DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DESIGN AND IMPLEMENTATION OF AN ELECTROMAGNETIC ACTUATION SYSTEM FOR STRUCTURAL RESPONSE CONTROL

by
Güray GENİŞ

July, 2019
İZMİR

DESIGN AND IMPLEMENTATION OF AN ELECTROMAGNETIC ACTUATION SYSTEM FOR STRUCTURAL RESPONSE CONTROL

A Thesis Submitted to the
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In Partial Fulfillment of the Requirements for the Degree of Master of Science of Mechatronics Engineering

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M.Sc THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"DESIGN AND IMPLEMENTATION OF AN ELECTROMAGNETIC ACTUATION SYSTEM FOR STRUCTURAL RESPONSE CONTROL"** completed by **GÜRAY GENİŞ** under supervision of **PROF.DR. ZEKİ KIRAL** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

Prof. Dr. Zeki KIRAL

Supervisor

Dr. Öğr. Üyesi Murat AKDAĞ

(Jury Member)

Dr. Öğr. Üyesi Barış Oğuz GÜRSES

(Jury Member)

Prof.Dr. Kadriye ERTEKİN

Director

Graduate School of Natural and Applied Sciences

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Güray GENİŞ

DESIGN AND IMPLEMENTATION OF AN ELECTROMAGNETIC ACTUATION SYSTEM FOR STRUCTURAL RESPONSE CONTROL

ABSTRACT

Vibration is a major problem in industry from household appliances to aerospace applications including satellite solar panels. Un-controlled vibration can lead to undesirable results such as broken welding joints, loose fixtures, lose of comfort of user. This kind of vibration can be taken under control by using active or passive devices. Passive devices such as dampers and shock absorbers are simple solutions but they cannot adapt themselves to the dynamic response of the system when the system dynamics are subject to a change. Also it is not possible to configure a passive absorber to manipulate the system's steady state final displacement. In contrast to passive devices active vibration suppression systems can adopt the variable system dynamics with the help of feedback control. In addition to this steady state position manipulation can be performed by using this control loop resulting with composite vibration suppression and displacement manipulation system.

Vibration can be sensed by measuring displacement, velocity or the acceleration. Measurement of displacement can be done by laser, ultrasonic or contact based instruments. Among these methods laser displacement measurement is the most suitable for the purpose because of its non contact nature does not alter the system dynamics. In this study vibration is suppressed by the help of magnetic field under the control of a closed loop system. The measured displacement values are evaluated by specially designed control electronics and the electromagnet coil is driven by the same board. This makes the system standalone and removes the traditional requirement of PC usage to perform vibration suppression task.

Keywords: Dynamic response, natural frequency, vibration suppression, cantilever beam, closed-loop control, manipulator

YAPISAL CEVAP KONTROLÜ İÇİN BİR ELEKTROMANYETİK TAHRİK SİSTEMİNİN TASARIMI VE UYGULANMASI

ÖZ

Titreşim problemi ev aletlerinden yapay uyduların solar panellerinin de içinde bulunduğu uzay-havacılık uygulamalarına kadar geniş alanda kendini gösteren endüstriyel bir problemdir. Kontrol altında tutulmayan titreşim kaynak noktalarının kırılması, parçaların gevşemesi veya kullanıcı konforunun kaybı gibi sonuçlara neden olabilir. Bu tip titreşimler aktif yada pasif bileşenler kullanarak kontrol altına alınabilir. Şok emiciler ve damperler gibi pasif bileşenler basit çözümlerdir ancak kendilerini sistemin değişen dinamik cevapların göre adapte edemezler. Aynı zamanda pasif bir sönümleyici yada şok emici sistemin denge durumundaki nihai yer değiştirmesini tayin etmek için konfigure edilemez. Buna karşılık aktif titreşim sönümleyici bileşenler, değişen sistem dinamiklerine karşı geri beslemeli bir kontrol stratejisi yardımı ile adapte olabilirler. Ek olarak denge durumu nihai yer değiştirmesi bu kapalı çevrim control sistemi kullanılarak gerçekleştirilebilir ki bu titreşim sönümleme ve manipulatörün bir arada olduğu bileşik bir sistemin ortaya çıkmasını sağlar.

