;
}

```

4.4.3.3.1 Description of the states

1. Reset State

The reset state is the application entry-point. It is the first state that should be executed as all low-level peripheral drivers and IRQ handlers are initialized in this state only. The exit point from this state points to the INIT state.

2. Init State

The init state is meant for various initialization tasks. The UART (LinFLEX) peripheral is initialized and various GSM module related operations are done to ensure that it is correctly turned on and functioning. After successful initialization the control moves to idle state.

3. Idle State

The Idle state is the entry point to the state machine loop (see figure 4.6). It is

also the default entry point after recovery from any fault. In the idle state the system waits for both GPS and GSM modules to acquire a good and stable signal strength for reliable communication. If the GPS and GSM modules acquire a good signal, the control moves to the GPS Acquire State.

4. GPS Acquire State

This is the data acquisition state. The geolocation data and other data like acceleration and velocity are acquired using the GPS module. The communication between the GPS module and micro-controller is done using a standard set of commands called the NMEA commands. The data acquired in this state is serialized and put in a central buffer for further processing. After this process, a check is done with the GSM module, if its signal is still above a threshold level and that it can reliably transmit or receive data. If it is able to, the control moves to the GSM Send state. Else it moves to the Standby state.

5. GSM Send State

This is the state where the acquired data is sent to the central server via GSM network. TCP is used in the transport layer. The system opens a socket on a dedicated port on the central server and sends the serialized data as a stream. The central server interprets the source system of data using a unique ID, called the *Vehicle ID*. Each installed system is assigned a unique vehicle ID derived from the IMEI number of the GSM equipment.

6. Standby State

The Standby state is entered if the GSM module loses its connection in between the process. In such a state the system cannot send the statistics to the central server as the connection has been hindered. So, as to not incur a loss of data, it is stored in an external flash memory device. The flash memory device has been discussed in detail in section 4.4.2.4. The data is stored in LIFO order, so that the data most recently stored is sent out the very first time, a reliable GSM connection is made again. This is to ensure that the central server gets the newest set of data first. A check with the GSM module is made again at the end of this state, if the signal is above a threshold the control moves to GSM Send state, else it moves to the Wait state.

7. Wait State

The Wait state is used to introduce a delay in between each cycle of data acquisition and transmission. This is done to

- **Reduce the duty cycle of the system**

Reducing the duty cycle results in a reduction in power consumption of

the system, as it will be functioning for a lesser duration. The delay duration is strategically set to balance efficiency and power consumption. The waiting period was earlier set to 5 seconds. Later an algorithm was devised to set the waiting period dynamically with changing battery voltage, so that when battery power is running low, the system inhibits its duty cycle.

- **Reduce Central Server traffic**

The central server is responsible to receiving the data and ensure that it is stored in the database properly. For this purpose, the central server has to maintain a live TCP stream link with every online vehicle tracking system. For a large number of such online systems, the central server would be easily overwhelmed, if every system was sending data continuously. Thus, to keep incoming traffic low, the vehicle tracking systems will only send data after a periodic interval.

4.4.4 Testing and Result

An Android app was developed as an user interface to the system. It queries the data collected at the server according to the date and time at which it was recorded. The prototype device was attached to a testing vehicle and the vehicle followed a well known path in the city, while the Vehicle Tracking System was engaged. The following figure figure 4.7 shows the various recorded statistics and the path of the vehicle on a map.

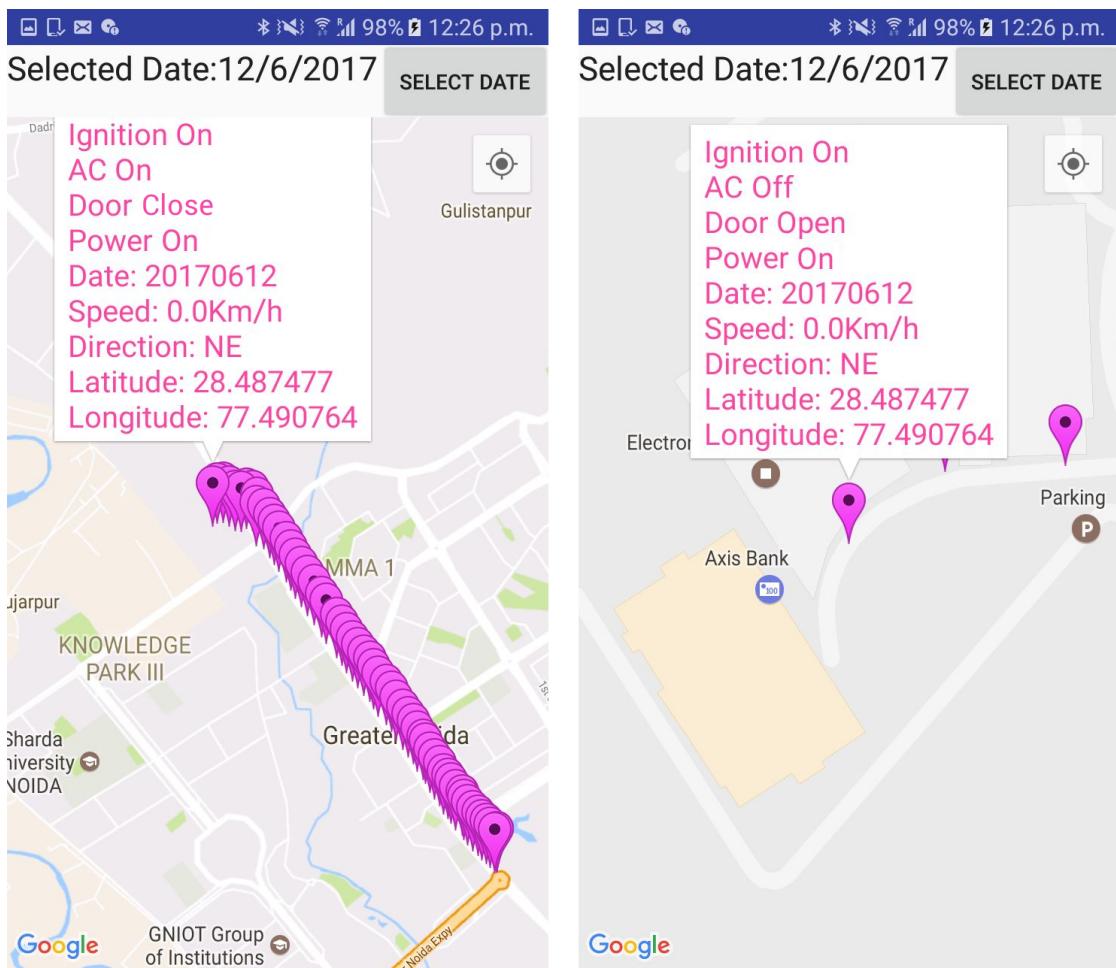


Figure 4.7: Demo run of the Vehicle Tracking System

Chapter 5

Automotive BLE Keyless Entry System

5.1 Introduction

Automotive security is a very important aspect in the Automotive Industry. A large budget in automotive development is solely dedicated towards security and reliability. Several anti-theft systems are present in the market. Considering the growing popularity for IoT and the emergence of very low power radio devices, it is a matter of time that market will be flooded with applications of such devices. The BLE Keyless Entry System is an attempt to merge IoT with Automotive Security.

5.2 Problem Statement

The problem is to devise a central locking system which can be operated via a BLE¹ enabled device. Most of the smartphones available in the market today support one or the other forms of Bluetooth. Thus, a smartphone should be able to operate this central locking system.

5.3 Current Solutions

Several kinds of wireless central locking systems are available in the market, but most of them are operable through proprietary hardware from a few vendors. All of them operate in the 2.4 GHz radio frequency range.

¹Bluetooth Low Energy

The solutions comprised of a key-fob, or a remote with a few buttons, to unlock and lock the car. A few of them had a feature of locating the car via sound and light so that the user may find his/her car easily in a parking lot.

5.3.1 Merits of the current solutions

All the current solutions were using proprietary protocols designed by the specific vendors. While this reduces the portability of the application and introduces many, at times conflicting, standards in the market, on the other hand, this also obscures its working. The 2.4 GHz radio frequency range is a widely used spectrum for wireless applications, and due to its popularity, the radio hardware for this spectrum is also very cheap.

5.3.2 Demerits of the current solutions

- Due to proprietary hardware and software no standard is present for this application. There is a large variation in the functionality and the security of the systems.
- The systems are susceptible to a number of security flaws, like
 - Injection attacks

A 3rd party key-fob can be tampered and made to mimic other key-fobs. This way, any vehicle can be unlocked using a single master key.

- Replay attacks

A specialized radio-transceiver can be made that can record RF communication packets when a legitimate key-fob is operated. After some time, this transceiver can be used to emit the same sequence of packets in the same RF range, and the central locking system mistakes it for the legitimate key and unlocks.

- Man-in-the-middle attacks

A specialized radio-transceiver is used that acts a repeater for RF signals. Many key-fobs continuously emit their handshake keys, and when the key-fob is in range of the vehicle it can unlock. The transceivers can act as transparent signal boosters and unlock the vehicle even if the key-fob is very far away.

- A separate key-fob is required for operating the system. Although, this increases the security of the system, but if the key-fob gets lost, the whole system is compromised.

5.3.3 Objectives

- To implement a system using the BlueNRG-1 SoC platform for central locking.
- An android application should be able to scan the vehicle from a distance of atleast 30ft, connect to it and unlock it.
- The connection establishment time should be kept as minimum as possible, in the order of a few hundred milliseconds.
- The system should be interface-able with any vehicles Body Control Unit.
- An additional feature known as flasher is to be implemented, which will flash some lights on the vehicle to help the user to find it.

5.4 Project Details

5.4.1 Bluetooth Low Energy Protocol (BLE) [2]

The Bluetooth Low Energy protocol is an extension of the Bluetooth Classic protocol. It has been developed and marketed by the Bluetooth SIG², which comprises of many corporations that oversea the development of Bluetooth specifications.

Compared to Classic Bluetooth, BLE is intended to provide considerably reduced power consumption and cost while maintaining a similar communication range. BLE was originally introduced under the name *Wibree* by Nokia in 2006. It was merged into the main Bluetooth standard in 2010 with the adoption of the Bluetooth Core Specification Version 4.0.

Some well known profiles that are found in common applications are as follows

1. Health care profiles

There are many profiles for BLE devices in health-care applications. The Continua Health Alliance consortium promotes these in cooperation with the Bluetooth SIG.

