Levitation, Drive Electronics & Monitoring of a Left Ventricular Assist Device (LVAD)

A Project Report

Submitted to the APJ Abdul Kalam Technological University

in partial fulfillment of requirements for the award of degree

Bachelor of Technology

in

Electronics and Communication Engineering

by

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CERTIFICATE

This is to certify that the report entitled **Levitation, Drive Electronics & Monitoring of a Left Ventricular Assist Device (LVAD)** submitted by **Ajay J. Thampy** (TVE17EC005), **Midhun P.** (TVE17EC027), **Sreejith S.** (TVE17EC049) & **Vipin Chandran M.** (TVE17EC061) to the APJ Abdul Kalam Technological University in partial fulfillment of the B.Tech. degree in Electronics and Communication Engineering is a bonafide record of the project work carried out by him under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

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DECLARATION

We hereby declare that the project report **Levitation, Drive Electronics & Monitoring of a Left Ventricular Assist Device (LVAD)**, submitted for partial fulfillment of the requirements for the award of degree of Bachelor of Technology of the APJ Abdul Kalam Technological University, Kerala is a bonafide work done by us under supervision of Prof. Sindhu N.

This submission represents our ideas in our own words and where ideas or words of others have been included, we have adequately and accurately cited and referenced the original sources.

We also declare that we have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. We understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

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Abstract

Heart failure (HF) is a frequent cause of inpatient admissions. A left ventricular assist device (LVAD) is a mechanical pump that we use for patients who have reached end-stage systolic heart failure. A LVAD is implanted inside a person's chest to help a weakened heart pump blood. It augments blood flow to the body and shares the workload of the Left Ventricle. Unlike a total artificial heart, the LVAD doesn't replace the heart. It just helps it do its job. The critical distinguishing factor between the second- and third-generation LVADs is the employment of contact versus noncontact bearings, respectively. The latter employs the technology known as magnetic levitation, which allows for rotation without friction or wear. The goal of our design is to further minimize the prothrombotic sites while enhancing the efficiency and durability of a third-generation Left Ventricular Assist Device.

Acknowledgement

We take this opportunity to express our deepest sense of gratitude and sincere thanks to everyone who helped us to complete this work successfully. We express our sincere thanks to Dr. Biji Jacob, Head of Department, Electronics and Communication Engineering, College of Engineering for providing us with all the necessary facilities and support.

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Chapter 1

Introduction

Left Ventricular Assist Device (LVAD) is a surgically implantable mechanical pump that is attached to the heart. An LVAD is different from an artificial heart. An artificial heart replaces the failing heart completely whereas an LVAD works with the heart to help it pump more blood with less work. It does this by continuously taking blood from the left ventricle (main chamber of the heart) and moving it directly to the aorta, which then delivers oxygen-rich blood throughout the body. This chapter presents the objectives and scope of our work.

1.1 Scope

The scope of our project is in the implementation of a Left Ventricular Assist Device (LVAD) which can improve survival and quality of life of patients with end-stage heart failure. Apart from the apparent advantage of not having to wait for a suitable donor, there are several advantages to using an LVAD. For instance, unlike cadaver transplants that require the intake of immuno-suppressants, to facilitate organ acceptance, patients with the implanted device need to take only one simple blood-thinning medicine to ensure the free flow of blood. By increasing blood flow to the body, the LVAD improves the function of the kidneys, liver, brain and other organs. It improves the patient's strength and ability to participate in activities such as cardiac rehabilitation. Another noteworthy advantage of an LVAD is that the device can be removed if the left ventricle recovers in due course of time. It is the only solution for patients who can't find a donor or may not survive a transplant.

1.2 Motivation

The number of people diagnosed with heart failure is increasing and projected to rise by 46 percent by 2030, resulting in more than 8 million people with heart failure, according to the American Heart Association's 2017 Heart Disease and Stroke Statistics [10]. Cardiovascular diseases including coronary artery disease, high blood pressure and stroke collectively remain the leading cause of death in the world. One way to get the heart back into a healthy rhythm, and help one get back to a normal routine, is with an implanted LVAD. However, the main drawback of the LVADs currently available in the market is their cost. Hospitals pay a range of prices around $80,000 for a HeartWare device, while the HeartMate III runs closer to $95,000 [11]. The average total cost to implant an LVAD was $175,000 (more than double the cost of a heart transplant), which is not affordable for the common man [11]. This was our motivation to accept the opportunity to work as a part of the project by ISRO Inertial Systems Unit (IISU) for developing cheaper and more efficient third-generation LVADs.

1.3 Objectives

We divide our project into three main parts: i) Levitation, ii) Drive electronics, and iii) Monitoring. The objective of the work is to implement a magnetically levitated wheel rotating at a desired rpm. The wheel supplements blood flow by pumping at 5-10 L/min to the body and shares the workload of the heart. The drive should be capable of functioning all day with an output voltage of 14V to 18V and deliver power of 8.8W for 11 hours. Due to the power constraints, sensors like Hall sensors cannot be used, thereby making utilisation of the back emf generated to control the motor using ICs. The controller should check the pump and driveline, and alert/communicate how the system is working. The machine should have 90 percentage survival rate and should extend its life for at-least 10 years. It should be available to all at a reasonable cost.

1.4 Report Outline

The chapter organization of the report is as follows:

Chapter 1: This chapter gives a brief introduction about the project, the objectives and the expected outcomes of the final product.

Chapter 2: This chapter provides an overview about the background study of LVADs carried out before the start of the work. Literature referred are also mentioned.

Chapter 3: The methodology of the proposed levitation, drive electronics and monitoring systems are described in this chapter. The steps followed by the system to get the expected outcome is also clearly explained.

Chapter 4: This chapter includes the interim and final results obtained and their analysis.

Chapter 5: The project is concluded in chapter 5. The future scope of the work is also discussed.

Appendix: Further details on the PCB designed, ICs used, DRV GUI Usage, I2C communication, and Code Composer Studio programming are included in the Appendix.

Chapter 2

Literature Review

A shift from the concept of totally artificial heart as heart replacement, towards the development of single-chamber pumps as cardiac support, initiated the area of ventricular assist devices (VAD). This chapter presents a literature survey of the technical papers and commercially available VADs.

2.1 First generation ventricular assist devices

The first ventricular assist devices generated additional blood flow in parallel with the particular ventricle. They were either pneumatically or electrically driven membrane pumps, generating pulsatile flow with artificial heart valves as inlet and outlet. Connected to the heart via cannulas, these pumps can be used either as isolated left-, right- or bi-ventricular assist devices. If used for bi-ventricular support, pump chambers have to be positioned extracorporeal due to the size [12]. Examples of first generation VADs are Berlin Heart EXCOR (Berlin Heart, Berlin, Germany), Thoratec PVAD and XVE (Thoratec, Pleasanton, CA, USA) [12]. Initially these systems were designed only as Bridge-to-Transplantation (BTT). Over the years, miniaturization of the devices created new possibilities: more patients could be discharged on VAD, still being listed and awaiting transplantation. However, first generation VADs had several disadvantages: large size, noise emission, infections of cannulas and malfunction induced by tears in the membrane or degradation of valves made everyday life difficult and sometimes caused fatal complications.

2.1.1 Heartmate I

The first generation of LVADs were known as pulsatile because, like a normal heart, they had a detectable beat. Blood flowed into an artificial chamber and was squeezed out to the rest of the body. A version called HeartMate I (Figure 2.1) that did so using air, with power coming from a large, external machine, became the first LVAD approved by the U.S. Food and Drug Administration [1]. Although the HeartMate I was a game changer for heart failure patients, they have many drawbacks. They caused thrombosis or the risk of bleeding and there is a need for strict anti-coagulation [13].

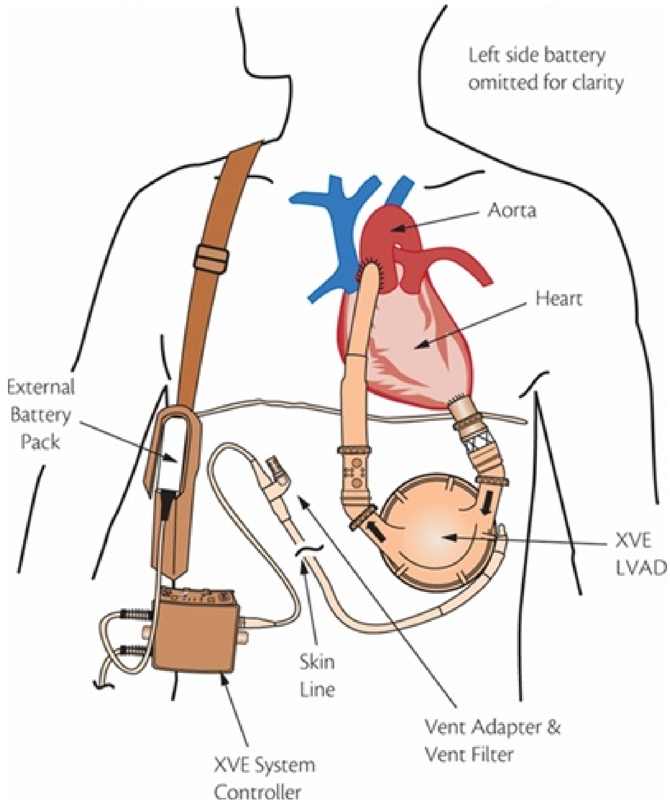

Figure 2.1: How patients connected to the HeartMate I [1]

2.1.2 Thoratec PVAD

Thoratec PVAD (Paracorporeal Ventricular Assist Device) provides maximum versatility for physicians in meeting the left, right or bi-ventricular support needs of advanced heart failure patients requiring acute (weeks) or intermediate (months) support with the opportunity for home discharge. With more than 20 years of clinical use, the PVAD can support a wide range of patients with advanced heart failure. The device is approved in the U.S. for Bridge-to-Transplantation (BTT) and Post-Cardiotomy Recovery from open-heart surgery [10].

2.2 Second generation ventricular assist devices

In the 1990's, development of continuous flow centrifugal pump devices improved patient outcome by reducing size and susceptibility for infections [12]. In addition, significant noise reduction enhanced the quality of life. Only utilization as LVAD was possible, as the devices were too large to be used as BIVAD. This wave of LVADs went from a pump to a stream, commonly called a continuous flow. The HeartMate II does this using a rotating screw. Blood comes into the chamber and twists through a device that is smaller and more comfortable than its predecessor. The development of continuous flow centrifugal pump devices improved patient outcome by reducing size and susceptibility for infections. In addition, significant noise reduction enhanced the quality of life [1].

2.2.1 Heartmate II

The most frequently used second generation LVAD is the Heartmate II (Figure 2.2). The device consists of a propeller surrounded by a metal case, referred to as an impeller. The combined mechanical and magnetical positioning of the impeller increases the durability up to a minimum of five years [12]. Since FDA approval in 2008, the Heartmate II can be used either as bridge to transplant or since 2010 as destination therapy. This provides patients with a better quality of life, including good mobility and restoration of endorgan function, in some cases even allowing them to return to work [12]. Some patients from the original clinical trials of Heartmate II, 10 years ago, are still alive, so the longevity of this LVAD is yet to be determined.

The incidence of thromboembolic events is relatively low for the HeartMate II and ranges from 3 to 6 events per 100 patient-years [14]. In the randomized destination therapy trial of the HeartMate II versus the HeartMate I, the hemorrhagic and ischemic stroke rates (at 0.06 and 0.07 events per patient-year) tended to be lower in comparison to HeartMate I (at 0.10 and 0.12 events per patient-year) [14]. Other second-generation devices (DuraHeart, VentrAssist) show somewhat higher incidence of neurological complications [15]. The incidence of driveline and pump infection is still remarkable, ranging from 13 to 27% [16]. In comparison to severe device-related infections with first-generation pumps, those with second-generation devices seldom lead to fatal outcomes [17].

Figure 2.2: How HeartMate II recipients are connected to the LVAD [1]

2.3 Third generation ventricular assist devices

Wear, heat generation, thrombus and hemolysis associated with the bearing systems paved the way for third generation LVADs. These LVADs eliminate all mechanical contacts inside the blood chamber. It is accomplished by employing either a magnetic bearing (magnetic levitation) and/or a hydrodynamic bearing between the impeller and the housing. Third generation LVADs offer improved device life expectancy, reduced hemolysis, reduced potential pump thrombosis, and an increased mechanical durability.

2.3.1 HVAD

The leading example of the third generation of LVADs is the LVAD by HeartWare. The HeartWare Ventricular Assist System, made by HeartWare, uses a chamber that is small and with no mechanical bearings. It also fits differently, attaching directly to the heart. Due to its reduced size, even a biventricular implantation is possible. [1] Designed as radial pump with magnetic and hydraulic positioning, no wear-out is to be expected with an estimated durability of 10 years [12].

The HVAD Pump (Figure 2.3), part of the HeartWare Ventricular Assist System, is a small centrifugal flow pump with a displacement volume of 50 ml and an output capacity of 10 L/min [17]. A unique wide-blade impeller is suspended by hybrid passive magnets and hydrodynamic forces. There are no points of mechanical contact within the pump, effectively ensuring a wearless system. The design integrates two motor stators for single-motor fault protection to increase reliability [18]. External system components include the microprocessor-based controller, a monitor, lithium-ion battery packs, alternating current and direct current power adapters, and a battery charger. Physiologic control algorithms are incorporated for safe operation [17]. Preclinical life cycle tests have shown the HVAD to be highly reliable. This system design offers reliability, portability, and ease of use for ambulatory patients [19]. The device size and the integrated inflow cannula allow it to be implanted completely in the pericardial space, directly adjacent to the heart, thereby avoiding the abdominal surgery generally required to implant competing devices [20].