Titreşim, deplasman, hız veya ivme ölçümü ile algılanabilir. Deplasman ölçümü laser, ultrasonik yada temaslı metodlar ile ölçülebilir. Tüm bu metodlar arasında laser deplasman ölçümü temassız olması nedeniyle sistem dinamiklerini etkilemediği için en uygun yöntemdir. Bu çalışmada bir ankastre kirişin serbest titreşimleri, kapalı çevrim bir kontrol sistemi yönetimindeki manyetik alan ile sönümlenmiştir. Ölçülen yer değiştirme değerleri özel tasarlanmış elektronik kontrol devreleri tarafından değerlendirilmiş ve elektromıknatıslar aynı devre kartı üzerinden sürülmüştür. Bu sayede sistem kendi başına çalışabilir hale gelmiş ve geleneksel olarak bir PC'yi titreşim sönümleme görevini yerine getirek için gereksiz kılmıştır.

Anahtar Kelimeler: Dinamik cevap, doğal frekans, titreşim sönümleme, ankastre kiriş, kapalı döngü kontrol, manipülatör

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CHAPTER ONE
INTRODUCTION

1.1 Introduction

Conventional mechanical systems are becoming smarter in terms of dynamic response characteristics as mechatronic structures are spreading in industrial field. Interaction of mechanics and electronics nowadays is not a big problem as the gap between them is rapidly closing. The basis of mechatronics approach is creating a common domain for mechanics and electronics. As the mechanics and electronics getting closer, mathematical theories and models are playing role of cement in order to stick them together. Mechatronical approach is solving major problems including active vibration suppression.

Vibration control systems are designed to suppress undesired oscillations (Grigorios, 2016). Vibration suppression problem is an important research field due to its industrial importance and this problem is widely studied in the literature (Kıral, 2008). Undesired vibration is a very common problem in traditional industrial processes as well as emerging new industrial applications. The span is beginning with everyday household appliances and reaching to aerospace applications. Vibration suppression is the common problem of a washing machine and an artificial communication satellite. As they share a common problem, this means that active vibration suppression has very wide application areas.

High amplitude un-controlled vibration can lead to undesirable results such as broken welding joints, loose fixtures, lose of comfort of user. If the system is allowed to vibrate in un-controlled manner the service life of the specific system is dramatically reduced. Vibration can be taken under control by using active or passive devices. Depending to the method used to suppress the vibration, total suppression or partially damping can be achieved. In general passive devices such as dampers and shock absorbers are simple solutions but they cannot adapt themselves to the dynamic response of the system when the system dynamics are subject to a change.

So this results with a partial damping in some specific frequencies and kinetic energy amplitudes.

In contrast to passive devices active vibration suppression systems can adopt themselves to the variable system dynamics with the help of feedback control. This opens the way to the complete vibration suppression even system parameters like frequency and kinetic energy amplitude are dynamically changing.

An active system can be configured to serve more than vibration suppression. Beyond the suppression, the system can be used in order to manipulate the steady state displacement of the controlled mechanics. A composite control system is implemented consisting of vibration suppression and cantilever beam displacement manipulator. By the help of composite system design simpler and a compact vibration suppression and displacement manipulation system can be realized.