- BLP (Blood Pressure Profile) — for blood pressure measurement.
- HTP (Health Thermometer Profile) — for medical temperature measurement devices.

²Specific Interest Group

- GLP (Glucose Profile) — for blood glucose monitors.
- CGMP (Continuous Glucose Monitor Profile) Sports and fitness profiles

2. Profiles for sporting and fitness accessories

- BCS (Body Composition Service)
- CSCP (Cycling Speed and Cadence Profile) — for sensors attached to a bicycle or exercise bike to measure cadence and wheel speed.
- CPP (Cycling Power Profile)
- HRP (Heart Rate Profile) — for devices which measure heart rate
- LNP (Location and Navigation Profile)
- RSCP (Running Speed and Cadence Profile)
- WSP (Weight Scale Profile)

3. Internet Connectivity

- IPSP (Internet Protocol Support Profile)

4. Generic Sensors

- ESP (Environmental Sensing Profile)
- UDS (User Data Service)

5. HID Connectivity

- HOGP (HID over GATT Profile)

6. Proximity sensing

“Electronic leash” applications are well suited to the long battery life possible for ‘always-on’ devices. Manufacturers of iBeacon devices implement the appropriate specifications for their device to make use of proximity sensing capabilities supported by Apple Inc. compatible iDevices.

7. Relevant application profiles

- FMP — the “find me” profile — allows one device to issue an alert on a second misplaced device.
- PXP — the proximity profile — allows a proximity monitor to detect whether a proximity reporter is within a close range. Physical proximity can be estimated using the radio receiver’s RSSI value, although this does not have absolute calibration of distances. Typically, an alarm may be sounded when the distance between the devices exceeds a set threshold.

8. Alerts and time profiles

- The phone alert status profile and alert notification profile allow a client device to receive notifications such as incoming call alerts from another

device.

- The time profile allows current time and time zone information on a client device to be set from a server device, such as between a wristwatch and a mobile phone's network time.

9. Battery

- The Battery Service exposes the Battery State and Battery Level of a single battery or set of batteries in a device.

5.4.1.1 Advertising and discovery

BLE devices are detected through a process based on broadcast advertising packets. This is done using 3 separate channels (frequencies), in order to avoid interference. Both the advertising devices, and the scanners looking for those devices, step through the three channels in sequence. This means that on average, there is only about a 1 in 9 chance of a scanner detecting a particular device's advertisement; in practice it is significantly lower than this.

5.4.1.2 Software model

All BLE devices use the Generic Attribute Profile (GATT). The application programming interface offered by a Bluetooth Smart aware operating system will typically be based around GATT concepts. GATT has the following terminology:

- **Client**

A device that initiates GATT commands and requests, and accepts responses, for example, a computer or smartphone.

- **Server**

A device that receives GATT commands and requests, and returns responses, for example, a temperature sensor.

- **Characteristic**

A data value transferred between client and server, for example, the current battery voltage.

- **Service**

A collection of related characteristics, which operate together to perform a particular function. For instance, the Health Thermometer service includes char-

acteristics for a temperature measurement value, and a time interval between measurements.

- **Descriptor**

A descriptor provides additional information about a characteristic. For instance, a temperature value characteristic may have an indication of its units (e.g. Celsius), and the maximum and minimum values which the sensor can measure. Descriptors are optional – each characteristic can have any number of descriptors.

5.4.1.3 Identifiers

Services, characteristics, and descriptors are collectively referred to as attributes, and identified by UUIDs. Any implementer may pick a random or pseudo-random UUID for proprietary uses, but the Bluetooth SIG have reserved a range of UUIDs (of the form `xxxxxxxx-0000-1000-8000-00805F9B34FB`) for standard attributes. For efficiency, these identifiers are represented as 16-bit or 32-bit values in the protocol, rather than the 128 bits required for a full UUID. For example, the Device Information service has the short code `0x180A`, rather than `0000180A-0000-1000-....`. The full list is kept in the Bluetooth Assigned Numbers document online.

5.4.1.4 GATT Operations

The GATT protocol provides a number of commands for the client to discover information about the server. These include:

- Discover UUIDs for all primary services
- Find a service with a given UUID
- Find secondary services for a given primary service
- Discover all characteristics for a given service
- Find characteristics matching a given UUID
- Read all descriptors for a particular characteristic
- Commands are also provided to read (data transfer from server to client) and write (from client to server) the values of characteristics:

An indication is similar to a notification, except that it requires a response from the client, as confirmation that it has received the message.

There is a significant difference between Bluetooth Classic and BLE. The key points are enumerated in the table 5.1.

Table 5.1: Differences between Bluetooth Classic and Bluetooth Low Energy protocols

Technical specification	Classic Bluetooth technology	Bluetooth Smart technology (BLE)
Distance/range	(theoretical max.) 100 m (330 ft)	>100 m (>330 ft)
Over the air data rate	1–3 Mbit/s	125 kbit/s – 1 Mbit/s – 2 Mbit/s
Application throughput	0.7–2.1 Mbit/s	0.27 Mbit/s
Active slaves	7	Not defined; implementation dependent
Security	56/128-bit and application layer user defined	128-bit AES with Counter Mode CBC-MAC and application layer user defined
Robustness	Adaptive fast frequency hopping, FEC, fast ACK	Adaptive frequency hopping, Lazy Acknowledgement, 24-bit CRC, 32-bit Message Integrity Check
Latency (from a non-connected state)	Typically 100 ms	6 ms
Minimum total time to send data (det. battery life)	100 ms	3 ms
Voice capable	Yes	No
Network topology	Scatternet	Scatternet
Power consumption	1 W as the reference	0.01–0.50 W (depending on use case)
Peak current consumption	<30 mA	<15 mA
Service discovery	Yes	Yes
Profile concept	Yes	Yes

From the comparison in table 5.1 it is clear that Bluetooth Classic supports a larger number of channels and hence a larger bandwidth, but at a cost of higher power consumption.

5.5 Hardware Components

The key component in hardware is the BlueNRG-1 SoC which has been discussed earlier in section 3.9. The BlueNRG-1 SoC has its own GPIO and ADC which are employed in this project to interact with the vehicles BCM³.

A block diagram of a BCM is given in figure 5.1. [3]

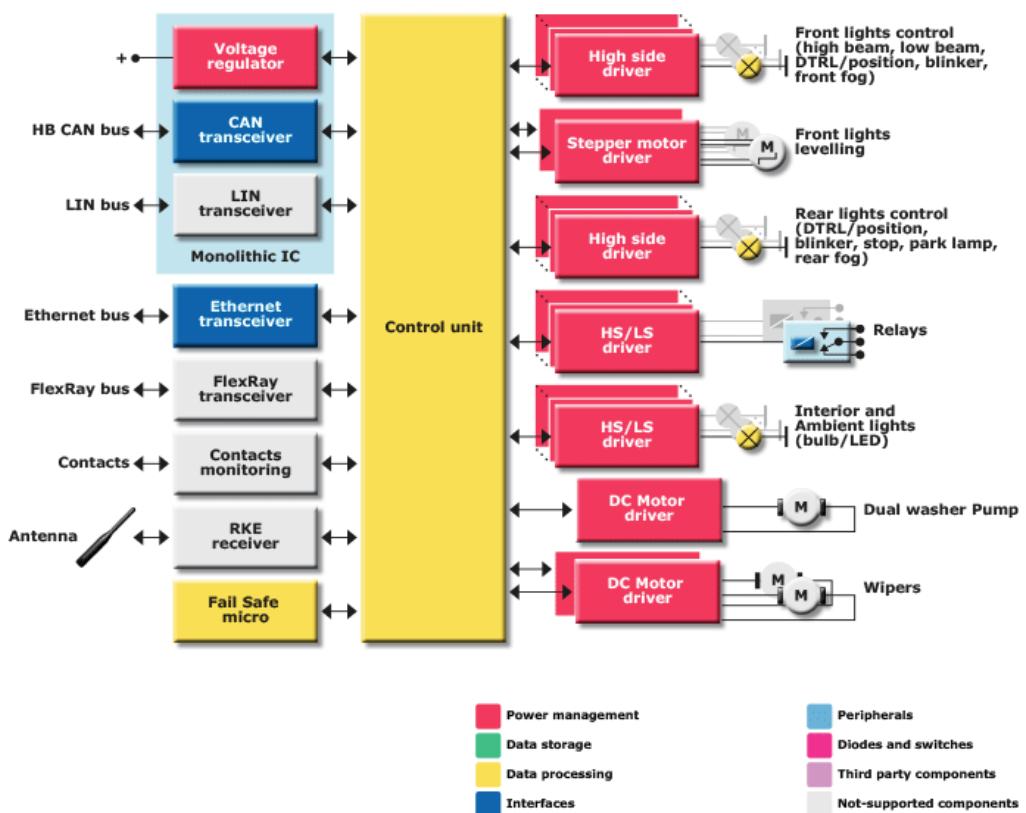


Figure 5.1: Block Diagram of a Body Control Module

A circuit diagram of the basic implementation of the system is as shown in figure 5.2. This circuit diagram does not consist of the Body Control Module. The Body Control Module is already present in a vehicle and its GPIOs are broken out using standard connectors.