Figure 2.3: The HeartWare HVAD (right), and its miniaturized version [1]

2.3.2 Heartmate III

Heartmate III uses a centrifugal pump with a bearing less fully magnetically levitated motor along with active magnetic mounting (Self bearing). It consists of the rotor with passive magnets for drive and bearing, the stator with electromagnetic coils for drive, as well as levitation including hall/distance sensors and microcontroller. Rotation and radial levitation are achieved through active control. Remaining degrees of freedom, axial motion and tilting are achieved by passive magnetic support. A clinical study of 366 patients compared survival of patients using the HeartMate 3 LVAS to those using the HeartMate II LVAS (currently available from the same manufacturer) [21]. The study showed that 77.9% of the HeartMate 3 patients, as compared to 56.4% of the HeartMate II patients, survived to 2 years without a disabling stroke and without the need to replace the pump [21]. About 1.6% of the HeartMate 3 patients needed the pump replaced within 2 years, compared to about 12.2% of the HeartMate II patients [21].

Table 2.1: Comparison of HeartMate II and HeartMate III [9]

Characteristic	**HeartMate II**	**HeartMate III**
Pump (flow)	Axial	Centrifugal
Bearing	Mechanical (blood washed)	Magnetic
Hydraulic Capacity	Up to 10.0 liters/min	Up to 10.0 liters/min
Implantation location	Extrathoracic	Intrathoracic
Typical clinical speed range	8000 to 10000 rpm	5000 to 6000 rpm
Textured surfaces (sintered titanium)	Yes	Yes
Inflow graft	14-mm sealed Vascutek	None
Outflow graft	14-mm sealed Vascutek	14-mm sealed Vascutek
Quick pump attachment	No	Yes
Modular drive - line	No	Yes
Electronics incorporated in pump	No	Yes
Software incorporated in pump	No	Yes
Artificial pulse	No	Yes
Flow estimator hematocrit adjustment	No	Yes
Power efficiency (battery run-time)	14 hours	20% longer than HeartMate II

Chapter 3

Design and Implementation

Mechanical circulatory support devices have become an important treatment tool for acute and chronic heart failure, since heart transplantation cannot meet the demands because of a lack of available donor organs. This chapter presents an overview on the levitation electronics, drive electronics and monitoring system of a third-generation Left Ventricular Assist Device (LVAD) which augments blood flow to the body and shares the workload of the Left Ventricle.

3.1 Block Diagram

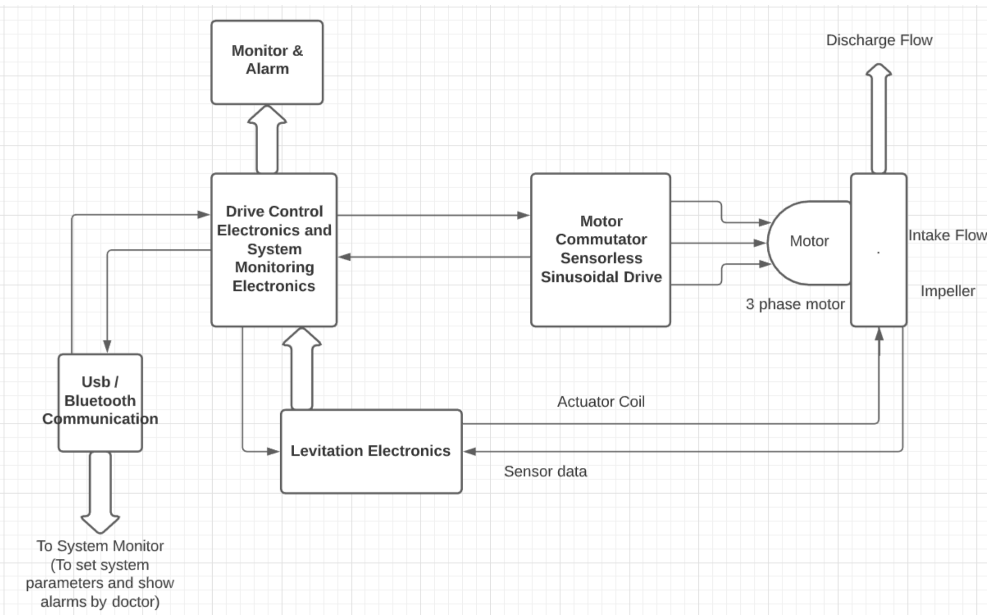

Figure 3.1: Block diagram of the system

The proposed block diagram for the system including the levitation electronics, drive electronics and the monitoring system is shown in Figure 3.1. The levitation electronics will be placed inside the patient body, while the drive control electronics, motor commutator sinusoidal drive and the monitoring electronics will be placed in a controller unit outside the patient body. The system monitor is a separate unit which allows the doctor to set the system parameters.

3.2 Levitation

Levitation systems utilized in third-generation rotary blood pumps suspend the moving impeller within the blood field without any mechanical contact. The magnetic and hydrodynamic levitation of the impeller without any contact bearings with the pump is the major advancement of the third-generation pumps. [12] The suspended impeller reduces heat generation, increases endurance and also the spiral groove hydrodynamic bearing are a backup in case primary magnetic bearing fails (in larger size LVAD pumps). The rotation speed is 1800-4000 rpm with 10 l/min maximum flow rate.

Magnetic bearings offer high reliability, show no wear or abrasion and can be used in a high-vacuum environment without the need for lubrication. They show no stiction and have very low rotational losses. They are not susceptible to temperature changes and should be less expensive to produce than conventional ball-bearings due to less demanding manufacturing tolerances. These properties are appreciated for satellite reaction/momentum wheels, which have to operate at high rotational speeds in a vacuum for long periods of time. This section describes the design suspension electronics for magnetic bearing used in Magnetic Suspension Reaction Wheels (MSRW).

3.2.1 Design Principle

Earnshaw's theorem states the condition for instability in magneto static inverse squire fields. Its practical consequence as applied to paramagnetic material is that external stabilizing means must be provided in at least one coordinate direction. A completely passive and contactless magneto static bearing, stable in all 6 degrees of freedom (DOF), cannot be realised under normal conditions. In practice, at least one axis has to be controlled actively by means of electromagnets. Table 3.1 shows the possibilities for the design:

Table 3.1: Levitation design possibilities

Number of actively controlled DOF	**Bearing Properties**
1 (axial)	Simple electronics, low power consumption but high axial dimensions, awkward mechanical construction; passive damping of radial oscillations difficult.
2 (radial)	High radial stiffness due to active control, simple construction, low axial height.
5	Complex system, therefore less reliable than other options; offers Vernier gimballing capability.

By considering various design and size constraints two axis active control method is chosen for the present design.

3.2.2 Block description

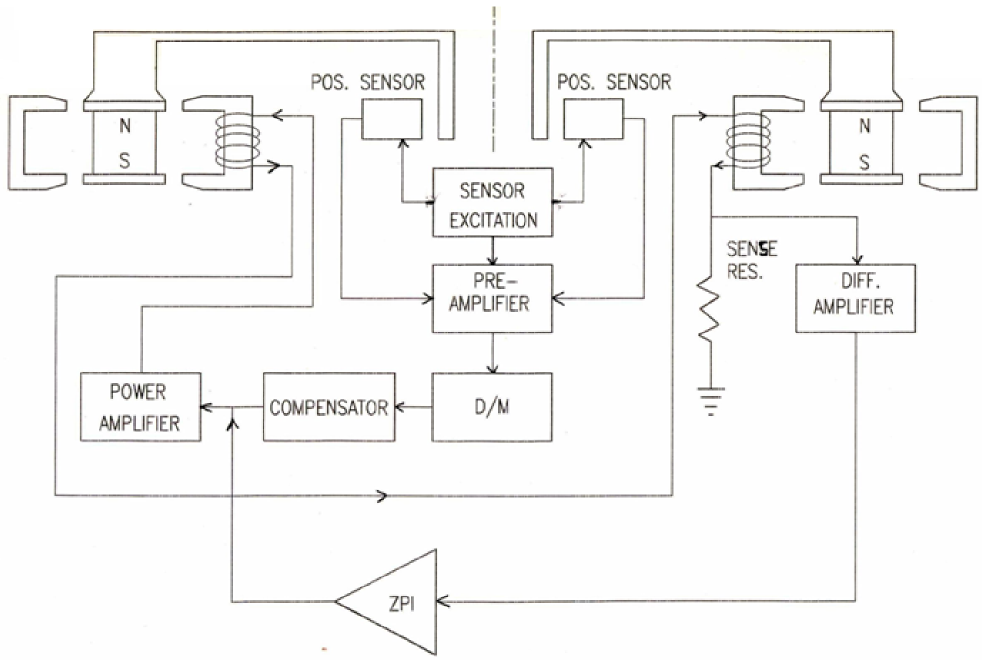

Figure 3.2: Functional block diagram of MSRW

Magnetic bearings can be realised by using attractive or repulsive forces. A better mass vs. stiffness ratio can be achieved by using the attractive force mode. Preference was given to the 2 DOF options where the wheel is actively controlled along two orthogonal radial directions where axial movements and all other degrees of rotor freedom are passively controlled by means of permanent magnets, except for the rotor spin. The two radial axes are independently controlled by their control loops. This design principle generally results in a flatter geometry, using less volume and being suitable for panel mounting.

The principle of operation is self-explanatory from the following figures:

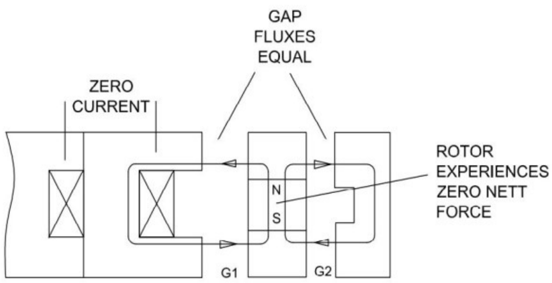

Figure 3.3: Zero Net force

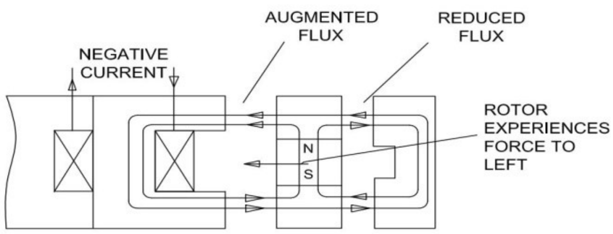

Figure 3.4: Net force towards left

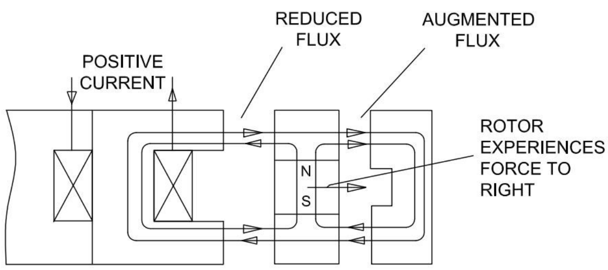

Figure 3.5: Net force towards right

3.2.3 Servo system for radial positioning

Two servo loops are required for radial positioning of the rotor in two axis controlled bearings. The position of the rotor is sensed by inductive position sensors along the two perpendicular axes. Along each axis two sensors are mounted diametrically opposite to each other. The sensor output is followed by a demodulator, compensation circuit and the power amplifier. The power amplifier drives the current through the coils of the electromagnet. The magnetic flux from the electromagnet modulates the flux due to permanent magnet in the rotor. This results in a force which corrects for any displacement of the rotor from the centre position. The servo system is unstable in open loop. For the design purpose, the two servo loops are assumed to be independent and are identical.

3.2.4 Lead compensation network

As mentioned earlier, the magnetic bearing system is basically unstable. Poles on the right side of the imaginary axis can be brought atmost to the imaginary axis by increasing the gain, thereby creating a critically stable system. A compensation network must be added in the loop to make it stable. A lead network is for stabilising the system and providing the required gain margin above 12 dB and phase margin above 30 degrees. The zero and pole of the lead network are adjusted to make the system stable.

3.2.5 Power amplifier

The output of the lead network is given to the power amplifier which drives current through the electromagnet coil to keep the rotor in the middle position. In order to operate in single ended power supply, two different configurations were studied:

- H bride based configuration
- Power Op amp based configuration

Finally, Power Op amp based configuration is finalized for the present design. IC SA160 has been identified as a power efficient PWM-type amplifier. The SA160 is a pulse width modulation amplifier that can supply 10 A continuous current to the load. The PWM circuitry is internal leaving the user to only provide an analog signal for the motor speed/direction. The internal PWM frequency can be programmed by an external integrator capacitor.

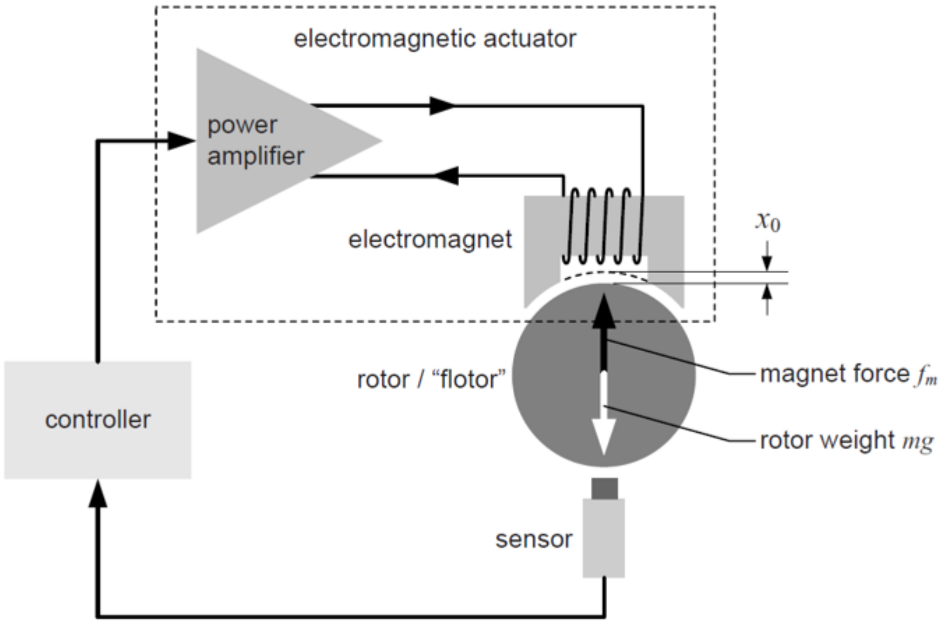

Figure 3.6: The basic magnetic bearing control loop and its elements

3.2.6 Sensors

In our application, eddy current sensors are used. Inductive sensors are based on the eddy current principle and designed for non-contact measurement of displacement. They have high resolution and temperature stability. They are suitable for applications in harsh industrial environments due to their superior tolerance for oil, dirt, dust, moisture and magnetic interference fields [22].