In order to suppress vibration under the control of a closed loop system feedback line realization is a must. Vibration measurement can be done by several methods including displacement, acceleration or speed measurement. In this study displacement based measurement methodology is used. When measuring a system’s dynamic properties it is important not to alter system dynamic response characteristics. In other words the measurement instrument shall not inject or extract energy in any means. Some common techniques are laser, ultrasound, and linear potentiometer based techniques. Potentiometer is the worst technique among these methods as it requires considerable amount of force to move its slider when compared with the limited kinetic energy of structure to create this force. Ultrasound based technique is seems to be a non-contact method but it sends significant amount of energy with sound waves and this energy injection can alter the system natural response characteristics. Laser displacement measurement technique is based on time of flight method like ultrasonic devices but this time the instrument sends a light pulse instead of an ultrasonic wave. Of course none of the measurement principle is totally interaction free with the system. When compared with sound, the light burst has a very very tiny energy in sub atomic level, so in practical application it has no interaction on macro scale structures like a cantilever beam. For this reason a laser displacement measurement instrument is used in order to capture real time displacement of the structure.

In order to suppress vibration and manipulate system steady state position an actuator is needed. A non-contact electromagnet is designed to serve an actuator purpose. This actuator converts electrical current to magnetic field as stated by Faraday's Law of Induction. The induced magnetic field causes the mechanical beam to move. There is a direct relation between the applied current and the displacement of the beam. This makes the designed electromagnet an ideal actuator for vibration suppression.

A control system has to be placed in between of the sensor and the actuator to evaluate the sensor data and to drive the actuator. In previous studies readymade PC based data acquisition and data output modules are used in order to link the control algorithm running on PC with the sensor and actuator. This method is most of the time seems to be the easiest and the fastest method. But it brings many drawbacks as the control system is not in a uni-body form. Also the communication delays of the modules can lead to undesired response times and timing error. In addition, standalone application with a bulky PC is not so easy to move nor energy efficient.

To overcome these shortcomings, a standalone control circuit is designed to serve as an end to end control system. In this design an analog front end (AFE), analog to digital converter (ADC), microcontroller and an inductive load driver is included to realize a total end to end signal chain implementation. In addition to essential components some supporting peripherals are integrated. Signal waveform capture buffer, VGA display driver, local LCD for debug, USB 2.0 interface, auxiliary galvanically isolated I/O are the supporting peripherals of the design.

Finally in this study a complete standalone end to end vibration suppression system is realized. The system is tested on cantilever beam structures and vibration suppression and manipulating tasks are performed.

1.2 Problem Statement

Active vibration suppression on a cantilever beam structure was studied. In this study vibration suppression of a cantilever beam is realized using an electromagnetic suppression system. The experimental setup is shown in Figure 1.1. Vibration suppression problem is limited to the free vibration which started via an initial displacement. Studied cantilever beam is a band of a metal fixed in a vertical squeezer. This orientation makes the beam vibrates freely independent of gravity effect. Vibrations on this structure sustains more than 5 seconds as shown on Figure 1.2 with its natural frequency of 12.7Hz as shown on Figure 1.3. This study solves this vibration problem and can manipulate the beam to the desired position.

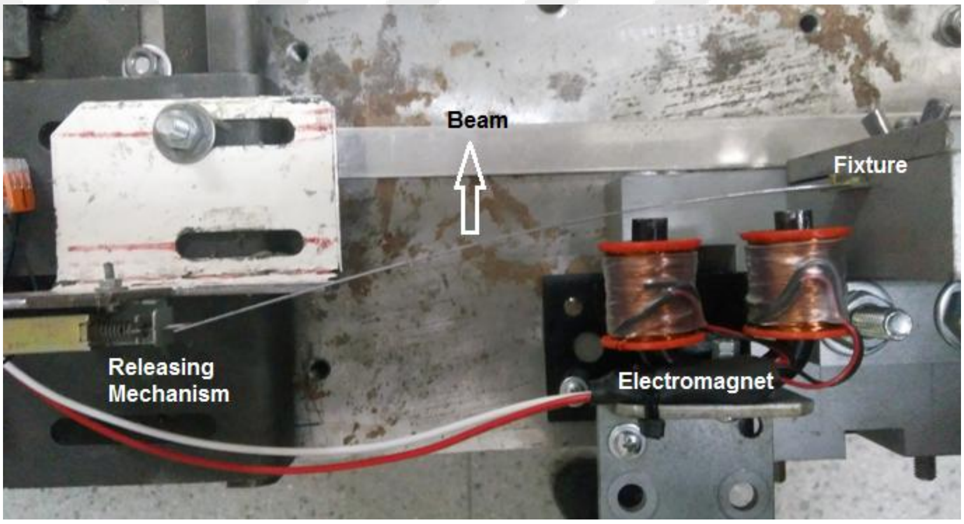

Figure 1.1 Experimental setup (Personal archive, 2019)