1. SPBTLE-RF BLE module

The SPBTLE-RF is a network processor module, with an embedded BlueNRG-1 SoC. It is Bluetooth 4.1 compliant and has the complete BLE stack embedded in it. It supports the following components of the BLE stack:

³Body Control Module

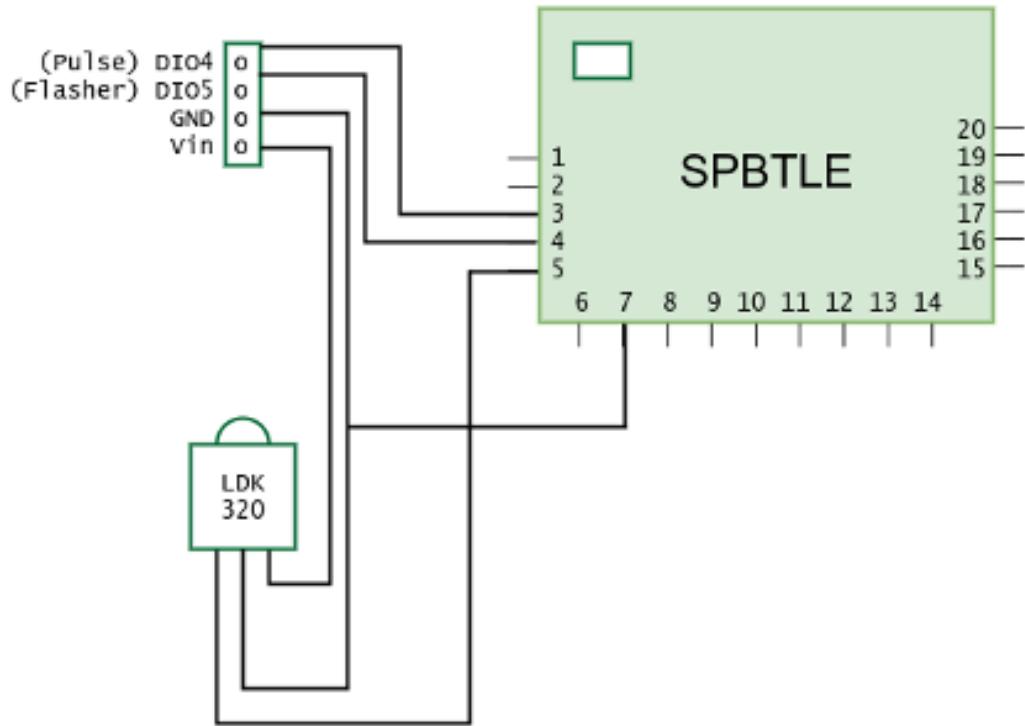


Figure 5.2: Circuit Diagram of the Keyless Entry System

- GAP : Generic Access Profile
- GATT : Generic Attribute Profile
- SM : Security Manager
- L2CAP : Logical Link Control
- LL : Link Layer
- RFPHY : Radio Frequency Physical Layer

It supports a maximum transmission range of +4dBm and a reception sensitivity of up to -88dBm. The SPBTLE-RF has an onboard chip antenna in the form of an inductive bead. The SPBTLE-RF runs on a clock frequency of 32MHz provided by an embedded crystal oscillator. The SPBTLE-RF can be powered directly with a standard 3 V coin cell battery, a pair of AAA batteries or any power source from 1.7 to 3.6 V.

The GAP layer in SPBTLE-RF stack provides generic roles that a BLE equipped device can take in the ecosystem. These roles may be categorised as of the following:

- **Connecting** : Devices in these roles need to be in a connected state in order to exchange data. The connection is done using a handshake method, where both of the devices exchange some keys and identification data.

- **Central Role :** The device acts as a central hub of BLE connections. It can initiate connections to other *peripheral* devices by first listening to their advertisement packets. A central device can connect to multiple peripheral devices.
- **Peripheral Role :** A device in this role only advertises its presence at a regular interval of time. A peripheral device is not allowed to initiate connections to any other devices and it can be in a connected state only if a central device requests a connection. A peripheral role device will no longer advertise or broadcast its data after it is connected to a central device. Peripheral devices can not initiate connections but it can terminate connections to a central device.
- **Broadcasting :** Devices in these roles do not need to be connected in order to send or receive data. This role is generally used in RF beacons like Eddystone beacon by Google and iBeacon by Apple.
 - **Broadcaster Role :** A device in the broadcaster role can only advertise data packets of a fixed size and type.
 - **Observer Role :** A device in the observer role only listens to the advertised packets by a broadcaster. No connection is necessary for data exchange.

The Link Layer in SPBTLE-RF is responsible for encryption and decryption of data. AES-128 is used for encryption. The security of communication is ensured by maintaining two sets of keys in both parties. These are called **Temporary Key (TK)** and **Long Term Key (LTK)**. Whenever a connection is established between two devices in a connection role, they exchange their temporary keys with each other. This enables both of them to send data encrypted with their respective temporary keys and the receiver can decrypt it by using the temporary key of the other party. The temporary key, as its name suggests, is refreshed at regular intervals. Apart from temporary key there is also a long term key which is not refreshed as frequently. The LTK is only shared whenever the two devices want to bond. Bonding is the process by which both devices authenticate each other for extended communication.

The L2CAP layer is responsible for maintaining connection between the two devices. It is analogous to TCP protocol in the TCP/IP stack.

2. LDK-320

The LDK-320 is a very popular low-dropout voltage regulator. Its maximum current capability is of 200mA which is sufficient for SPBTLE-RF module. It supports an input voltage of 2.5V to 18V. In this case the input V_{in} to the circuit is given as +5V. The output of LDK-320 is +3.3V.

3. Pulse and flasher GPIO

These GPIO pins are used for communication with the Body Control Module. The Pulse pin is used to provide short pulses of specific durations to the BCM and the Flasher pin is used to signal the BCM to flash the indicator lights.

The time period of pulses is given in table 5.2

Table 5.2: Time periods for various operations in the Body Control Module

	On-time	Off-time	No. of pulses
Find Vehicle	200ms	100ms	2
Lock	500ms	100ms	3
Unlock	150ms	100ms	3
Flasher	1000ms	1000ms	4

4. Debugging GPIOs

Apart from the above mentioned GPIOs, the SPBTLE-RF also provides some GPIOs for easy debugging and flashing of code. The GPIOs are

- **SWCLK** (pin number 12)

The SWCLK pin is provided for clock synchronization between the debugger and the device.

- **SWDIO** (pin number 13)

The SWDIO pin is provided for the debugger (master) to send and receive data from the device (slave). When the NRST pin is pulled down by the debugger (master), the device (slave) enters the RESET state and the debugger sends its data to the device through SWDIO. After this the debugger, sets the NRST to either high voltage (+3.3V) or floating voltage, and the device responds to the debugger using the SWDIO pin.

- **NRST** (pin number 19)

This pin is analogous to chip select for the master. The master can put the slave in a RESET state and transmit data through the single-wire IO pin.

Chapter 6

ACIM and BLDC Variable Frequency Drives

6.1 Overview

A Variable Frequency Drive is an electronic device that can be used to adjust torque and speed of electro-mechanical drive systems by varying the voltage and frequency at the input. A variable frequency drive may be implemented as a firmware in a micro-controller platform. For an increase in speed it can also be implemented on an FPGA and then redesigned to an ASIC. This provides a significant decrease in latency, as many operations can be done in parallel. Variable Frequency Drives find many household and industrial applications like, compressor motor control, industrial electrical machines, precise disk rotations on Hard Disk and DVD drives, ceiling fans, washing machines, hybrid electric vehicles, etc.

6.2 Problem

The project consisted of implementation, testing and porting of variable frequency drives of several types of motors in several platforms like STM8, STM32 and SPC. The project consisted of many sub-tasks, of which the key ones were:

1. Porting of AC Induction Motor Drive Firmware from one platform to **STM32F303RE** platform.
2. Testing and analysis of BLDC Motor Drive Firmware on SPC platform.
3. Implementation of BLDC Motor Drive on **STM8** platform.
4. Implementation of a BLDC Motor Drive for Ceiling Fan application.

5. Implementation of a Hardware Abstraction Layer library for generic servo motors.

6.3 Project Details

6.3.1 ACIM VFD for STM32F303RE platform

6.3.1.1 Hardware

Table 6.1: Specifications for the Hardware solution

Specification	Value
Maximum input voltage	450V
Nominal input voltage	330V
AC Induction motor pole pairs	4
Maximum PWM frequency	20 kHz
Voltage Level for logic units	3.3V
Shunt resistance value	30 mΩ
Power Factor Correction	No
Power Factor	>0.9
Nominal Motor RPM	3000
Maximum Motor RPM	4500

The hardware consists of a cascading connection between a number of components:

1. **Control Stage** (the micro controller)
2. **Gate Driver Stage** : logic units for driving the MOSFET/IGBT gates and protection units.
3. **Power Stage or Inverter Stage** : Power MOSFETs or IGBT for switching
4. **AC Induction Motor**

A block diagram of the system is given in figure 6.1.

6.3.1.1.1 Explanation of the blocks

1. Control Stage

The Control Stage consists of a micro-controller unit. In this case the micro-controller unit belongs to the STM23F3 series of STM32 micro-controllers. It is a general-purpose product line ranging from a basic, cost-efficient peripheral

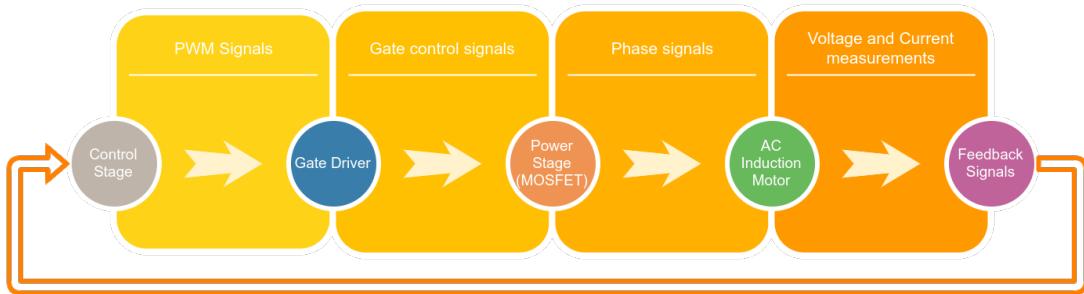


Figure 6.1: Block Diagram of ACIM Drive

set, up to more performance and analog functions. It has an ARM Cortex M4 core with a number of peripherals like 21 channel Sigma-Delta ADC, System Timers, Advanced Timers, DACs, ultra-fast comparators, etc.

The Control Stage block is responsible for

1. Generating various control signals like PWM and logic signals required to drive the motor
2. Processing the feedback signals

There are several strategies for driving a motor

1. Scaler control
2. Open Loop V/Hz control
3. Open Loop Vector Control
4. Closed loop Vector Control

For this particular project Closed loop Vector Control with V/Hz control was suitable. Vector Control is also known as Field-Oriented Control or FOC. In this strategy the control stage produces a set of two signals corresponding to each motor phase. The signals are produced by varying the pulse-widths of PWM generation using a peripheral called an Advanced Timer. These signals are provided to the gates of the MOSFET arranged in a half bridge pattern. This is discussed in detail in section ??.

Vector Control is so called because it the stator currents of a 3-phase electric motor are identified as orthogonal components and can be thought of as vectors. One component defines the magnetic flux of the motor, the other the torque. The control system of the drive calculates the corresponding current component references from the flux and torque references given by the drive's speed control. Contrary to this the **Scaler Control** only adjusts the magnitude or frequency of the motor current or voltage. While vector control is a high performance drive strategy, scaler control is a low performance strategy and is

widely used in low cost systems like brushed DC motor drives. An example of scalar control is to adjust the speed of a Brushed DC motor by either decreasing the input voltage or by providing the input voltage as a PWM signal and varying its pulse-width. Both the techniques will result in a decreased speed but will also result in a decreased torque because the input current will also be reduced. In Vector Control technique, the two components magnetic-flux and torque are varied to change speed or torque of the motor. The torque component is directly proportional to the input current of the motor. While scalar control is very easy to implement, vector control is a complex process. Thus, a reusable library was developed at ST Catania, Italy, for sensor-ed and sensor-less Vector Control.