Eddy current sensor operates based on the inductive eddy-current principle. It measures the distance based on the extraction of energy from an oscillating circuit, which is required to generate eddy current in an electrically-conductive materials. When the sensing coil is supplied with an alternating current, it causes a magnetic field to form around the coil. If an electrically conducting material is placed in this field, eddy current field is induced according to the Faraday's induction law. When the rotor moves, it causes the change in the impedance of the coil, which is proportional to the change in the distance between the sensor and the target [22].

Unlike in satellite applications, inductive bridge sensors cannot be used in an LVAD as they are bulky and need an inductance ring. Eddy current sensors, on the other hand, do not need a coil and fit in the 60 mm diameter of the system. Other alternative sensors for gap measurement include capacitive sensors and optical sensors. The properties of the blood may change the dielectric value of the capacitor and change the gain of the system thereby making it unstable. Hence, we need additional adaptive circuitry if capacitive sensors are used. The drawback in the case of optical sensors is that the optical source should be able to work without fail for over 10 years (expected lifespan of the LVAD). Also, the ferromagnetic material used is not be haemo-friendy and will be rejected by the body. Hence, a titanium coating (which is haemo-friendly) needs to be given over the optical sensor.

3.2.7 Software implementation for higher-order controller

Neural networks are very useful for solving time series problems. A neural network with elements (called neurons) can address a non-linear dynamic systems with arbitrary accuracy [23]. The network for modelling magnetic levitation will be designed by using the recordings of an actual levitated magnet's position responding to a control current. The implementation is carried out in MATLAB.

We attempt to build a neural network that can predict the dynamic behavior of a magnet levitated using a control current. The system is characterized by the magnet's position and a control current, both of which determine where the magnet will be an instant later. This is an example of a time series problem, where past values of a feedback time series (the magnet position) and an external input series (the control current) are used to predict future values of the feedback series.

Preparing the data

Data for the problem is set up for a neural network by organizing into two matrices, the input time series X and the target time series T [23]. The input series X is a row cell array, where each element is the associated timestep of the control current. The target series T is a row cell array, where each element is the associated timestep of the levitated magnet position. Both X and T have 4001 columns. These represent 4001 timesteps of the control current and magnet position.

Creating a neural network

The next step is to create a neural network that will learn to model how the magnet changes position. Two-layer NARX (nonlinear autoregressive with external input) neural networks can fit any dynamical input-output relationship given enough neurons in the hidden layer [23]. Layers which are not output layers are called hidden layers. A single hidden layer of 10 neurons is used. Two delays for the external input (control current) and feedback (magnet position) are used to model this dynamic system. The output y(t) is also an input, whose delayed version is fed back into the network.

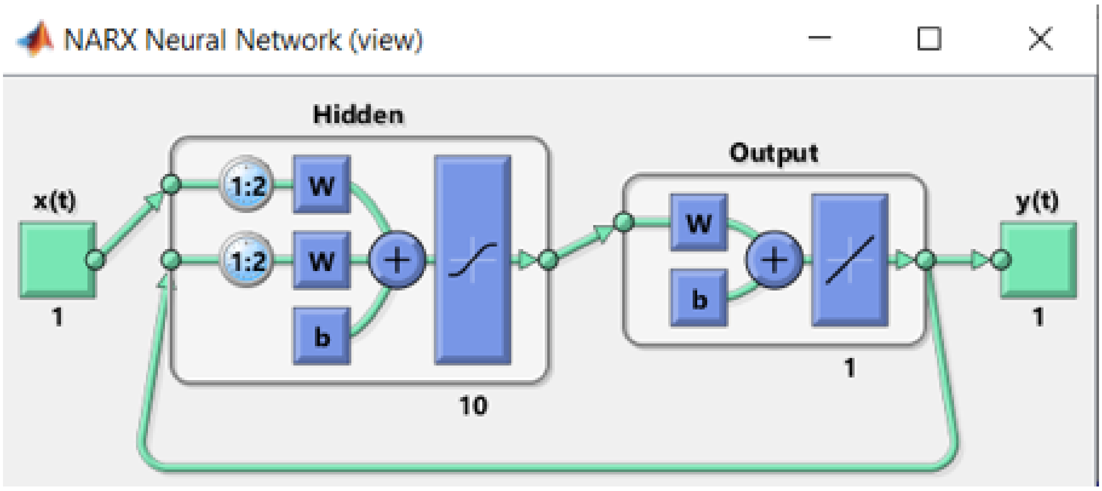

Figure 3.7: Simulating the neural network in closed loop form

Training and testing the network

The function PREPARETS prepares the time series data for simulation and training. The timesteps are automatically divided into training, validation and test sets. The training set is used to teach the network about the data. Training continues as long as the network continues improving its performance on the validation set. The test set provides a completely independent measure of network accuracy. The mean squared error of the trained neural network for all timesteps is measured to be 2.9245e-06. Further results and graphs on the network response and the autocorrelation of errors are shown in Chapter 4.

3.3 Drive Electronics

This section of our LVAD system was implemented by designing a PCB to drive either a brushless DC electric motor (BLDC motor) or a permanent magnet synchronous motor (PMSM) which has ability to provide Torque (BEMF constant) > 30 mN, in the speed range of 1800-4000 rpm with an accuracy of ± 2 rpm. Only such a motor will be able to overcome both the Cogging Torque and friction due to blood flow. The design also provides access to proprietary sensorless control (unlike the normal ones using Hall sensors for position tracking) and the ability to tune motor parameters for optimizing performance according to the end-application needs [6].

3.3.1 PCB Design and Functioning

The PCB designed is a small-form-factor (SFF), cost-effective, single-layer, three-phase sinusoidal motor drive for BLDC motors with rated specifications as detailed in Table 3.2. The complete schematic diagram of the design is shown in the Appendix A.2. Some of the major components (Driver IC and MCU) along with the key system specifications are outlined below, whereas the rest of the components used in the board are provided in the Appendix A.1.

DRV10983-Q1 :

The DRV10983-Q1 device is a three-phase sensorless motor driver with integrated power MOSFETs, which can provide continuous drive current up to 2 A. It uses a proprietary sensorless control scheme to provide continuous sinusoidal drive, which significantly reduces the pure tone acoustics that typically occur as a result of

Table 3.2: PCB specifications

Parameters	Specifications
Dc Input Voltage	8 to 16 V
Current	1A continuous
Power level	design for 8- to 16-W operation
Analog speed input	0 to 3.3 V
Control method	Integrated 180° sinusoidal control
Protection circuits	Overcurrent, voltage surge protection

commutation, along with a programmable I2C interface [6]. The device also supports both sleep mode (48 µA) version or standby mode (8.5mA), and hence, it has been found apt for our system owing to power constraints. For additional details based on which this IC has been used in our system, refer Appendix C.1.

MSP430G2553 :

MSP430G2x53 series are ultra-low-power mixed signal microcontrollers qualified for automotive applications featuring 16-Bit RISC Architecture, 16-bit registers, and constant generators that contribute to maximum code efficiency. It has five low-power modes, which are optimized to achieve extended battery life in portable measurement applications [24]. It also possesses flexible user interface options and I2C interface for accessing registers for command and feedback. These are some of the important features based on which it has been found apt for our project. For additional details related to the IC, refer Appendix C.2.

PCB Working Description :

The System Block Diagram (Figure 3.8) shown below consists of the DRV10983-Q1 motor driver and MSP430G2553 MCU intefaced together. The board is supplied with a motor supply voltage of 12 V, which is fed to the DRV10983-Q1 device providing the three motor phase outputs to drive the BLDC motor sinusoidally. The DRV10983-Q1 driver's P3V3 LDO (LowDropout Regulator) regulator supplies 3.3 V to power the MSP430 MCU. The board also has a speed pin input (Vsp), which is connected to the ADC10 pin of the MSP430 MCU. The ADC10 takes an input voltage from 0 to 3.3 V and converts it to a digital 10-bit value. This value controls the percentage duty cycle for the output PWM signal [6].

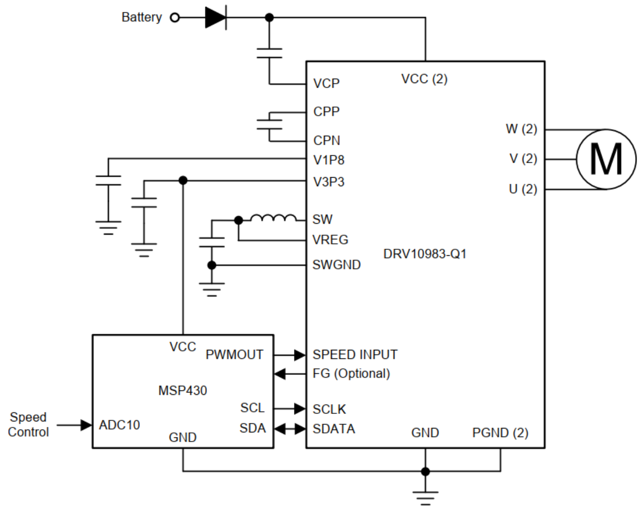

Figure 3.8: Interfacing MSP430g2553 and DRV10983-Q1 for Speed Control

The MSP430 MCU creates a pulse width modulation (PWM) signal output, which connects to the DRV10983-Q1 SPEED input pin. The DRV10983-Q1 then uses this input to control the speed of the motor. The DRV10983-Q1 device provides motor speed measurement information on the Frequency Generator (FG) output or I2C, which can be used to implement the speed control loop [6]. The I2C interface is also available as a header where an external graphical user interface (GUI) can be used for programming the DRV10983-Q1 device along with JTAG pin headers are used for MSP430 programming.

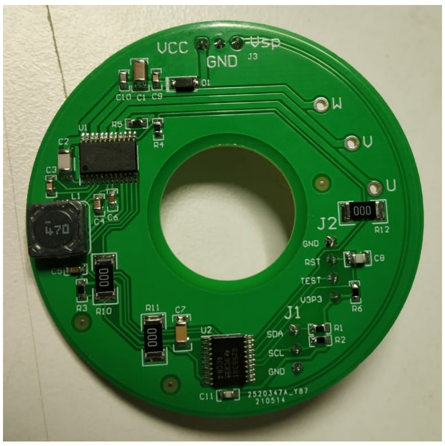

Figure 3.9: Drive Electronics PCB

3.3.2 System Software Description

The firmware is written for the on-board MSP430 controller. It can configure the DRV10983-Q1 device, and is usually a one-time configuration unless the user wants to modify parameters during runtime of the configuration. The firmware also processes the input speed using the ADC10 of the MSP430 MCU and implements a PI (Proportional Integrator) speed control system using feedback from the DRV10983-Q1 from either I2C or FG.

Using GUI to Configure DRV10983-Q1 :

Configuring the DRV10983-Q1 refers to programming the tuning parameters, which are written to the EEPROM. In this aspect, our major goal was to acquire the intrinsic motor parameters unique to our motor being used. Motor parameters help determine whether it is suitable for DRV10983-Q1 device and what proper settings are to be implemented for the specific application. The following section below describes how each parameter is measured and the overall measured parameters are shown in the Table 3.3 given below.