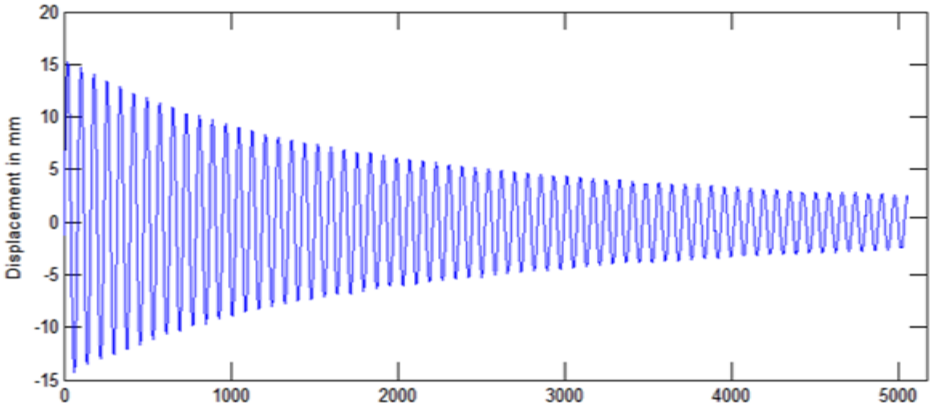

Figure 1.2 Free vibration response

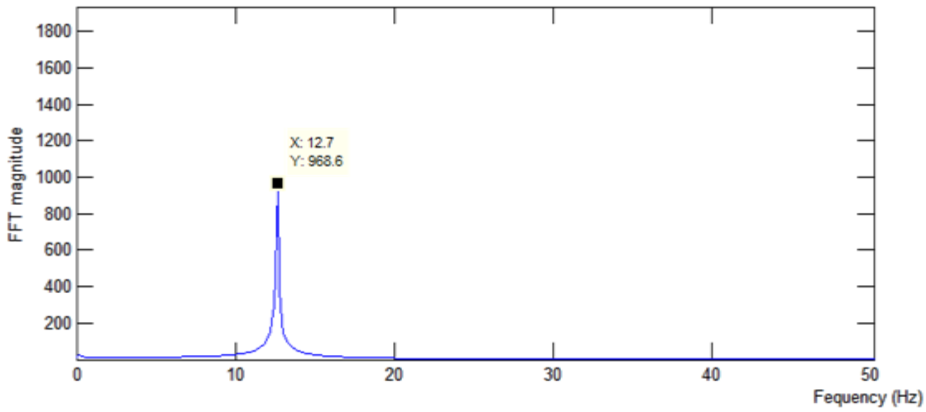

Figure 1.3 Free vibration frequencies

1.3 Motivation

Vibration suppression and displacement manipulation are the requirements of almost any dynamic mechanical system. If this requirement can be solved in a compact and composite method the needs of industry can be fulfilled by means of vibration suppression and position manipulation. If a vibration problem is ignored and related actions not taken in to account the results can be devastating. As known as this problem is a challenging among the scientific research field this study is based on the requirements of the real industrial problem.

1.4 Literature Survey

Vibration suppression is a very abundant field of research in the literature. The previous studies offer many alternative methods for the sake of vibration suppression and manipulation techniques. They have both advantages and disadvantages for the solution of vibration suppression problem.