There are two types of control modes

1. Speed Control Mode

In this the Control Stage tries to maintain the motor at a constant speed. Thus any external torque will not result in a decrease in the speed. This is done by adjusting the torque vector in a such a way that the net speed is the same. As a result the motor applies more torque and takes more current at the input.

2. Torque Control Mode

In this mode, the Control Stage tries to maintain the torque of the motor. Thus the torque vector is fixed. The torque is measured with respect to a reference current value at speed of 0 RPM, also called the stall current.

The Control Stage produces a third-harmonic injected sinusoidal wave at its end. The third-harmonic is injected so as to increase the power output of the system. A waveform of one phase is given in figure 6.2. The output of the control stage is represented by the second waveform in cyan colour.

The Control Stage is also responsible for maintaining and executing of a PI controller at a regular interval of time. PI control stands for Proportionate-Integrative control. According to this the control stage changes the process variable in such a way that, the setpoint is reached smoothly. The **process variable** is defined as the variable in the system to be monitored. For example in torque control mode, the process variable is the input per-phase current and for speed control mode, the process variable is the rotor speed in RPM obtained from the hall sensors or resolver. This data is obtained as a part of the feedback system, which is discussed later in this section. The **setpoint** is defined as the target value for the particular process variable. The PI control theory defines a quantity called the **error**

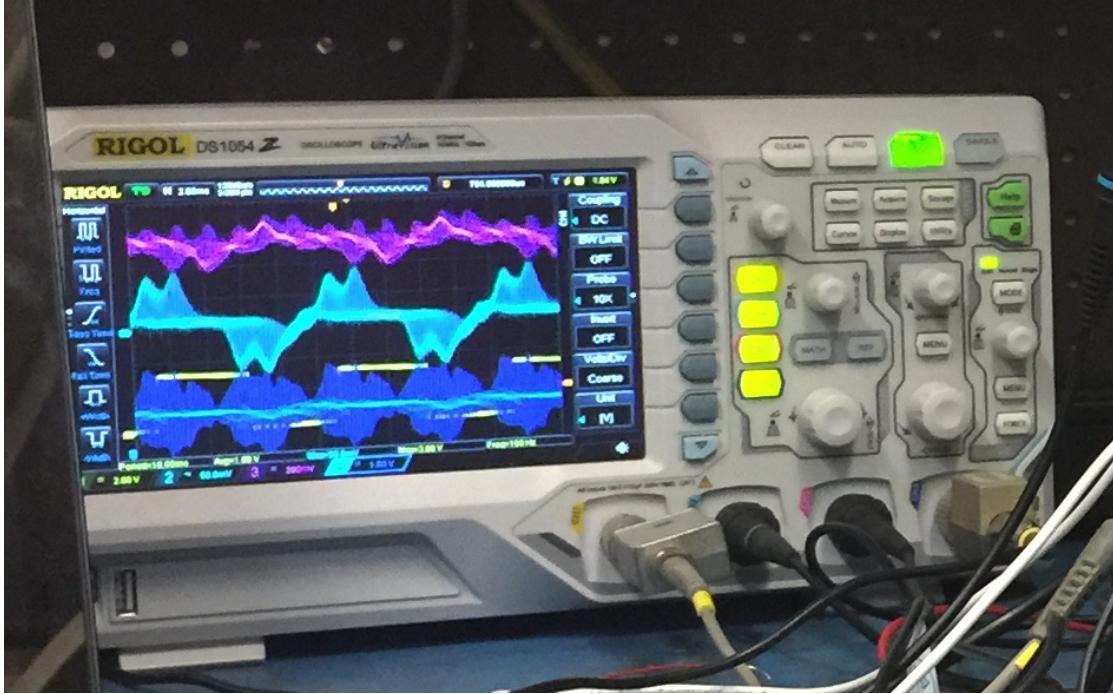


Figure 6.2: Waveform of FOC Control Stage

as the difference between the current process variable value and setpoint. The motive of a PI controller is to minimize the error, by following the smoothest curve possible and in a time period which is a function of two parameters known as the **K_p** and **K_i**, called the Proportional Gain and Integral Gain.

According to PI theory the control variable value at time t, $u(t)$, is defined as the weighted sum of a term proportional to the error and a term obtained by integrating the error over time.

$$u(t) = K_p \cdot e(t) + K_i \cdot \int_0^t e(t)dt$$

where error, $e(t)$ is defined as

$$e(t) = x(t) - S$$

The PI controller needs to be tuned in order for it to work under a certain time period. Tuning the controller involves adjusting the values of K_p and K_i in such a way that the motor can achieve any speed or torque in the given specifications under a certain time smoothly, provided a load of certain amount is attached to the rotor shaft. The PI controller tuning

is important as an untuned PI control loop may not be able to drive the motor properly.

2. Gate Driver Stage

The gate driver stage is an intermediate stage which is responsible for boosting the output signals of the control stage. As the power IGBTs require relatively large amount of current at their gates the control signals need to be amplified either in voltage or current to be able to drive the power stage. In this project the gate driver stage consists of quad-buffer ICs, 74HCT7007 amplify the +3.3V control stage signals to +5V signals and L6386D IC which drives the gates of the IGBT. The L6386D has built in over-current protection on hardware level, which has a very low response time and shuts down the system, if the current crosses a threshold level.

The circuit diagram of one phase of the Gate-driver and Power Stage is shown in figure 6.8.

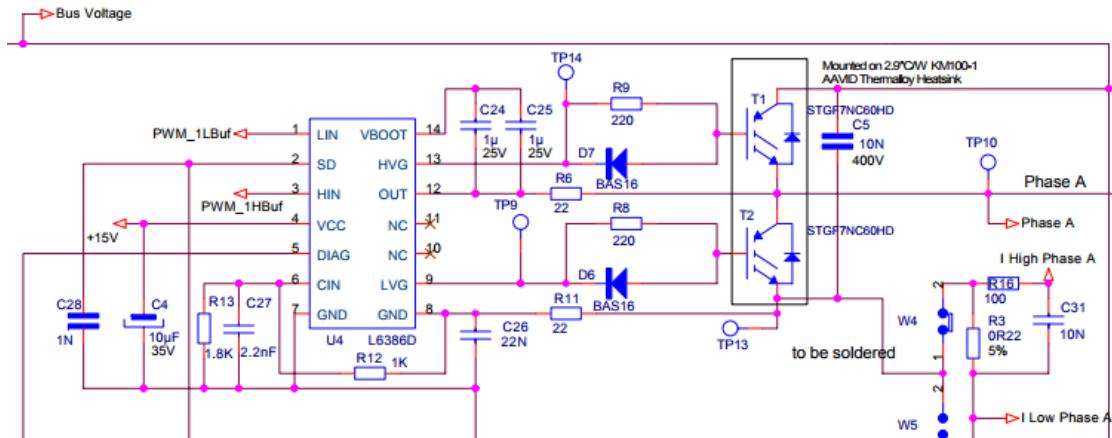


Figure 6.3: Circuit diagram of Gate-driver and Power Stage [4]

The inputs labeled **PWM_ILBuf** and **PWM_IHBuf** are the outputs of the buffer IC, T1 and T2 represent the IGBT, and U4 represents the gate-driver. The diodes D6 and D7 in combination with R8 and R9 are responsible for speeding up the turn-off time of the switches. The turn-off time of the MOS-FET is determined by the reverse recovery time of the gate. Thus faster the gate capacitor can be discharged, faster is the turn-off response. The diodes D6 and D7 provide a low resistance path during turn-off for the gate charge to dissipate through the gate-driver.

3. Power Stage or Inverter Stage

The Power Stage is responsible for actually transmitting power to the motor. The Power stage comprises of either Power MOSFETs or IGBTs. Power MOS-

FETs are generally used for high voltage applications pertaining to voltages more than 80V, while IGBTs are used in a wide range of voltages but are relatively expensive than power MOSFETs. The MOSFETs of IGBTs are arranged in a half-bridge pattern which is depicted in figure 6.3. The two switches are connected in series in a Totem-pole like fashion, but instead of a single input, two complementary inputs are provided. Generally both switches used are of the same kind, both N-type or both P-type, because different switches have a variation in their switching speeds. The drain of the top switch is connected to V_{bus} or Bus voltage. This bus voltage is derived from the on-board power supply section, and is of the magnitude of around +330V for the tested AC Induction Motors. The phase output is taken from between the two switches and the source of the bottom switch is connected to the ground via a shunt resistor or current-transformer to measure the phase current.

The two switches are complementary i.e. they are never in the ‘on’ position simultaneously. If they are both in the ‘on’ position simultaneously, a short circuit will occur between the Bus voltage and the ground. So two complementary signals are provided to each of the gate terminals of the switches. As the switch-on time and the switch-off time of a MOSFET are significantly different, at very high switching frequencies, it may happen that one switch is not completely off and the other switch is turned on. This will result in a lot of current flow in a very short duration of time and will produce a spike. This leads to electrical wear of the MOSFETs and may result in premature failure of the hardware. To avoid this, a **dead time** is kept between the turn-off of one switch and turn-on of the other switch. This dead time is of the order of a few hundred nanoseconds. Generally, for MOSFETs of voltage ranges above 80V, the dead time is kept between 1200 to 1400 ns.