Table 3.3: BLDC Motor Parameter Table

Operation Voltage	**Number of Poles**	**Maximum Speed (RPM)**	**Maximum Current**	**R (PHASE-CT)**	**Kt (PHASE-PHASE)**
12 V	4	3000	34 A	1.54	51.3 mV/Hz

The first four parameters are obtained from the motor specification sheet or are predefined. These include IPD (Initial Position Detection), Start-Up and Advanced settings available in Tuning Guide [25]. Knowledge of the Number of Poles enables the conversion of Motor Speed in Hz to rpm. The rest two parameters are motor specific and are measured based on the details given below :

(i) **Motor Phase Resistance :**

It is measured using the fact that the phase to center tap resistance is half of the phase to phase resistance of the windings. The maximum value of resistor value that can be programmed for DRV10983-Q1 is 18.624Ω and the minimum value is 0.0097Ω. Its corresponding 7-bit digital register value can be obtained from the Motor Phase Resistance Look Up table [6].

$$R_{PH-CT} = R_{PH-PH}/2$$

(ii) **Motor Velocity Constant**

It describes the motor phase to phase Back Electromotive Force (BEMF) voltage as a function of motor velocity. The maximum value that can be programmed in DRV10983-Q1 is 1766 mV/Hz and the minimum is 0.92 mV/Hz [6].

$$KT_{PH-CT} = E_P * T_e$$

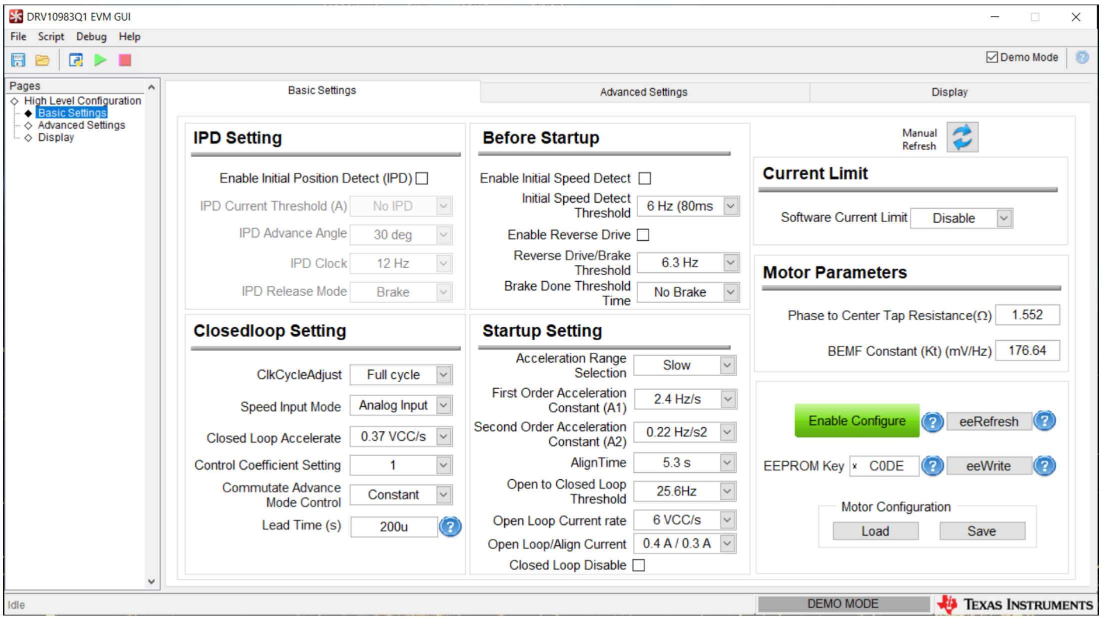

Figure 3.10: DRV10xx Software GUI [2]

Apart from the above, setting the open loop control includes other features like **Disabling IPD**, **Before StartUp Features**, **Configuring StartUp Settings** (including Open to Closed loop threshold, First and Second Order Accelerate). The DRV10983-Q1 device can be configured to work with slew rate to improve EMC and EMI performance [6]. Dead time must be changed to account for this change in slew rate, and hence spinning the motor in open loop based on I^2C speed command. All the details of the above implementation are based on referring to Texas Instruments DRV10983-Q1 Tuning Guide [25] and DRV10983-Q1 Evaluation Module User's Guide Datasheets [2] which provides overview of the DRV10xx Software GUI installation and usage. Now finally Save the motor configurations using the GUI. This action saves the seven CONFIG registers as a .csv file which be used in later section.

3.3.3 Programming MSP430 MCU using CCS and JTAG

We have used the JTAG emulator like the one found through the MSP430 LaunchPad Value Line Development Kit (MSP-EXP430G2) [refer Figure C.3] to interact with the MSP430G2553 IC in our PCB. Though DRV10983-Q1 can drive the motor without the use of an MCU, the design uses the MCU for implementing the Speed Loop functionality and providing varying PWM speed signals for motor drive.

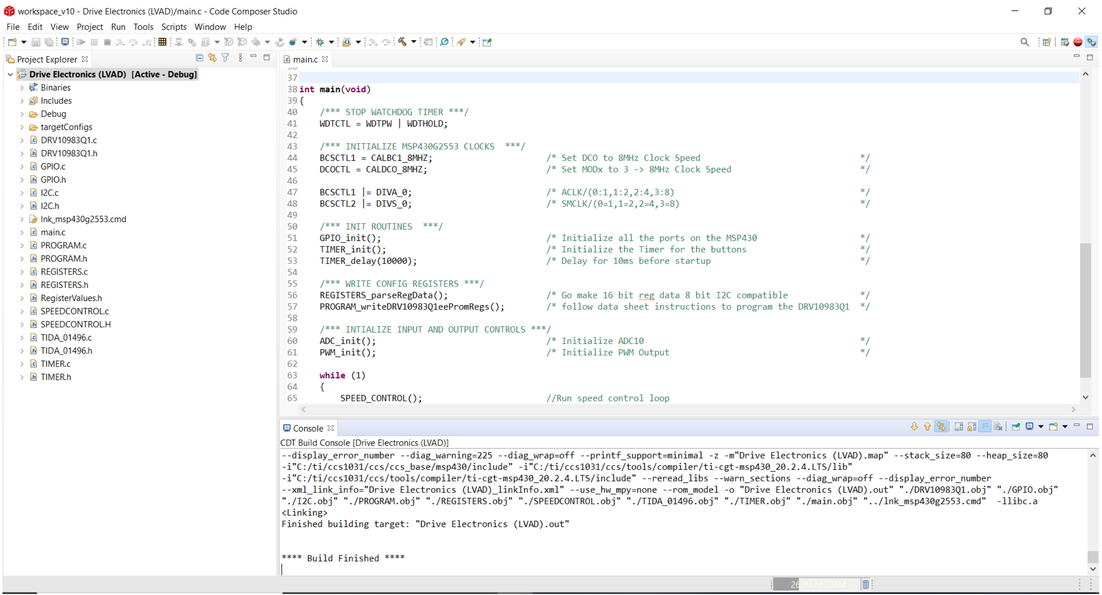

Figure 3.11: CCS IDE User Interface [3]

Code Composer Studio (CCS) has been used instead of Energia IDE, as our system involves register level programming. Entire Software flow is depicated in the (Figure 3.12) below. In order to Stop Watch Dog Timer [WDT], initialize the clocks and timers (routines) we have referred to the MSP430G2553 datasheet [24] and its Family Users Guide [3] and has been implemented in the main.c, as detailed in the Appendix D.1.

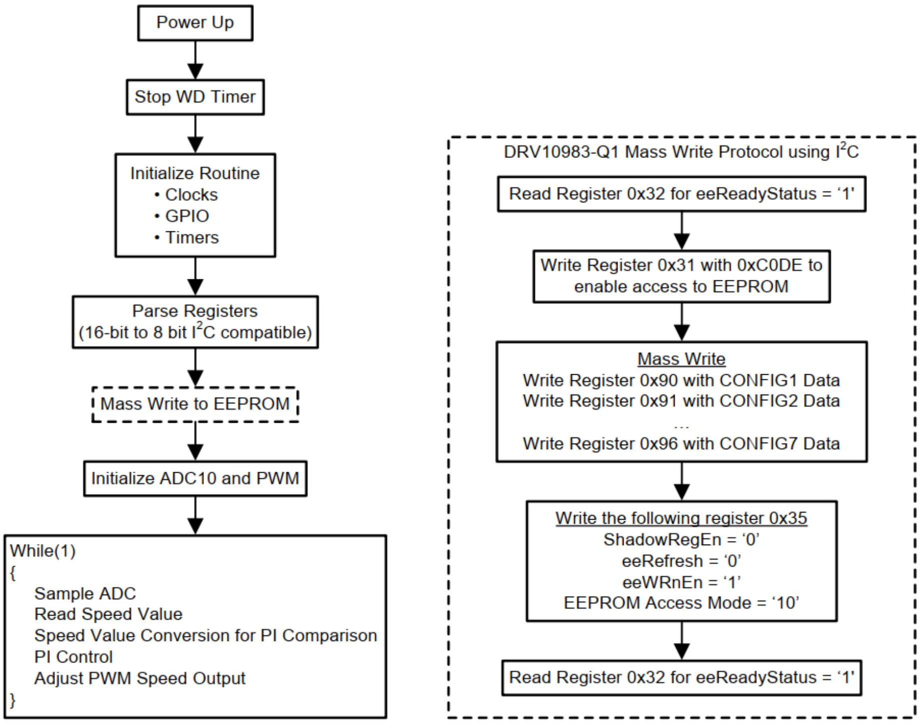

Figure 3.12: System Software Flow

Into the RegisterValues.h header file of CCS LVAD (Drive Electronics) project, place the CONFIG values obtained from .csv file (DRV GUI) as shown in the (figure 3.13) below. These seven EEPROM registers (0x90:0x96) can be accessed to program motor parameters and optimize the spin-up profile for the application. The entire code of RegisterValues.h is detailed in Appendix D.2. Define the register address in the REGISTERS.c source file in both corresponding arrays as detailed in Appendix D.3.

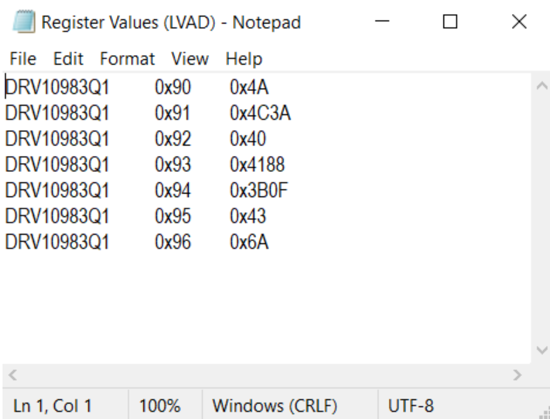

Figure 3.13: Motor Configuration File in DRV10x GUI

Now, define the number of total registers in the REGISTERS.h file. Define the register address in the REGISTERS.c source file in both corresponding arrays as shown in Appendix D.3. Now once the initialization stage (Mass Write to EEPROM + Initialize ADC10 and PWM) is complete the program stays in the while loop continually running the SPEEDCONTROL function [Appendix D.4]. The SPEEDCONTROL function flows by the following process :

1. ADC samples voltage of MCU and translates into a bit value defined by ADC_Value.
2. Using this bit value, a speed level is assigned (that is, 0 to 5) defined by Speed_Level.
3. The speed level determines the target speed of the electrical cycle (Hz), defined by SPEED_INPUT, and scale value, defined by Scale.
4. The current speed of the electrical cycle speed is read through I2C from the DRV10983-Q1 defined by SPEED_MEASURED.
5. The difference between the target speed and current speed is defined by Error.
6. The PI loop operation calculates the error and adjustments needed to reach the target speed defined by OutPreSat.
7. An if statement is used to bound the error and adjustments if the error is too large defined by Out (Hz).
8. The error for the next cycle used by the PI loop is determined by SatError.
9. The PWM signal uses the error and adjustments. This is defined by CCR1 (Hz).

3.4 Monitoring

We intend to have a miniature monitoring system (Figure 3.15) to monitor the important health parameters of the LVAD, such as battery percentage indication, speed (rpm), power and levitation status. It also includes necessary alarm signals using a buzzer in case it overrides the specified limit set on the levitation alignment. OLED Graphic Display interfacing with MSP-EXP430G2 TI Launchpad is used under this section as it involves least power consumption, which is one of the major constraint in our application.

SSD1306 OLED Module

OLED (Organic Light-Emitting Diode) modules are driven by SSD1306 IC which is a driver IC for 128x64 Dot Matrix OLED segments [4]. The SSD1306 has its own controller and supports both SPI and I2C communication protocols [4]. SSD1306 is a

CMOS OLED driver with controller for OLED dot-matrix graphic display system [4]. Due to use of SSD1306 driver, number of external components required and power consumption has reduced. SDA pin is used to transmit data between master and slave. The data and acknowledgement are sent through SDA. SCL pin transmits clocks to slave, SCL. Data will be sent to other devices on clock tick event. Only master device has control over this SCL line. I2C interface devices are recognized by their slave address. OLED display has slave address format as shown in below image (Figure 3.14).

7	6	5	4	3	2	1	0
0	1	1	1	1	0	SA0 bit	R/W bit

Figure 3.14: OLED Address Format

If SA0 (Slave Address) bit is 0, then microcontroller can do read/write operation with OLED display using the below I2C address [4].

(i) I2C write address is 0x78

(ii) I2C read address is 0x79

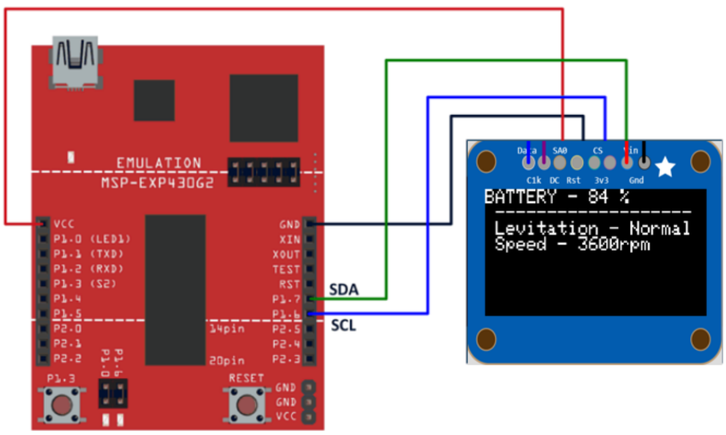

Figure 3.15: Interfacing OLED with MSP-EXP430G2 TI Launchpad [4]

The SCL and SDA for MSP-EXP430G2 TI Launchpad are on pins 14 (P1_6) and 15 (P1_7) respectively [4]. The software-based I2C implementation is defined with pins 9 (P2_1) and 10 (P2_2) as SCL and SDA pins. Here, we have used the hardware I2C pins of the MSP-EXP430G2 board. The hardware I2C implementation is faster than software I2C implementation [4]. It is easy to change the I2C speed from 100 kHz to a higher speed (101-400 kHz) for the hardware I2C. For software I2C, it is not as easy to achieve the same [4]. I2C header connections (J1) in our PCB are not only used to program the registers [Appendix B.2] onto the DRV10983-Q1 but as well as to provide speed feedback data for the speed control loop back to the MCU. So, based on this feedback data available, the monitoring section displays the useful details like speed(rpm), levitation status, battery percentage are set up.