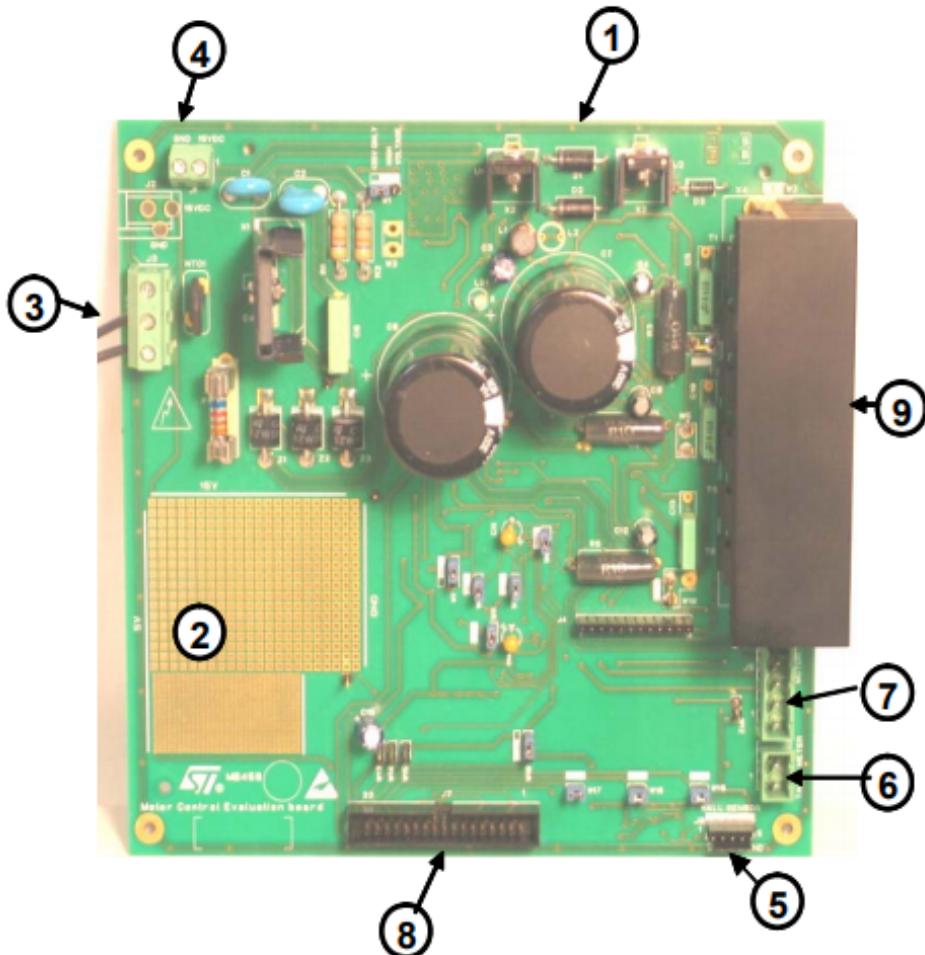
The Power stage switches are designed to be operated at very high voltages, frequencies and currents. They have a very low $R_{DS(on)}$ of about 30 mOhms, to reduce the heat dissipation of the MOSFETs.

The integrated Gate-driver and Power Stage board (MB459) used in the project is shown in figure 6.4.

4. AC Induction Motor

An AC Induction Motor is an asynchronous electric machine that produces rotation from electromagnetic induction from the magnetic field of the stator winding. An induction motor’s rotor can be either wound type or squirrel-cage type.

A 3-phase AC Induction Motor has three input leads, each connected to the three phases of the windings. A rotating magnetic field needs to be produced



1. Motor and board input power stage, auxiliary power supply, and voltage rectification
2. Prototype area
3. J3 connector: power supply input
4. J1 connector: auxiliary supply input
5. J8 connector: Hall sensors / encoder input
6. J6 connector: tachometer input for closed-loop controlled AC motors
7. J5 connector: Three-phase output to motor
8. J7 motor connector: link to STR75x and to STM3210B-EVAL evaluation board, or other control board
9. 7A inverter and level shifter

Figure 6.4: MB459 Integrated Gate-driver and Power Stage [4]

for rotating the ACIM, which is done by providing a sinusoidal input to the phases that are separated by 120° . The Control stage accounts for slip and compensates it by providing a slightly higher frequency signal than required, in the range of 1% to 5%.

5. Feedback Signals

The feedback mechanism is responsible for providing some signals back to the Control Stage, so that it can adapt itself according to the present conditions. For example, if a over-current situation is encountered, the control stage should stop the system, or if the bus-voltage overshoots, the control stage should turn on the bleeder resistors. Following are several scenarios where feedback signals are used:

1. Over-Current Protection

The motor may draw a large amount of current at the start of its rotation because of absence of back-EMF. Over-current may also occur if the motor is stalled, i.e. a large amount of torque is applied at the shaft and the motor is not able to rotate. This results in an increased current flow through the windings, which may not be designed for such a high current and they may get damaged. Apart from that, the Power MOSFETs also have a current limit and they also may get damaged. To protect from this situation, the gate-driver stage has a dedicated comparator for measuring the instantaneous current flow through each phase, and if it gets triggered, it will shut down the switching of MOSFETs and indicate the control stage by pulling down an EMERGENCY_STOP line.

The current is measured using shunt resistors in series with the Power MOSFETs. Shunt Resistors are very low resistances (of the order of mOhms) used for measuring the current flow through them. As current flows through a shunt resistor, a very low voltage drop is produced across it, which is amplified and read by using an ADC. A shunt resistor amplification and voltage-offset circuit is shown in figure 6.5. Here U represents the offset voltage and r_1 , r_2 and r_3 form a voltage divider network. An op-amp in a negative-feedback configuration is used to amplify the signal and provide it to the ADC of the micro-controller.

2. Bus Voltage Sensing

The Bus Voltage refers to the aggregate voltage provided to the motor via the power MOSFETs. In certain cases the bus voltage may be increased or decreased due to inefficiencies in the power supply stage and the motor.

The bus voltage may decrease when the motor demands in-rush current,

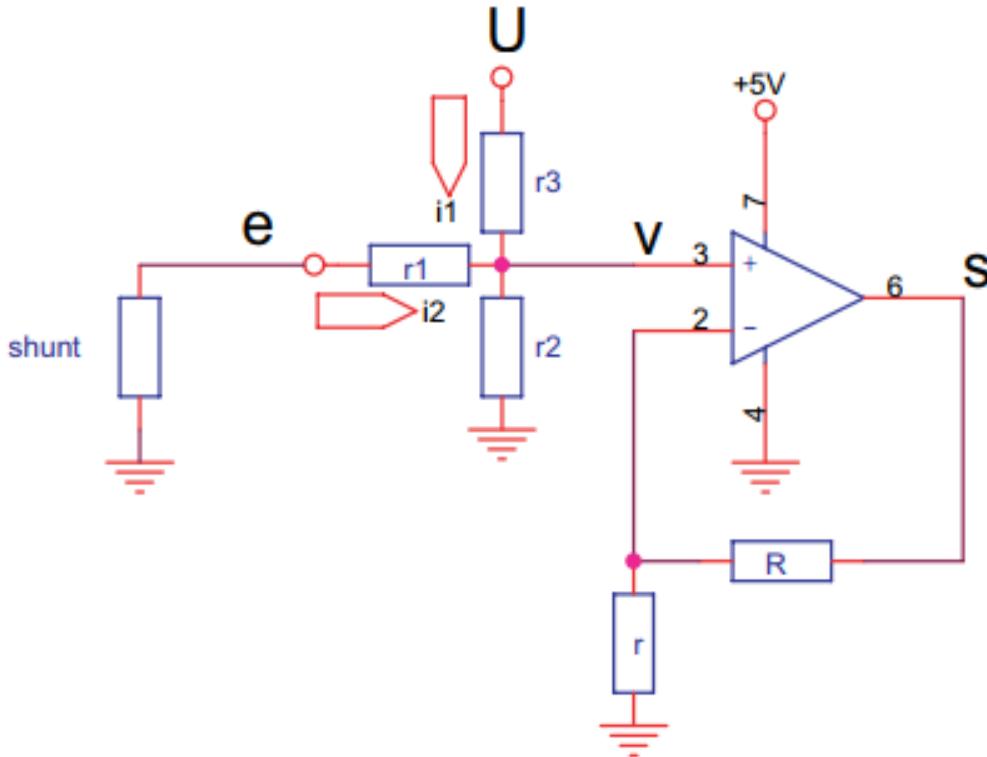


Figure 6.5: Circuit Diagram of a Shunt Amplification Network [4]

or starting current, because no back-EMF is present. In such a case the power-supply may not cope with the sudden decrease in the impedance and the bus-voltage may drop. In this case, the control stage might not get its operating voltage and that may result in either it being reset or enter an unpredictable state.

The bus voltage may increase when the motor is regenerating more voltage than it is provided. In such a case the back-EMF is larger than the bus voltage and the extra current is fed back to the power supply. This may result in a large amount of voltage, upto 2-3 times of the bus voltage and this may result in failure of the power supply system.

3. Motor Speed and Position Feedback

Several motors are equipped with positional or speed sensors for measuring the movement of the shaft. This is important because the control stage has no way to know whether the motor is actually moving at the intended speed. There are a number of sensors used

1. Hall Sensors

Hall Sensors work on the basis of Hall effect. They produce a signal

in the presence of a magnetic field. Thus when the rotor core rotates, the magnetic field periodically triggers the hall sensor, thus producing a square wave of frequency proportional to the RPM of the rotor. For precise position measurement three hall sensors are placed at a mechanical angle of 120° . The waveforms from the hall sensors are shown in figure 6.6.

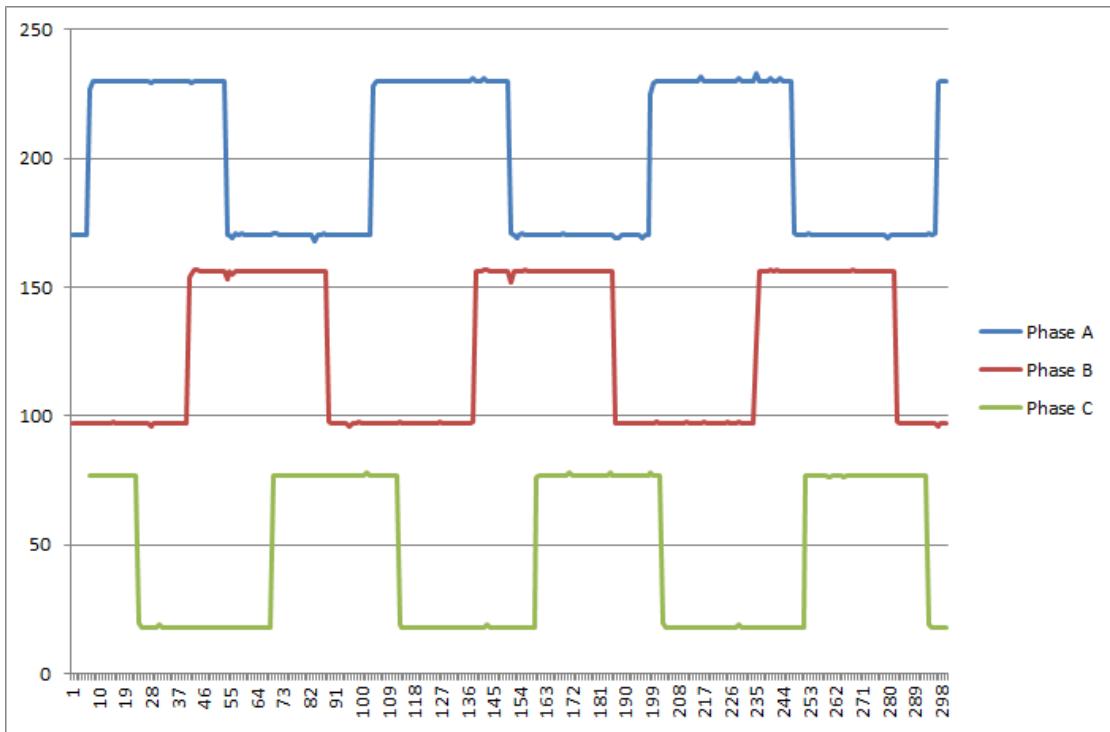


Figure 6.6: Hall Sensor Waveforms [5]

2. Quadrature Encoder

Quadrature encoders provide a position feedback with the help of two signals that are 90° apart in phase, hence the name quadrature encoders. The speed can be assessed by measuring the pulse-width of any of the quadrature pulse.