Chapter 4

Results & Discussion

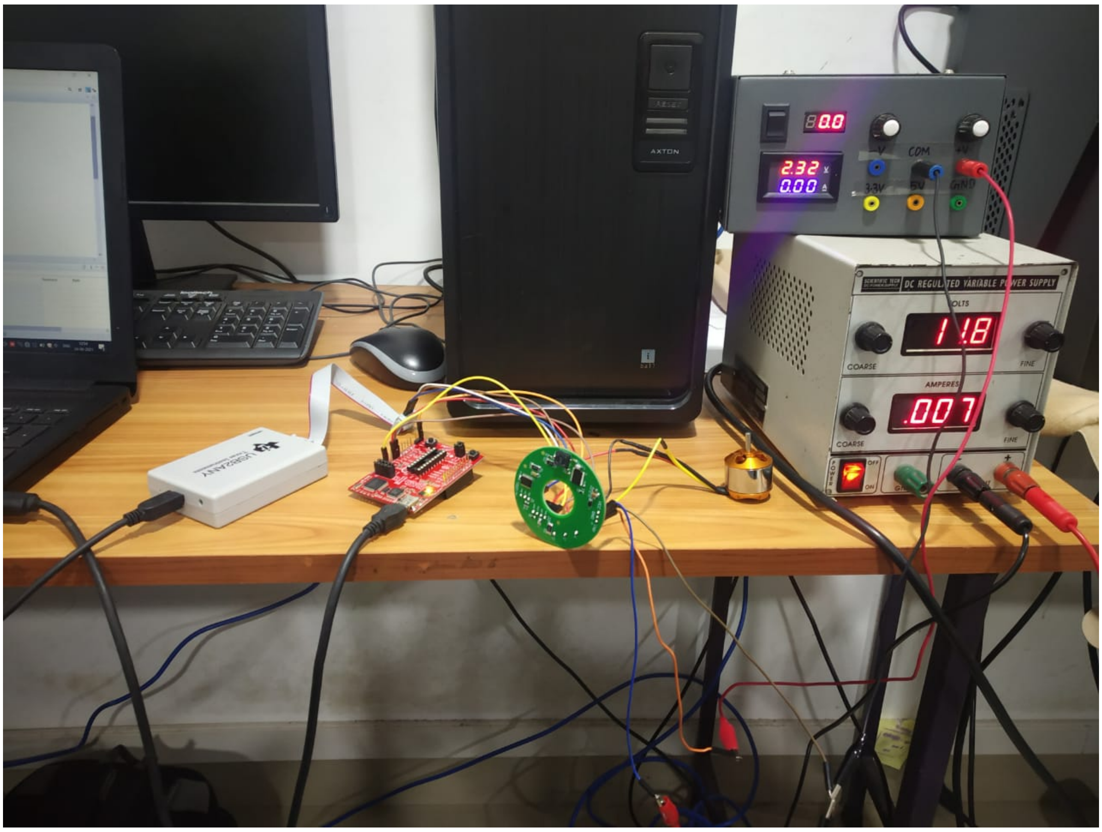

Figure 4.1: Lab Set-Up of Drive Section

Finding Appropriate Scale for Each Speed Level :

The ADC_Value input, by extension the SPEED_INPUT, will be compared to the SPEED_MEASURED and put through the PI loop. Setting the CCR1 value will manually determine the PWM duty cycle and ignore the effects of the PI loop. This is important because unique motor parameters will cause different speeds at 100% duty

Speed Level	PWM Duty	CCR1 Value	SPEED_MEASURED	SCALE
0	0%	0	0	—
1	20%	205	31	6.61
2	40%	409	63	6.49
3	60%	614	94	6.53
4	80%	818	126	6.49
5	100%	1060	163	6.5

Table 4.1: Results Obtained by Tuning SPEED_INPUT Using Scale Functionality

cycle. Determining the max speed will determine the scale between the PWM duty cycle and the SPEED_INPUT. To determine the scale, observe the PWM duty cycle and SPEED_MEASURED for each CCR1 value and determine the scale value by dividing the CCR1 value by the SPEED_MEASURED. Each time a speed is set, run the motor and check the SPEED_MEASURED variable. To do this, run the debugger and add SPEED_MEASURED to the expressions table by right clicking the table and selecting ”add global variable”. Pause the debugger while the motor is running in closed loop to observe the speed value measured by the DRV10983-Q1 using I2C.

Speed Loop Regulation Test :

In the implementation of Scaled SPEED_INPUT (Appendix D.4) five motor specific speed levels are programmed. Each speed level is tested for voltage ranging from 8 to 16 V in 2-V increments. Measurements are taken in Hz but converted to RPM based on information known from the number of poles present and by referring DRV10983-Q1 GUI.

Table 4.2: Output Speeds versus Input Speed Commands and Input Voltage Ranges

Voltage Input	Speed Input = 1000 rpm	Speed Input = 1692 rpm	Speed Input = 2236 rpm	Speed Input = 2636 rpm	Speed Input = 2956 rpm
8V	1001	1691	2041	2210	2314
10V	1000	1691	2236	2559	2686
12V	1000	1691	2236	2636	2956
14V	1000	1691	2236	2640	2956
16V	1001	1691	2236	2641	2956

Levitation simulation :

Performance is measured in terms of mean squared error, and is shown in a log scale (Figure 4.2). It rapidly decreased as the network was trained. Performance is shown for each of the training, validation and test sets.

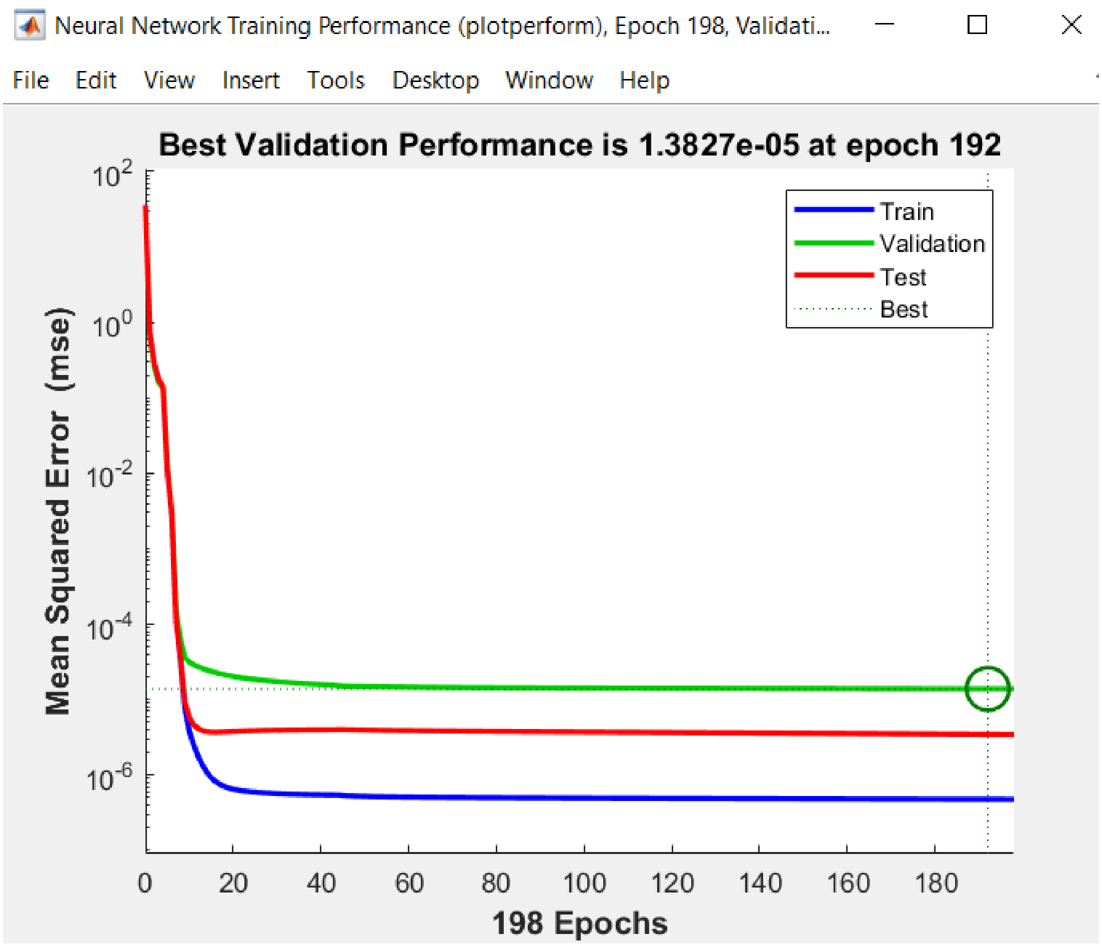

Figure 4.2: Performance of the network

PLOTRESPONSE will show us the network's response in comparison to the actual magnet position (Figure 4.3). If the model is accurate the '+' points will track the diamond points, and the errors in the bottom axis will be very small. PLOTERRCORR shows the correlation of error at time t, e(t) with errors over varying lags, e(t+lag) (Figure 4.4). The center line shows the mean squared error. If the network has been trained well all the other lines will be much shorter, and most if not all will fall within the red confidence limits. The function GSUBTRACT is used to calculate the error. This function generalizes subtraction to support differences between cell array data.

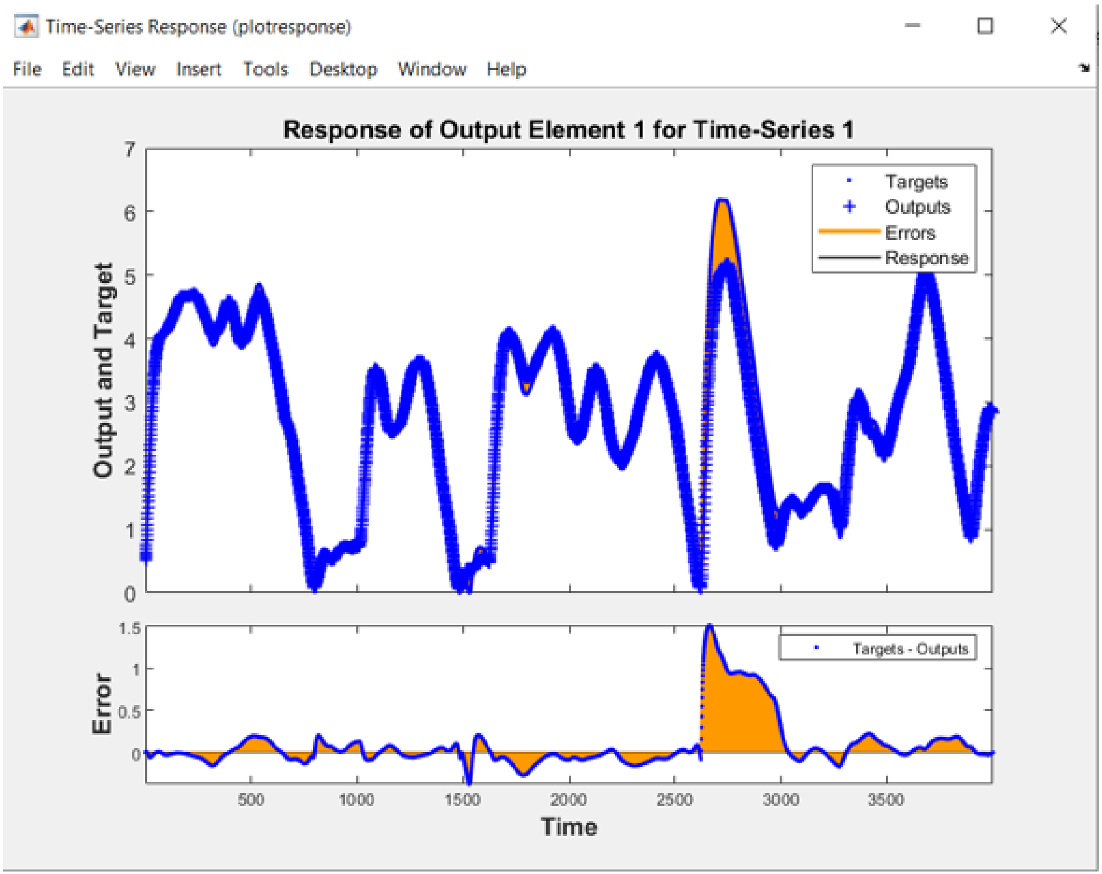

Figure 4.3: Network Response vs Actual Response

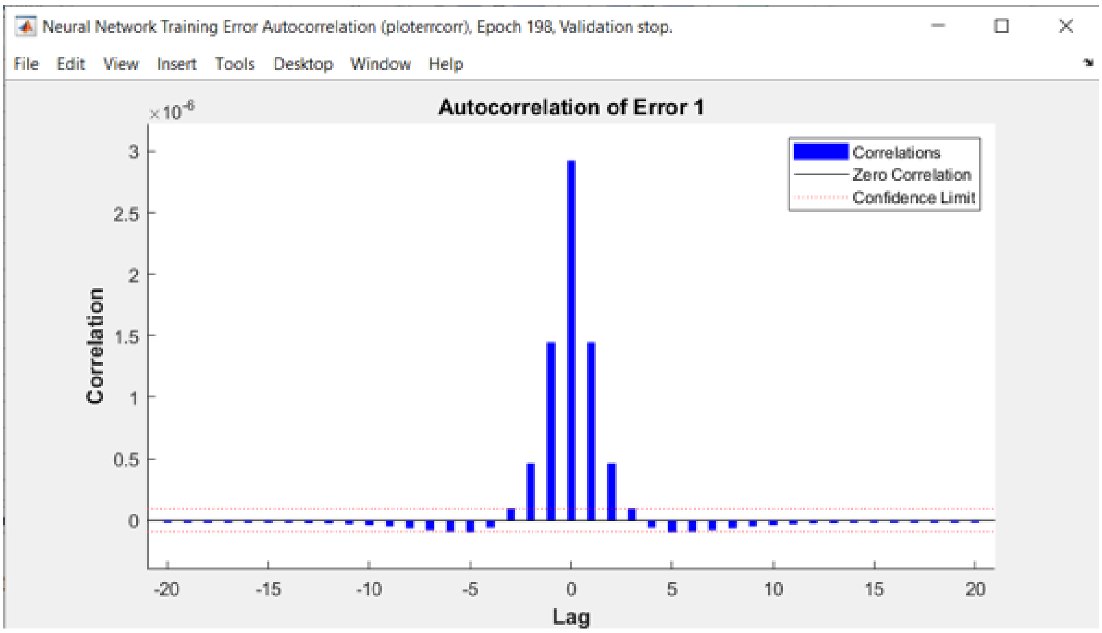

Figure 4.4: Autocorrelation of errors

Chapter 5

Conclusion & Future Scope

We have designed a magnetically levitated wheel, rotating at a desired rpm, which supplements blood flow from the Left Ventricle to the aorta, thereby helping the weakened heart pump blood. Hardware implementation and software simulations using MATLAB were carried out for the levitation system. The PCB designed will drive the axial flux motor in the speed range of 1800-4000 rpm and also tune the motor parameters for optimizing the performance. The monitoring system will keep track of the important health parameters.