3. Resolver

A resolver provides speed information in the form of pulses of a particular pulse-width. Increasing pulse-width means an increase in speed. Resolvers are widely used in automobiles to judge the speed of automobile from frequency of rotation of a component.

6.3.1.2 Software / Firmware

The software design mainly consisted of writing the program for the control stage. The programming language used was C. The following were the key objectives of the software solution

1. Produce three sets of complementary PWM signals to drive the high side and low side of the Half-bridge.
2. Provide abundant dead time of about 1300ns between signals.
3. Provide a State-full, FSM like architecture for easy debugging and modularity.
4. Implement a PI controller that takes values from the feedback loop and manipulates the control variable (input voltage or current).
5. Implement a fault reporting system to notify the user of the various faults that may occur in the motor drive.
6. Optionally provide an user interface via a 16x2 LCD display for easy control over the motor.

To produce the three sets of six complementary PWM signals the Advanced timer peripheral was used. The Advanced Timer provides a total of six channels of which three are complementary channels. The Advanced Timer peripheral has a dedicated clock supply from a high speed PLL. The PLL is responsible for multiplying the system clock frequency of 16 MHz to a higher frequency of the order of 48 to 64 MHz. The amount of multiplication is decided by the contents of the prescaler register. This clock is fed to the advanced timer allowing it to generate very precise PWM signals. The advanced timer peripheral consists of a 16-bit counter register which keeps track of the current count. A separate 16-bit auto-reload register holds the auto-reload value which gets automatically copied to the count register when the timer overflows. The timer can be run either in a one-shot mode or a continuous mode. For generating PWM signals of varying pulse the Capture/Compare register (CCR) is used. It stores value of the count register at which the PWM signal toggles. Thus to achieve a duty cycle of 25% with a value of 0x00FF in the counter register, a value of 0x003F should be set in the CCR register.

The PWM signal should follow a third-harmonic injected sine wave curve. To do this, a lookup table of 1024 values of the sine wave is created from 0 to 2π radians and stored in the code flash memory. Thus the code looks up the value of the waveform from the table and substitutes the value in the CCR register.

A state machine was then created for easy debugging. The figure 6.7 shows the relation between the states in the FSM.

The PI controller was implemented using a general purpose timer. The timer was set to overflow at every 1ms and execute the PI control algorithm. Thus a resolution

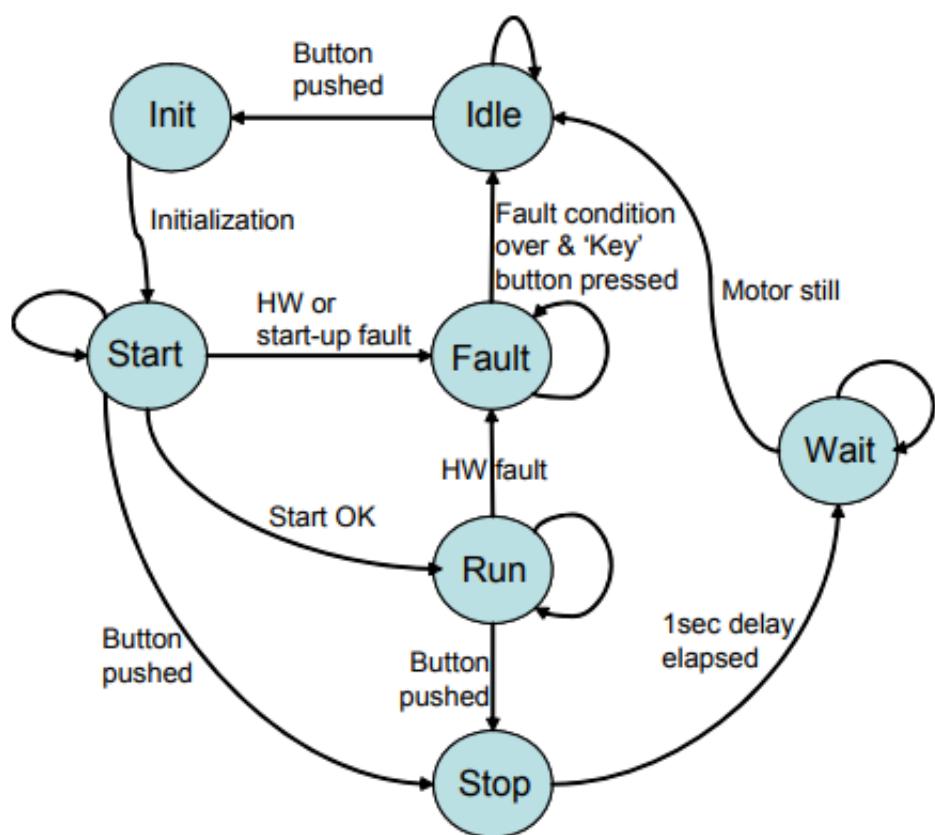


Figure 6.7: State Machine Diagram for the ACIM Drive

of 1000 checks every 1 second was obtained for the PI controller. The PI controller checks for the deviation of current value of speed or torque from the set point and minimizes it over time. More the resolution of the PI controller faster it will try to bring the deviation to minimum. The following code snippet provides the implementation of the PI controller.

```
#include "pid_controller.h"

double pid(PID_vars *vars, double current_err) {

    /* current_error = setpoint - current_process_variable */

    vars->_integral_sum += current_err*(vars->_dt);

    double output = (vars->Kp)*current_err
                    \
                    + (vars->Ki)*(vars->_integral_sum);

    vars->_prev_err = current_err;

    /* limit output within output_min and output_max */
    if (output>(vars->output_max))
        output = vars->output_max;
    else if (output<(vars->output_min))
        output = vars->output_min;

    return output;
}
```

6.3.2 BLDC Motor Drive Firmware on SPC platform

The project consisted of testing and analysis of a BLDC motor driver implemented at ST Catania, Italy. The motor drive is designed for low power applications to drive a NEMA-compliant 3-phase Brushless-DC Motor.

6.3.2.1 Hardware

The Hardware is very similar to the ACIM drive project with a few changes in the hardware specifications.

Specification	Value
Maximum input voltage	35V
Nominal input voltage	24V
BLDC motor pole pairs	5
Maximum PWM frequency	20 kHz
Voltage Level for logic units	5V
Shunt resistance value	10 mΩ
Nominal Motor RPM	2000
Maximum Motor RPM	3000

6.3.2.1.1 Explanation of the blocks

1. Control Stage

The Control Stage is similar to that of ACIM Drive project. The Control Stage is composed of a SPC micro-controller, SPC560P50L5. This micro-controller belongs to the Pictus series of SPC micro-controllers which is designed for automotive applications. An evaluation board for the micro-controller is depicted in figure 6.8.

The control stage uses the FOC Vector Control algorithm and supports speed and position feedback signal processing from hall sensors, quadrature encoder and resolver.

2. Gate Driver Stage and Power Stage

The Gate driver Stage consists of a dedicated gate driver IC, L9907. It has in-built over current and over voltage protection circuitry, level-shifters and bootstrap capacitor inputs. The input voltage for the L9907 is provided through an auxiliary power supply stage of 12V-15V rating. The L9907 communicates to the control stage via a dedicated SPI bus. Through this, the control stage can manipulate various parameters like dead-time, over-current threshold, PWM frequency, etc.

The Gate Driver stage is depicted in figure 6.9 on the left. The 148-pin connector on the top-left of the image is used to connect it to the control stage. The bunch of wires shown are connected to the Hall Sensor output of the motor.

The Power Stage is depicted in the figure 6.9 on the right. The Gate Driver and Power Stage are connected to each other via two 16-pin asymmetric connectors. The Power stage consists of six power MOSFETs of 60V rating arranged in three half-bridge circuits for three phases, a separate connector for 24-35V bus voltage and a dedicated connector for phase supply to the motor. The Power Stage

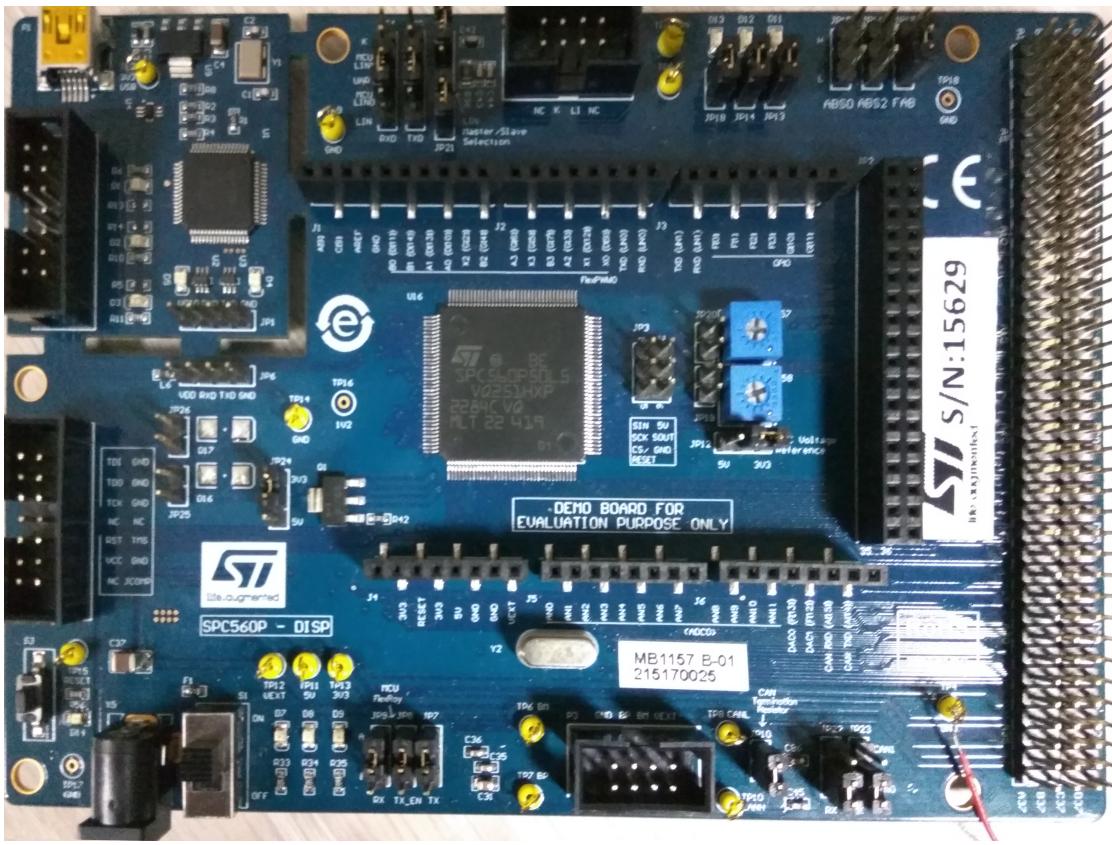


Figure 6.8: SPC560P Evaluation Board

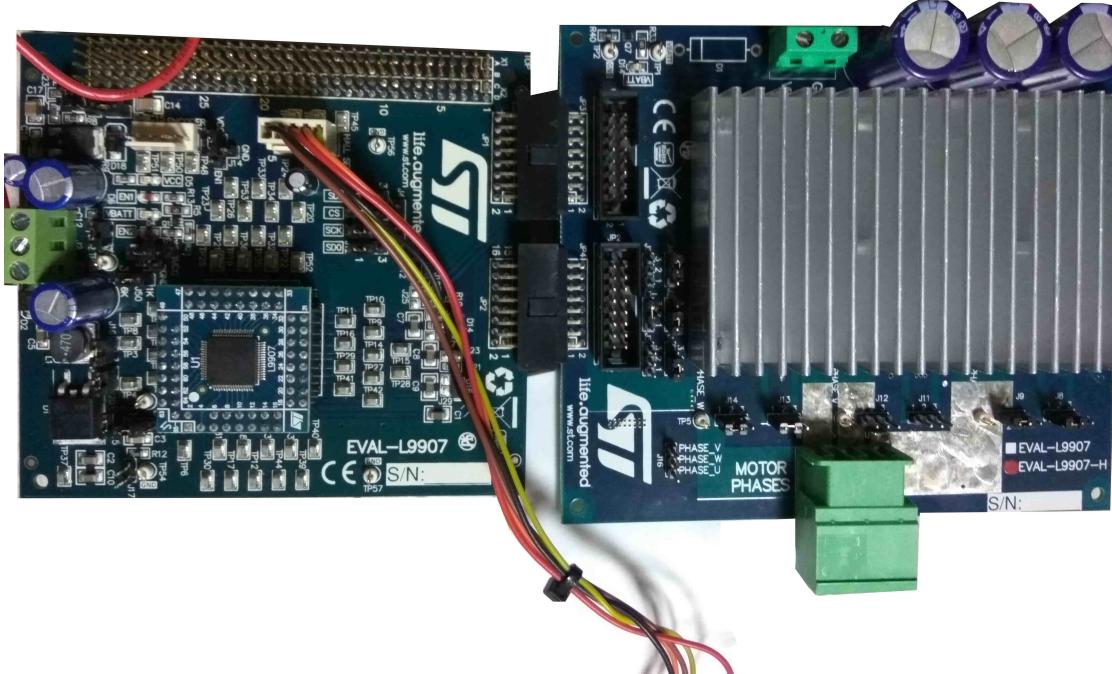


Figure 6.9: EVAL-L9907-H Gate Driver and Power Stage

also features a heat-sink to keep the MOSFETs cool by dissipating the heat energy into the environment.

3. 3-phase BLDC Motor

A 3-phase NEMA-compliant BLDC Motor from Nanotec was used for the project. The motor is depicted in figure 6.10.



Figure 6.10: Nanotec DB-41 3-phase BLDC motor [6]

A Brushless-DC Motor is also known as the Electronically Commutated Motor are synchronous motors whose construction is very similar to a Brushed-DC motor but lacking a mechanical commutator.

The construction of a 3-phase BLDC motor involves a stator with phase windings, either in star or delta form. The rotor contains permanent magnets either embedded in its core or surface-mounted. This is why this motor is also called a Permanent Magnet Synchronous Motor (PMSM). A 3-phase sine wave input signal is required at the stator windings to produce a rotating magnetic field, because of the absence of a commutator. As a result, the BLDC motor is very quiet and provide high speeds. A BLDC motor may be of either outrunner type or inrunner type. The out-runner consists of permanent magnets on the outer surface of the rotor and the stator is housed inside the rotor. While in an in-runner type, the rotor is housed inside a stator.

6.3.2.2 Software

The software consisted of a reusable library for FOC Vector control ported to the SPC platform. The library was provided as a FreeMarker template for SPC5Studio (section 3.2). The configuration of the library was done by modifying some C header files. Upon successful compilation and integration of the firmware, the hardware was

tested for performance in speed and torque achievement. PI parameters were tuned in order to achieve better results.

6.3.3 BLDC Motor Drive on STM8 platform (E-vehicle Control System)

6.3.3.1 Hardware

Specification	Value
Maximum input voltage	14V
Nominal input voltage	12V
BLDC motor pole pairs	4
Maximum PWM frequency	20 kHz
Voltage Level for logic units	5V
Shunt resistance value	10 mΩ
Nominal Motor RPM	2000
Maximum Motor RPM	3000

For the BLDC motor drive on STM8 platform, the same hardware from the ACIM drive project was used, except the control stage which is this project was based on an STM8 micro-controller. The control stage was an STM8 evaluation board designed for motor control applications. The figure 6.11 depicts the evaluation board used for the project.

The evaluation board features a dedicated 34-pin motor control connector and SWIM/STice debugging support. The control stage was connected to the gate driver and power stage using the 34-pin motor control connector.

6.3.3.2 Software

In six-step scalar control, the motor phases are provided signals in a six step process. Each step involves two of the three phases to either be positive or negative and the other phase to be in high-impedance or floating state. A particular order for this process is followed so that a rotating magnetic field is produced and the rotor is moved in the required direction. This sequence is stored in the code flash memory in the form of a commutation table. The commutation table contains reference between a certain position of the shaft of motor to the pair of phases need to excited to reach that position. The position is generally stored as a 3-bit number pertaining to the position

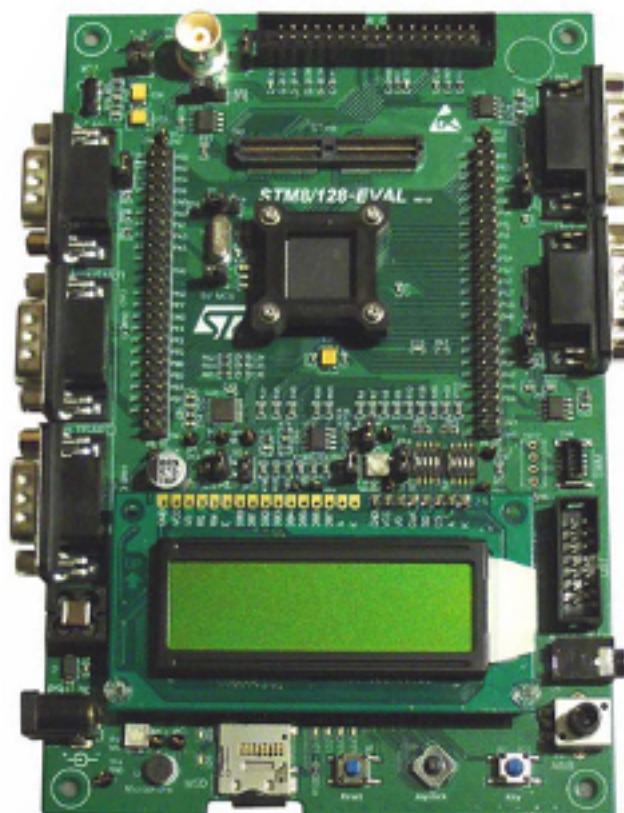


Figure 6.11: STM8/128 Evaluation board [7]

information obtained from the Hall sensors. A commutation can be visualized as shown in figure 6.12.

Clockwise Rotation (Lead End)							
ELECTRICAL DEGREES							
	0	60	120	180	240	300	360
S1							
S2							
S3							
HALL EFFECT COMMUTATOR OUTPUTS							
Commutation Code	110	100	101	001	011	010	
MOTOR PHASE	ØA	off	+	+	off	-	-
POLARITY	ØB	+	off	-	-	off	+
	ØC	-	-	off	+	+	off

Figure 6.12: Six Step Commutation Table for a 3-phase BLDC Motor [8]

The complete block diagram of the system is shown in figure 6.13

6.3.4 Hardware Abstraction Layer library for servo motors

A software library was written for a Hardware Abstraction Layer for driving Servo Motors. The Servo Motors tested were metal-gear servo motors, TowerPro MG996R. This motor features a 180° rotation, stall torque of $9.4\text{-}11 \text{ kgcm}^{-1}$ and an operating speed of $0.2\text{s} / 60^\circ$. The figure 6.14 shows the servo motor construction in detail.

6.3.4.1 Construction and Working of a Servo Motor

A servo motor is an actuator which provides precise control over rotational position or angle of its shaft. A servo motor has an inbuilt closed-loop control system which consists of a feedback system that provides data about the current position or angle of the shaft. In a general-purpose servo motor a potentiometer is used to provide the angle of the shaft as a potential difference to the ground of the system.