5.1 Future scope

Minimally invasive LVAD surgery will be made possible by newer surgical techniques focusing on two main areas: less-invasive cardiac access and off-pump technique. A totally implantable LVAD system represents the next logical advancement in LVAD design wherein Thermal energy transfer system (TETS) technology or Coplanar Energy Transfer (CET) system will be been incorporated into numerous mechanical support designs. Incorporating a Distant Monitoring and Control Station (DMCS) set up would increase its acceptance not just in its native country but be viable to people across the globe. As our understanding of heart failure continues to grow, there is little doubt that LVADs will continue to play a pivotal role as a therapeutic option for those suffering from end-stage heart failure.

References

[1] "The past, present and future of the device keeping alive carew, thousands of hf patients," www.heart.org. [Online]. Available: https://www.heart.org/en/news/2018/06/13/the-past-present-and-future-of-the-device-keeping-alive-carew-thousands-of-hf-patients

[2] "Drv10983 and drv10975 evaluation module user's guide," 2014. [Online]. Available: https://www.ti.com/lit/ug/slou393e/slou393e.pdf?ts=1625234209261&ref_url=https%253A%252F%252Fwww.google.com%252F

[3] "Msp430x2xx family user's guide," 2004. [Online]. Available: https://www.ti.com/lit/ug/slau144j/slau144j.pdf

[4] "Oled graphic display interfacing with msp - exp430g2 ti launchpad .." www.electronicwings.com. [Online]. Available: https://www.electronicwings.com/ti-launchpad/oled-graphic-display-interfacing-with-msp-exp430g2-ti-launchpad

[5] "Lab 14: Inter-integrated circuit (i2c) communication — embedded lab." [Online]. Available: http://embedded-lab.com/blog/lab-14-inter-integrated-circuit-i2c-communication/

[6] "Drv10983," Ti.com, 2020. [Online]. Available: https://www.ti.com/product/DRV10983

[7] . a. . P. Said, "Introducing the msp430g2553 hardware," Benn Thomsen, 11 2014. [Online]. Available: https://bennthomsen.wordpress.com/engineering-toolbox/ti-msp430-launchpad/introducing-the-msp430g2553-hardware/

[8] "Apex microtechnology - power operational amplifers - pwm amplifiers - voltage references :: Sa160 - 10a h-bridge motor driver," www.apexanalog.com. [Online]. Available: https://www.apexanalog.com/products/sa160.html

[9] "Clinical trial design and rationale of the multicenter study of maglev technology in patients undergoing mechanical circulatory support therapy with heartmate 3 (momentum 3) investigational device exemption clinical study protocol," *The Journal of Heart and Lung Transplantation*, vol. 35, p. 528–536, 04 2016. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1053249816000693

[10] "Thoratec ® pvad? thoratec ® ivad? - thoratec corporation - pdf catalogs — technical documentation," pdf.medicalexpo.com. [Online]. Available: https://pdf.medicalexpo.com/pdf/thoratec-corporation/thoratec-pvad-thoratec-ivad/78730-137477.html

[11] "Lvad," Max Healthcare. [Online]. Available: https://www.maxhealthcare.in/top-procedures/lvad

[12] A. Prinzing, U. Herold, A. Berkefeld, M. Krane, R. Lange, and B. Voss, "Left ventricular assist devices—current state and perspectives," *Journal of Thoracic Disease*, vol. 8, pp. E660–E666, 08 2016. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4999658/

[13] R. Gianluca, S. Francesco, and F. Giuseppe, "Past and present of cardiocirculatory assist devices: a comprehensive critical review," *Journal of Geriatric Cardiology*, vol. 9, pp. 389–400, 01 2013.

[14] M. S. Slaughter, J. G. Rogers, C. A. Milano, S. D. Russell, J. V. Conte, D. Feldman, B. Sun, A. J. Tatooles, R. M. Delgado, J. W. Long, T. C. Wozniak, W. Ghumman, D. J. Farrar, O. H. Frazier, and H. I. Investigators, "Advanced heart failure treated with continuous-flow left ventricular assist device," *The New England Journal of Medicine*, vol. 361, p. 2241–2251, 12 2009. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/19920051/

[15] M. Morshuis, A. El-Banayosy, L. Arusoglu, R. Koerfer, R. Hetzer, G. Wieselthaler, A. Pavie, and C. Nojiri, "European experience of duraheart™ magnetically levitated centrifugal left ventricular assist system," *European Journal of Cardio-Thoracic Surgery*, vol. 35, p. 1020–1028, 06 2009. [Online]. Available: https://academic.oup.com/ejcts/article/35/6/1020/473475

[16] J. K. Kirklin, D. C. Naftel, R. L. Kormos, L. W. Stevenson, F. D. Pagani, M. A. Miller, K. L. Ulisney, J. T. Baldwin, and J. B. Young, "Second intermacs annual report: More than 1,000 primary left ventricular assist device implants," *The Journal of Heart and Lung Transplantation*, vol. 29, p. 1–10, 01 2010. [Online]. Available: https://www.jhltonline.org/article/S1053-2498(09)00821-3/fulltext

[17] J. Garbade, H. B. Bittner, M. J. Barten, and F.-W. Mohr, "Current trends in implantable left ventricular assist devices," Cardiology Research and Practice, 05 2011. [Online]. Available: https://www.hindawi.com/journals/crp/2011/290561/

[18] R. Hetzer, T. Krabatsch, A. Stepanenko, E. Hennig, and E. V. Potapov, "Long-term biventricular support with the heartware implantable continuous flow pump," *The Journal of Heart and Lung Transplantation*, vol. 29, p. 822–824, 07 2010. [Online]. Available: https://www.jhltonline.org/article/S1053-2498(10)00148-8/fulltext

[19] J. A. LaRose, D. Tamez, M. Ashenuga, and C. Reyes, "Design concepts and principle of operation of the heartware ventricular assist system," *ASAIO Journal*, vol. 56, p. 285–289, 07 2010. [Online]. Available: https://journals.lww.com/asaiojournal/Fulltext/2010/07000/Design_Concepts_and_Principle_of_Operation_of_the.3.aspx

[20] G. M. Wieselthaler, G. ODriscoll, P. Jansz, A. Khaghani, and M. Strueber, "Initial clinical experience with a novel left ventricular assist device with a magnetically levitated rotor in a multi-institutional trial," *The Journal of Heart and Lung Transplantation*, vol. 29, pp. 1218–1225, 11 2010.

[21] C. f. D. Health and Radiological, "Heartmate 3 left ventricular assist system (lvas) - p160054/s008," *FDA*, 12 2019. [Online].

Available: https://www.fda.gov/medical-devices/recently-approved-devices/heartmate-3-left-ventricular-assist-system-lvas-p160054s008

[22] “Eddy current sensor : Operating principle and applications,” Bestech Australia, 12 2018. [Online]. Available: https://www.bestech.com.au/blogs/eddy-current-sensor-principle/

[23] “Maglev modeling - matlab simulink example - mathworks india,” in.mathworks.com. [Online]. Available: https://in.mathworks.com/help/deeplearning/ug/maglev-modeling.html

[24] “Msp430g2553 data sheet, product information and support — ti.com,” www.ti.com. [Online]. Available: https://www.ti.com/product/MSP430G2553

[25] “Acquire motor parameters motor resistance bemf constant read datasheet watch quick start video install gui try i 2 c communication connect motor power on launch gui configure closed loop current limit, lock detect pwm output, avs and fg options enable entering to closed loop enable configuration set the parameters configure startup setting disable closed loop speed control by gui exercise current control and protection fine tune start-up setting adjust lead angle to optimize efficiency exercise lock detect and avs function 1 st milestone motor spinning in open-loop 2 nd milestone motor speed control in closed loop drv10983 and drv10975 tuning guide user’s guide drv10983 and drv10975 tuning guide,” 2014. [Online]. Available: https://www.ti.com/lit/ug/slou395d/slou395d.pdf?ts=1625420789381&ref_url=https%253A%252F%252Fwww.google.com%252F#:~:text=The%20maximum%20resistor%20value%20(RPH_CT

Appendix A

PCB design

A.1 External components

Table A.1 shows the components required for the DRV10983-Q1 device to function.

Table A.1: PCB components

Component	**PIN 1**	**PIN 2**	**Specifications**
C1	VCC	GND	10-µF ceramic capacitor rated for VCC
C2	VCP	VCC	0.1-µF ceramic capacitor rated for 10 V
C3	CPP	CPN	10-nF ceramic capacitor rated for VCC × 2
C4	VREG	GND	10-µF ceramic capacitor rated for 10 V
C5	V3P3	GND	1-µF ceramic capacitor rated for 5 V
C6	V1P8	GND	1-µF ceramic capacitor rated for 5 V
C7	DVCC	GND	0.1-µF ceramic capacitor
C8	RST	GND	2200-pF ceramic capacitor
C10	VCC	GND	(DNP) 10-µF ceramic capacitor rated for VCC
C11	PLL	GND	470-pF ceramic capacitor
C9	VCC	GND	0.1-µF ceramic capacitor rated for VCC
D1	VSource	VCC	Schottky diode rated for 30 V, 2 A
L1	SW	VREG	47-µH ferrite rated for 1.15 A (inductive mode)
R1	FG	V3P3	4.75-kΩ pullup to V3P3
R2	SDA	V3P3	4.75-kΩ pullup to V3P3
R3	SCL	V3P3	4.75-kΩ pullup to V3P3
R4	SPEED	GND	4.75-kΩ pulldown
R5	DIR	GND	4.75-kΩ pulldown
R6	DVCC	RST	47 kΩ
R10	FG	FG	Jumper

A.2 Complete schematic diagram

Figure A.1 shows the schematic diagram for the PCB designed.

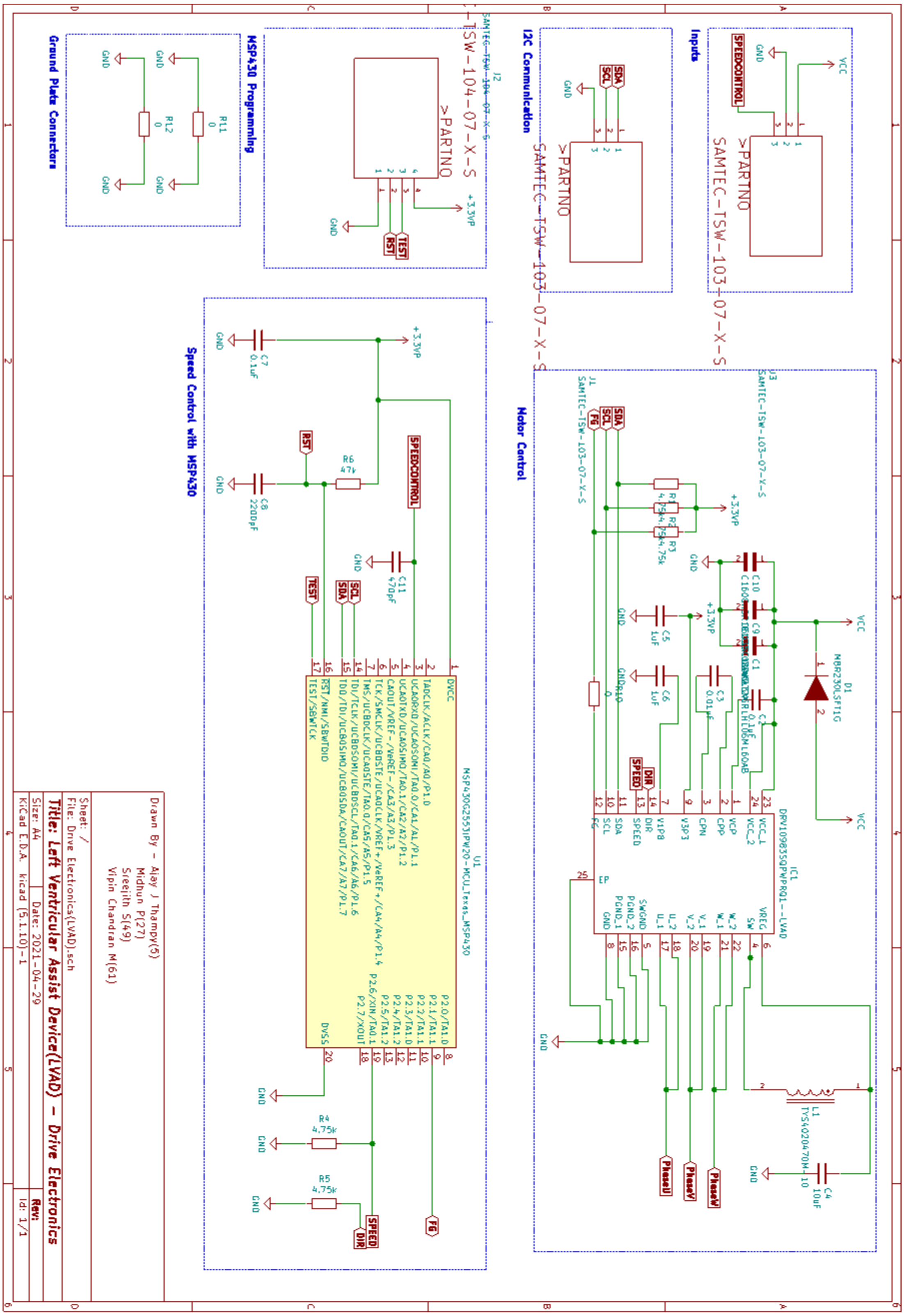

Figure A.1: Drive Electronics PCB Schematic

A.3 PCB layout

Figure A.2 and Figure A.3 show the layout of the PCB designed and the 3D view respectively.