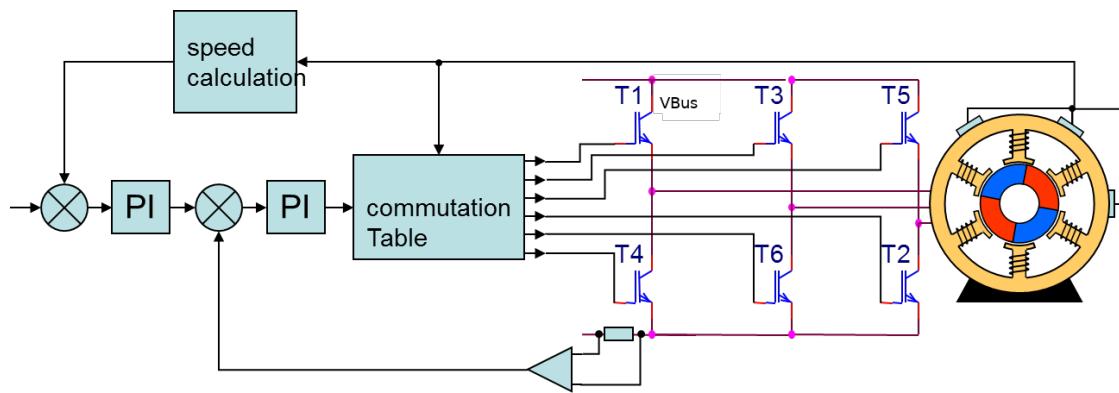


Figure 6.13: Control Loop for 3-phase BLDC Motor Drive [8]

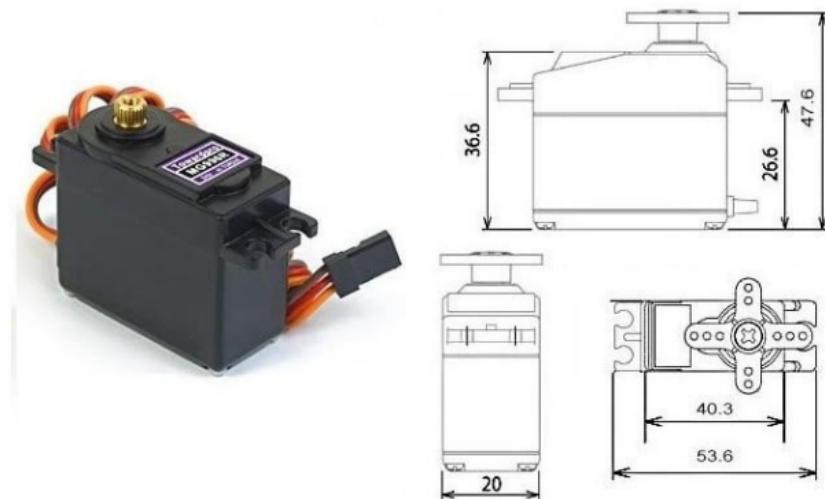


Figure 6.14: MG996R Servo Motor [9]

A servo motor takes a 50Hz PWM signal as its input and according to the duty cycle of the PWM signal, it adjusts the angle of the shaft. The minimum and maximum angle that can be obtained is 0° and 180° with respect to the body of the servo motor.

6.3.4.2 Firmware Library

The APIs were implemented for the firmware library which included APIs for setting the position, setting the acceleration of shaft, setting the angular velocity of the shaft and acquiring the current position of the shaft by processing the position feedback signal with the help of an ADC. A general-purpose 16-bit timer was used for the signal generation.

Chapter 7

Company Profile

7.1 Company Information

- **Company Name:** STMicroelectronics India Ltd
- **Site Address:** Plot No. 1, Knowledge Park III, Greater Noida – 201308 (UP)
- **President & CEO:** Carlo Bozotti
- **Corporate Headquarters:** Geneva, Switzerland
- **Founded:** 1957 as Società Generale Semiconduttori, 1987 as SGS-Thomson, renamed as STMicroelectronics in May, 1998
- **Annual Revenue:** US\$ 6.90 billion, as per 2015 report.
- **Total Number of Employees:** 43,200 Employees
- **Primary Line of Business:** Integrated device manufacturer and designer serving all electronics segments.

7.2 Company Overview

STMicroelectronics is a French-Italian multinational electronics and semiconductor manufacturer. Commonly called ST, it is Europe's largest semiconductor chip maker with net revenue of US\$ 6.90 billion in 2015. ST is among the world leaders in a broad range of segments, including semiconductors for industrial applications, inkjet print heads, MEMS (Micro-Electro-Mechanical Systems) and sensors, set-top-box and home-gateway SOCs and smartcard chips, automotive integrated circuit, computer peripherals, and chips for wireless and mobile applications. ST is among the industry leaders in R&D, almost one fifth of its employees work in R&D and product design. Among the industry's most innovative companies, ST owns and continuously refreshes a substantial patent library (~15,000 owned patents in ~9,000

patent families and 500 new patent filings). The Company draws on a rich pool of chip fabrication technologies, including advanced FD-SOI (Fully Depleted Silicon-on-Insulator) CMOS (Complementary Metal Oxide Semiconductor), mixed-signal, Analog and power processes.

In manufacturing aspects, ST operates a worldwide network of front-end (wafer fabrication) and back-end (assembly, testing and packaging) plants. ST's principal wafer fabs are located in Agrate Brianza and Catania (Italy), Crolles, Rousset and Tours (France), and in Singapore. The wafer fabs are complemented by world-class assembly-and-test facilities located in China, Malaysia, Malta, Morocco, the Philippines and Singapore.

7.3 Department / Team Introduction

AMG Central Labs is a central group responsible to creating synergy between various product divisions. It created complete system solutions including the hardware and software that could be used by customers to realize a marketable product.

Vision of AMG Central Labs is:

To deliver value to our Customers through innovative system solutions and technical support.

Mission of AMG Central Labs is:

- To provide customers with high value solutions (hardware, software and firmware) and technical support.
- To support divisions' roadmaps and Go To Market strategies by sharing system know how and the related product requirements.
- To support sales and marketing organizations for the promotion of the portfolio in order to maximize product awareness and identify new business opportunities.

Chapter 8

Review

8.1 Work Environment

The workplace provided a very professional environment which helps with the ability to learn, develop and fulfill the clients needs. A wide range of functional equipment was also available for every stage of the development process.

8.2 Team

A team of professionals was made for working on each project and every person had a definite role. This promoted skill sharing and learning in the workplace. There was continuous support and co-operation from all the team members.

Project	Site team members	Roles
Vehicle Tracking System	Bipin Chandra Pande	Mentor, Project Lead
	Giuseppe Russo	Hardware Support (SPC), ST Catania
	Fernando Caranante	Software Support (SPC5Studio), ST Catania
	Hemlata Pandey	PCB Design and Layout
	Pradeep Kumar	Hardware Rework and Soldering
ACIM & BLDC Drives	Subodh Vikram Shukla	Mentor
	Akash Kapashia	Software Support (EWARM & STM32)
BLE Keyless Entry System	Bipin Chandra Pande	Project Lead
	Akash Kapashia	Firmware Support (BLE stack)
E-vehicle Control System	Subodh Vikram Shukla	Mentor
	Hemlata Pandey	PCB Design and Layout

8.3 Project Workflow

8.3.1 Phase I - Planning

Many projects are introduced as a result of a specific demand from a customer or client. The mentor of the project organizes a meeting to inform about the needs and expectations of the client. A rough road-map is created for the project and higher authorities are notified of the same.

8.3.2 Phase II - Implementation, Testing & Analysis

Once a road-map was finalized and a design is made for the project. Several projects required reusable components like PCB layouts and firmware libraries from previous projects to speed up the development. A hardware prototype is made for testing using standard evaluation boards available, like the Nucleo and Discovery boards. Several projects required additional hardware rework which requires trained professionals. Often some small prototype extension modules were made from ICs onto a perforated circuit board, so that it can be readily and easily integrated with the project prototype. This kind of approach to prototyping was followed in the VTS project, wherein several modules were made as need for extending the hardware arose, like adding serial flash support, adding level translators, adding CAN bus functionality, etc. After a working prototype was made, it was tested on site for nearly every scenario possible in a controlled environment.

8.3.3 Phase III - Documentation

Often the client is not familiar with the particular libraries or terminologies used. Often the client has to make some changes on their own end to suite their particular needs. For this the firmware code needs to be easily understandable and concise. Documenting the code is a very important task that every programmer should try to do. It not only helps another co-worker/programmer understand the code but also helps the author understand it at a later point in time.

8.3.4 Phase IV - Customer Demo

Many projects required the hardware prototype or the final design to be presented to the customer or client. A presentation and a demo of the working of the project is done to the customer.

Chapter 9

Conclusion

Various kinds of technologies were used to make end products for the company's clients. Some technologies like BLE and IoT show a very wide scope of advancing in the near future.

The Vehicle Tracking System was implemented which helps bringing the Automotive Industry and IoT a bit closer. This will result in a larger acceptance of smart electronics products among the consumers and the market.

The BLE Keyless Entry System was also a stepping stone in the wider acceptance of low power wireless and radio equipment in more mainstream applications like the automotive industry. It is evident that, such technologies need to be mature for wider acceptance but progress is made everyday and it can only get better.

Brush-less DC motors, on the other hand, are widely accepted technology but are not suitable for cost efficient systems due to their being expensive. As the market widens, the BLDC motors have become more mainstream leading to more production and development. BLDC motors are widely used now-a-days in fields like medical equipment, high power machinery, mining equipment due to their rugged nature and low maintenance.

Future Work

1. Several modifications and extensions of the Vehicle Tracking System are possible. Some features like live updation of data, control of vehicle BCM from remote location can be improved further. Many other kinds of data can also be acquired using the CAN bus network of an automobile and transmitted to the central server. This system can also be extended to be integrated with the BLE Keyless Entry System.
2. The E-vehicle control system also has a wide scope of improvement. Several hardware features like regenerative-braking and sensor-less open-loop startup can also be implemented in the system, which will result in an even smoother running and less wear and tear of the electrical and mechanical components.

Impediments, Difficulties and Suggestions

A few technical difficulties were faced during development of projects like

1. Many hardware and software platforms like SPC, were at a nascent stage of development. Thus, many firmware libraries were regularly being changed. This produced a problem for code re-basing, as even some basic API names were changed. An example, was when a new firmware abstraction layer known as the OSAL (Operating System Abstraction Layer) was introduced, it broke the delay API in VTS, because some C variables were made static at the source and not otherwise accessible.
2. The BLE stack for BlueNRG-1 was also under active development, so many security features like whitelists and blacklists were unavailable for version 4.1. Instead some crude workarounds were made for that functionality.
3. Some problems were faced regarding the SPI peripheral in STM32F303RE micro-controller. There was some fault in the design of hardware FIFO buffers in the SPI peripheral due to which byte-order of data was jumbled at a specific clock frequency. Later this problem was mentioned in the errata sheet for the device on ST website.

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