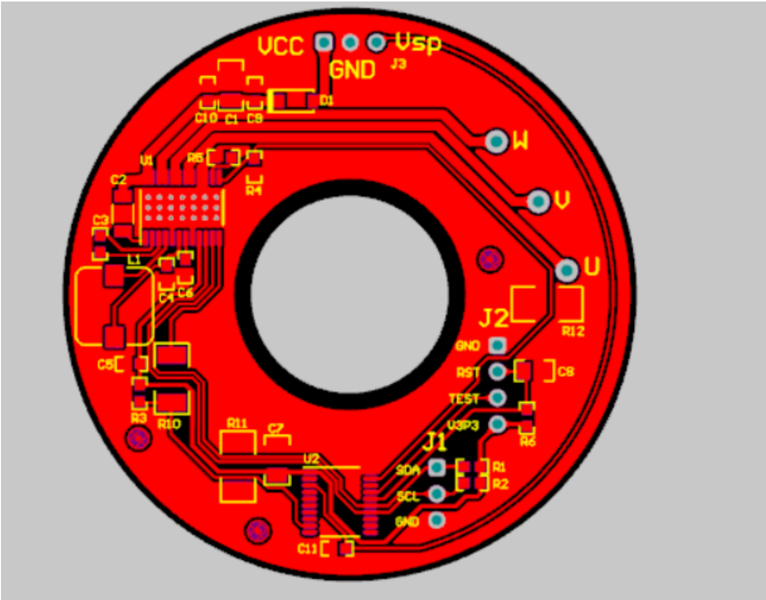

Figure A.2: Drive Electronics PCB Layout

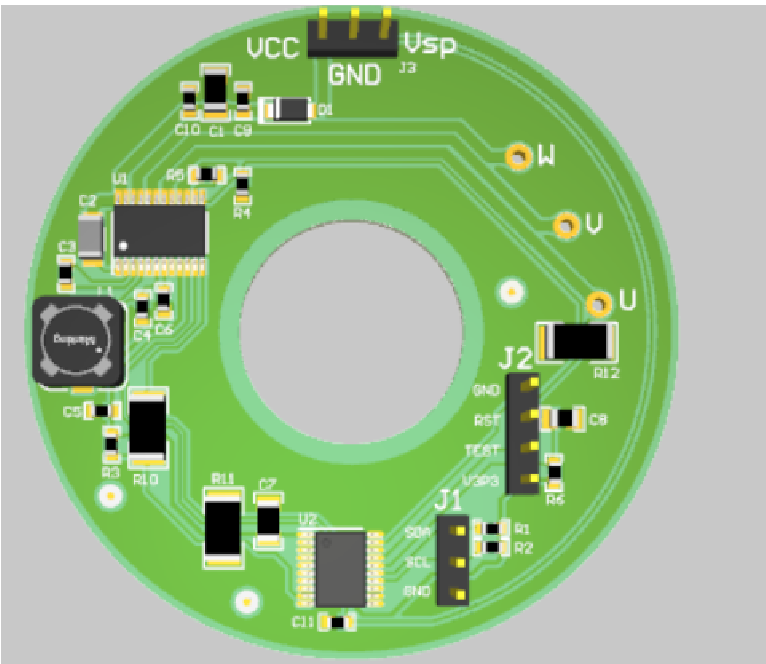

Figure A.3: Drive Electronics PCB 3D view

Appendix B

I2C communication

B.1 I2C Basics

I2C (Inter-Integrated Circuit) is a short distance serial interface that requires only 2 bus lines for data transfer: a serial data line (SDA) and a serial clock line (SCL). Any data sent from one device to another goes through the SDA line, whereas the SCL line provides the necessary synchronization clock for the data transfer. The devices on an I2C bus are either Masters or Slaves. Only a Master can initiate a data transfer and Slaves respond to the Master. It is possible to have multiple Masters on a common bus, but only one could be active at a time. The SCL clock line is always driven by the master. Slaves can never initiate a data transfer but they can transfer data over the I2C bus, and that is always controlled by the Master [5].

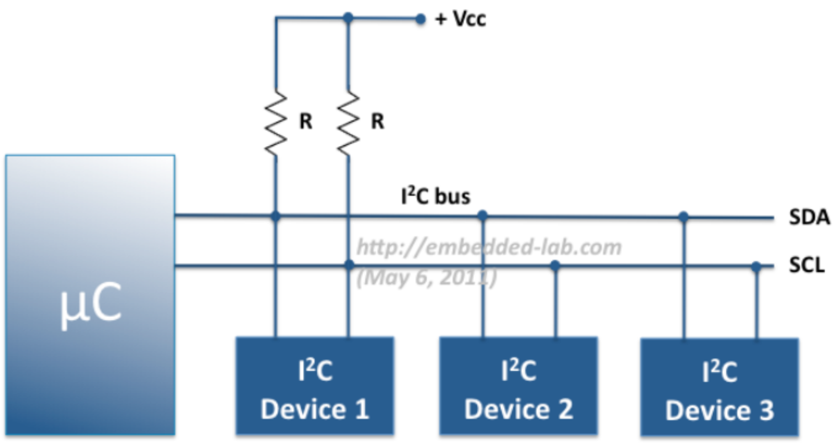

Figure B.1: Multiple devices on common I2C bus [5]

B.2 I2C Serial Interface

- DRV10983-Q1 provides an I2C slave interface with slave address 1010010.
- A pullup resistor of 4.7kΩ to 3.3V for I2C interface ports SDA & SCL.

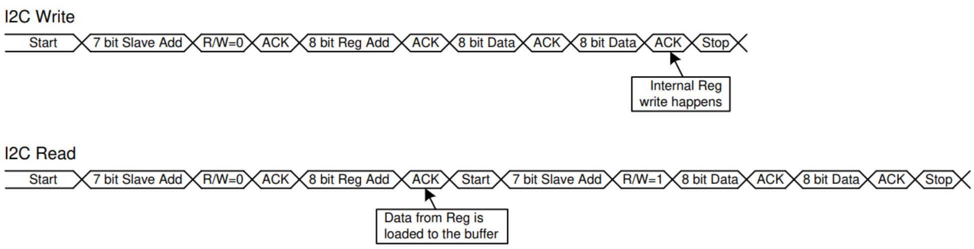

Figure B.2: I2C Protocol

- Seven read/write registers (0x30 : 0x36) are used to set motor speed and control device registers and EEPROM.
- Device operation states can be read back through nine read-only registers (0x00 : 0x08).
- Seven EEPROM registers (0x90 : 0x96) can be accessed to program motor parameters and optimize spin-up profile for application.
- Each register address is 8 bit with 16 bit data.
- Unused register addresses are:
  - 0x010 through 0x2F
  - 0x37 through 0x5F
  - 0x61 through 0x8F
- The description of each registers in their respective pin values are provided in the DRV10983 data sheet [2].

Appendix C

Additional details on ICs used

C.1 DRV10983-Q1

DRV10983-Q1 has 112 bits (7 registers with 16-bit width) of EEPROM data, which are used to program motor parameters using the I2C interface as described in Appendix B.1. The 24-Pin HTSSOP of the device with Exposed Thermal Pad detailing pin configuration and application schematic view is shown in Figure C.1.

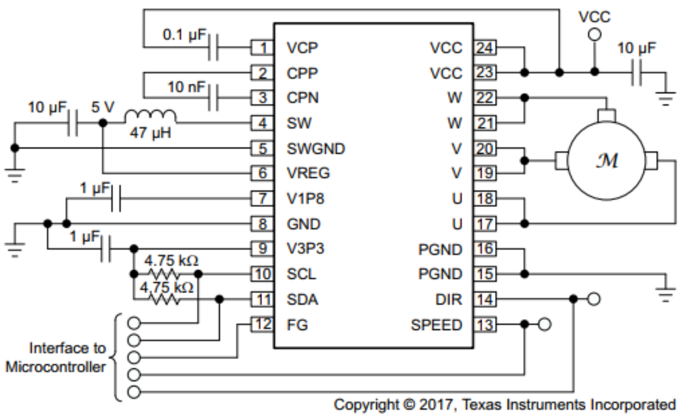

Figure C.1: Application Schematic [6]

As shown in the functional block diagram (Figure C.2) given below, the DRV10983-Q1 device includes a step-down hysteretic voltage regulator that can be operated as either a switching buck regulator using an external inductor or as a linear regulator using an external resistor. The best efficiency is achieved when the step-down regulator is in buck mode hence we have used external inductor of 47uH [6]. The DRV10983-Q1 device includes a 3.3-V LDO and a 1.8-V LDO. The 3.3-V LDO is powered by VREG and 1.8-V LDO is powered by 3.3-V LDO [6]. The 1.8-V LDO is for internal circuits only. The 3.3-V LDO is mainly for internal circuits, but can also drive external loads only upto a specified limit.

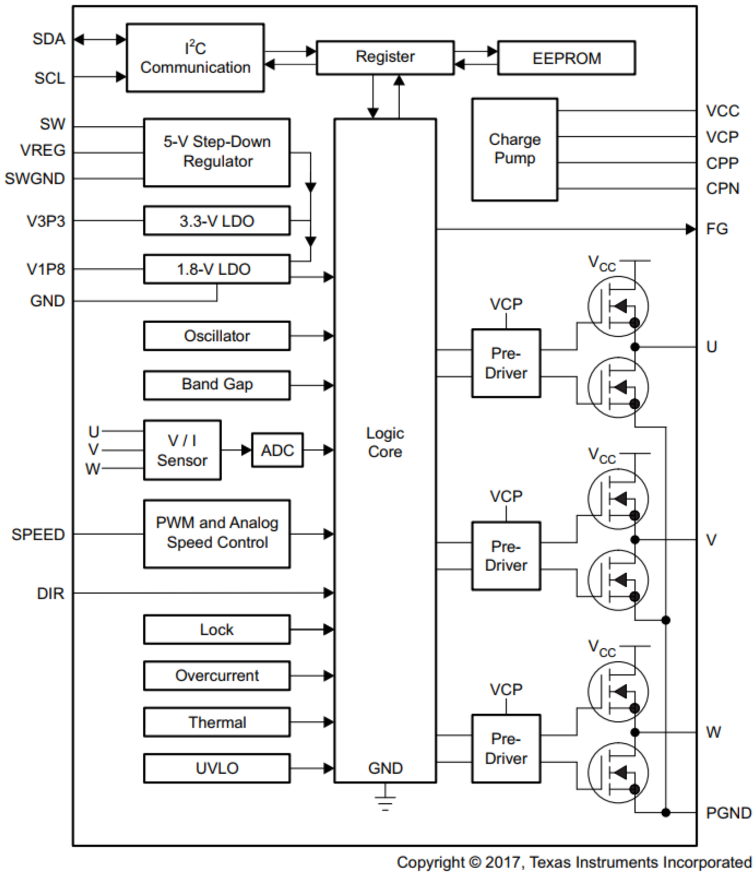

Figure C.2: Functional Block Diagram [6]

VREG serves as a stepdown regulator and feedback point. EEPROM is integrated as memory for motor parameters and operation setting. It also transfers data to registers after power ON and exit from sleep mode. This device can operate in Register Mode i.e if a system includes a MCU communicating through I2C interface, then the device can dynamically update parameters and operation settings by writing to registers in such situation the EEPROM data is bypassed by register setting. The device includes **Protection Circuits** such as:

- **Thermal shutdown :** Quick shutdown is enabled in case of high temperature beyond specified limit. OverTemp status bit (0x00, bit 5) is set, TempWarning bit of FaultReg register (address 0x00, bit 14).

- **Undervoltage Lockout (UVLO) :** Comes into account when VCC is below a specified value.

- **Overcurrent Protection :** It sets the OverCurr status bit of FaultReg register (0x00, bit 11).

- **Lock :** This protection comes into play when the motor is stopped by an external load or force, then it momentarily stops driving to avoid overheating and other damages.

This IC offers 4 methods of indirectly controlling speed by adjusting output voltage amplitude by (i) Varying Supply VCC (ii) Controlling Speed Command by PWM input, Analog input and command issued directly through the I2C port [6].

C.2 MSP430G2553

MSP430 family of ultra-low-power microcontrollers consists of several devices featuring different sets of peripherals targeted for various applications. The architecture, combined with five low-power modes, is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency [7]. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1 μs [7]. Figure C.3 shows an overview of the MSP-EXP430G2 hardware.

The MSP430G2553 series are ultra-low-power mixed signal microcontrollers with built-in 16-bit timers, up to 24 I/O capacitive-touch enabled pins, a versatile analog comparator, and built-in communication capability using the universal serial communication interface [7]. In addition, the MSP430G2553 family members have a 10-bit analog-to-digital ADC Figure C.4 shows the pinout of the MSP430G2553 20-pin N (PDIP) package. Typical applications include low-cost sensor systems that capture analog signals, convert them to digital values, and then process the data for display or for transmission to a host system.

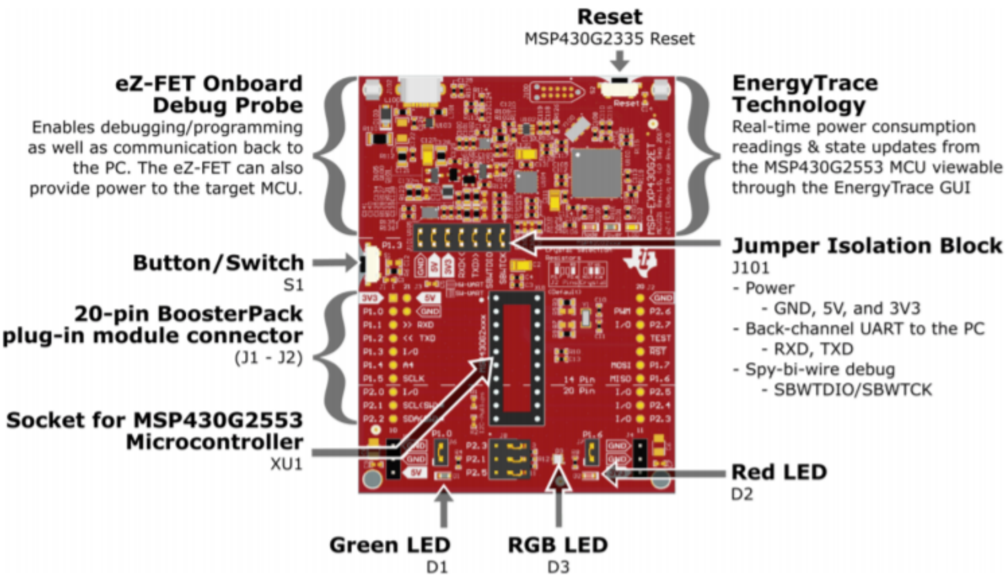

Figure C.3: MSP430 overview [7]

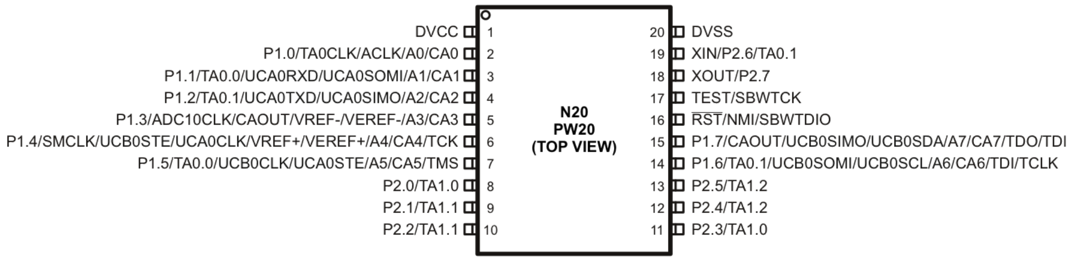

Figure C.4: MSP430G2553 20-Pin N Package (Top View) [7]

MSP430G2553 device features include:

- Low Supply-Voltage Range: 1.8 V to 3.6 V.
- 16-bit RISC architecture up to 16-MHz system clock.
- 16KB of flash memory and 512 bytes of SRAM.
- 8-channel comparator.
- Two 16-bit timers with three capture/compare registers (Timer_A).
- One universal serial communication interface (USCI_A) supports UART, IrDA, and SPI.
- One USCI (USCI_B) supports SPI and I2C.

Table C.1: MSP430G2553 parameters [7]

Parameters	**Specification/Details**
Non-volatile memory (kB)	16
RAM (KB)	0.5
ADC	10-bit SAR
GPIO pins (#)	24
Features	Spy-bi-wire, Watchdog timer, Real-time clock
UART	1
USB	No
Number of I2Cs	1
SPI	2
Comparator channels (#)	8

C.3 SA160

The SA160 is a pulse width modulation amplifier that can supply 10A continuous current to the load. The full bridge amplifier can be operated over a wide range of supply voltages. All of the drive/control circuitry for the lowside and highside switches are internal to the hybrid. The PWM circuitry is internal as well, leaving the user to only provide an analog signal for the motor speed/direction, or audio signal for switchmode audio amplification. The internal PWM frequency can be programmed by an external integrator capacitor. Alternatively, the user may provide an external TTL compatible PWM signal for simultaneous amplitude and direction control for four quadrant mode. Figure C.5 shows the block diagram of SA160 IC [8].

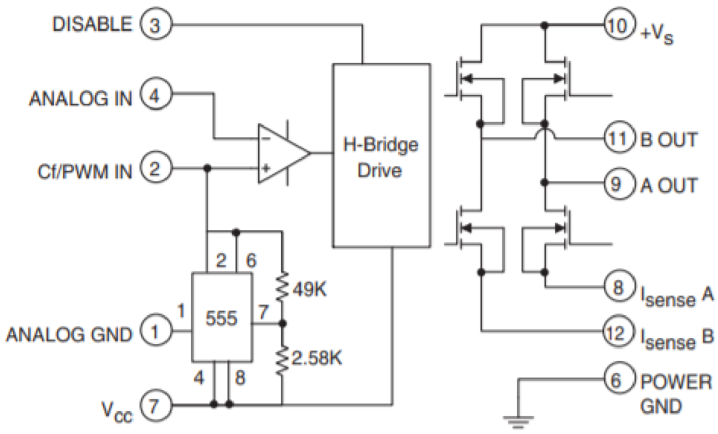

Figure C.5: SA160 IC block diagram [8]

A wide variety of loads can be driven in either the voltage mode or the current mode. The most common applications (Figure C.6) use three external blocks: a low pass filter converting pulse width data to an analog output, a difference amplifier to monitor voltage or current and an error amplifier. Filter inductors must be suitable for square waves at the switching frequency (laminated steel is generally not acceptable). Filter capacitors must be low ESR and rated for the expected ripple current [8]. A difference amplifier with gain of less than one translates the differential output voltage to a single feedback voltage. Dashed line connections and a higher gain difference amplifier would be used for current control. The error amplifier integrates the difference between the input and feedback voltages to close the loop.

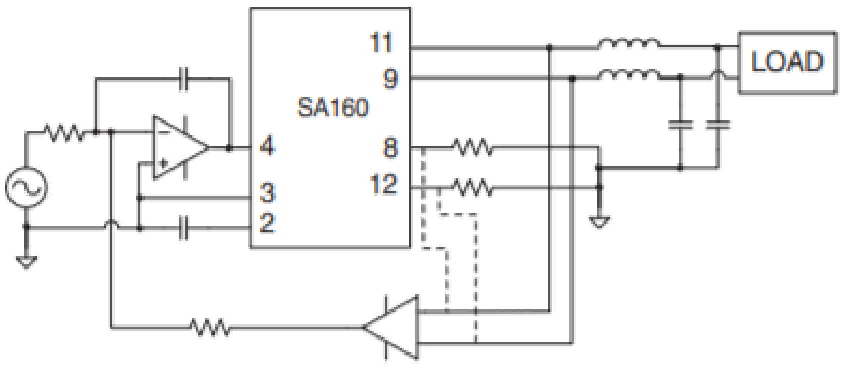

Figure C.6: SA160 IC application [8]

SA160 IC features include:

- Low cost complete H-bridge.
- Self contained smart low-side/high-side drive circuitry.
- Wide supply range (up to 80 V).
- 10A continuous output.
- Isolated case allows direct heat sinking.
- Four quadrant operation, torque control capability.
- Internal/programmable PWM frequency generation

Appendix D

Drive electronics programs in CCS

D.1 main.c

```
int main(void) {
/*** STOP WATCHDOG TIMER ***/
WDTCTL = WDTPW  WDTHOLD;

    /*** INITIALIZE MSP430G2553 CLOCKS ***/
BCSCTL1 = CALBC1_8MHZ; /* Set DCO to 8MHz Clock Speed */
DCOCTL = CALDCO_8MHZ; /* Set MODx to 3 -> 8MHz Clock Speed */
BCSCTL1 = DIVA_0; /* ACLK/(0:1,1:2,2:4,3:8) */
BCSCTL2 = DIVS_0; /* SMCLK/(0=1,1=2,2=4,3=8) */

    /*** INIT ROUTINES ***/
GPIO_init(); /* Initialize all the ports on the MSP430 */
TIMER_init(); /* Initialize the Timer for the buttons */
TIMER_delay(10000); /* Delay for 10ms before startup */
/*** WRITE CONFIG REGISTERS ***/
REGISTERS_parseRegData(); /* Go make 16 bit reg data 8 bit I2C compatible */
PROGRAM_writeDRV10983Q1eePromRegs(); /* follow data sheet instructions to
program the DRV10983Q1 */
```

```
/*** INTIALIZE INPUT AND OUTPUT CONTROLS ***/
ADC_init(); /* Initialize ADC10 */
PWM_init(); /* Initialize PWM Output */

while (1)
{
SPEED_CONTROL(); //Run speed control loop
}
}
```

D.2 RegisterValues.h

```
#ifndef TIDA_01496_SEATVENTILATION_REGISTERVALUES_H_
#define TIDA_01496_SEATVENTILATION_REGISTERVALUES_H_
#include msp430.h
#include"msp430G2553.h"
#defineREG_50_DATA_1 0x0000
#defineREG_50_DATA_2 0x0000
#defineREG_51_DATA_1 0x0000
#defineREG_51_DATA_2 0x0000
#defineREG_62_DATA 0x0000
#defineREG_30_DATA 0x0000//Resetsdigitalspeedinputcommand
#defineREG_90_DATA 0x0049//0x015B
#defineREG_91_DATA 0x2D3A//0x393C
#defineREG_92_DATA 0x0044//0x0C40
#defineREG_93_DATA 0x118F//0x2397
#defineREG_94_DATA 0x3FDF//0x3A0D
#defineREG_95_DATA 0xB030//0xBC03
#defineREG_96_DATA 0x097A//0x0969

#defineREG_50_DATA_1 0xB3F9
#defineREG_50_DATA_2 0x3A6C
```

#defineREG_51_DATA_1 0xA84B

#defineREG_51_DATA_2 0x7F3C

#defineREG_62_DATA 0x001F

#endifTIDA_01496_SEATVENTILATION_REGISTERVALUES_H_

D.3 Register.c

#include "TIDA_01496.h"

/*** Global variables ***/

uint8_t ge_ConfigRegAddress[NUMCONFIGREGS] = { 0x50, 0x50, 0x51, 0x51, 0x62, 0x30, 0x90, 0x91, 0x92, 0X93, 0x94, 0x95, 0x96};

uint16_t ge_ConfigRegData[NUMCONFIGREGS] = { REG_50_DATA_1, REG_50_DATA_2, REG_51_DATA_1, REG_51_DATA_2, REG_62_DATA, REG_30_DATA, REG_90_DATA, REG_91_DATA, REG_92_DATA, REG_93_DATA, REG_94_DATA, REG_95_DATA, REG_96_DATA};

uint8_t ge_Reg_Write_Data_Parsed[NUMCONFIGREGS][3];

uint8_t ge_Reg_Read_Data_Parsed[NUMCONFIGREGS][2];

D.4 SpeedControl.c

Tuning Speed Levels :

//PI Loop

Error = SPEED_INPUT/Scale - SPEED_MEASURED; //

Up = Kp * Error;

Ui = Ui + Ki * Up + Kc * SatError;

OutPreSat = Up + Ui;

//Bounds error if too large or small, otherwise,

if (OutPreSat > 1060) //Where 1060 is the max error for driving CCR1

{

Out = 1060;

}

```
else if (OutPreSat < 0 )
{
Out = 0;
}
else
{
Out = OutPreSat;
}
SatError = Out - OutPreSat; //Error is determined for next cycle
if (Speed_Level == 0) //Avoid dividing by 0
{
CCR1=0;
}
else
{
NEW_SPEED = Out;
CCR1 = NEW_SPEED; //PI Loop output speed
// CCR1 = ADC_Value ; //Used for testing speed levels
// CCR1 = 1060; //Fixing output speed by fixing PWM duty cycle
}
```

Implementation of Scaled SPEED_INPUT :

```
void SPEED_CONTROL(void)
{
ADC_Value = SampleADC();
if (ADC_Value <= 50) {Speed_Level = 0;}
else if (ADC_Value > 50 && ADC_Value <=205) {Speed_Level = 1;}
else if (ADC_Value >205 && ADC_Value <=409) {Speed_Level = 2;}
else if (ADC_Value >409 && ADC_Value <=614) {Speed_Level = 3;}
else if (ADC_Value >614 && ADC_Value <=818) {Speed_Level = 4;}
else if (ADC_Value >818 && ADC_Value <=1023) {Speed_Level = 5;}
else {Speed_Level = 5;}
```

```
if (Prev_Speed_Level != Speed_Level)
{
switch (Speed_Level){
case 0:
SPEED_INPUT = 0;
Scale = 6.5; //Scale = SPEED_MEASURED/(CCR1), needed to adjust dynamic range
break;
case 1:
SPEED_INPUT = 352;
Scale = 6.5;
break;
case 2:
SPEED_INPUT = 593;
Scale = 6.5;
break;
case 3:
SPEED_INPUT = 781;
Scale = 6.5;
break;
case 4:
SPEED_INPUT = 922;
Scale = 6.5;
break;
case 5:
SPEED_INPUT = 1024;
Scale = 6.5;
break;
default:
break;
}
Prev_Speed_Level = Speed_Level;
}
```