Nature inspired way of approach suggests using micro-organism team algorithm to solve the vibration suppression problem in an optimum way. Swarm Optimization is one of the leading optimization method among the nature inspired techniques. This is called Particle Swarm Optimization (PSO) in the literature. PSO suggest a way to optimize physical displacements of particular individual in the swarm with decent algorithm of good balanced global and local exploration abilities. With this basic method particle swarm optimization can be used to solve vibration suppression problem on flexible structures (Marinaki, Marinakis, & Stavroulakis, 2008). Industrial systems and their revolution speed forces the researchers to to develop modern approaches to suppress vibration. Bang-bang control is another approach of vibration suppression control and can solve several basic vibration suppression problems (Geniş, & Kıral, 2019). This kind of control suggest controlling power totally either in on or off state. Fuzzy logic method can be used to solve complex industrial vibration problems. A fuzzy logic controller design can be derived by using fuzzy logic methodology to suppress vibration (Tairidis, Foutsitzi, Koutsianitis, & Stavroulakis, 2016). This much of opportunities open the way to the creation of smart composite structures. Combining an actuator and a sensor with the structure itself is the main phenomena of smart structures. Using piezoelectric materials can serve both sensor and actuator purpose on the surface of smart composite structures to suppress undesired vibration in a smart way (Marinaki, Marinakis, & Stavroulakis, 2008). Cantilever beam structures are very common structure example that can be found in aerospace applications. These structures are subject to very high level of amplitude undesired vibration and these vibrations cannot be naturally damped in the reasonable time periods. Shape memory alloy can be used to solve the vibration problem when they are constructed as an actuator (Vishal, Kaliperumal & Padhi, 2018). Also passive vibration suppression methods can be applied by using magnetomechanical coating to enhance materials for a high damping capacity (Yen, & Shen, 1999).

Baea, Kwakb & Inman, (2004) studied vibration suppression by using magnetic field in terms of eddy current principle. If you move a electrically conductive material in a magnetic field eddy currents will start to flow inside the conductive material. As the conductive material is a closed loop for electrical current the induced voltage short circuited on the material. This causes the electrical energy to turn into heat and this created a resistance to the movement in the magnetic field. With this approach vibration can be suppressed.

There are many many approaches are listed in the literature. Most of them depend on readily available data interaction system like DAQ boards, Arduino, Raspberry Pi devices. Siddiqui, Ahmad, Khan, & Ahmad, (2015) used an Arduino board to control the experiment. Also they used a separate driving electronics, actuator and sensor interfaces. Their method does not use a single board end to end solution.

1.5 Objective of Thesis

This study attempts to design a complete single board end to end system to suppress vibrations and make steady state displacement manipulations on cantilever beam structures.

The objectives and milestones of the road map of the study as follows:

- Literature survey to investigate the roots of the vibration problem and common methods for vibration suppression.
- Collecting the basics of cantilever beam structures.
- Simulations of beam on SolidWorks software.
- Simulations of electromagnet actuator on ANSYS software.
- Choosing right materials for experiment.
- Beam production.
- Electromagnet producing.
- Testing and verifying electromagnet's mechanical and electrical parameters.
- Designing electronic circuit board.
- Producing electronic circuit board.
- Testing and verifying electronic circuit board's electrical and performance parameters.
- Primary cold tests for overall system functionality.
- Bang-bang control algorithms implementations and tests.
- Theoretical background study and implementations on the application.
- Advanced control strategy theory development for real world demands.

- Proportional control algorithms implementations and tests.
- Manipulator algorithms implementations and tests.
- Optimization for the industrial demands.

CHAPTER TWO

MATERIAL AND METHOD

2.1 Experiment Overview

The mechanical section of the experimental setup consists of one cantilever beam and initial condition trigger. Electronic section includes a laser displacement sensor, a specially designed electronic control board PCB, a power supply, a VGA monitor as a dashboard and finally electromagnet coil as a main actuator. An overview of the experiment setup can be seen on figure 2.1.

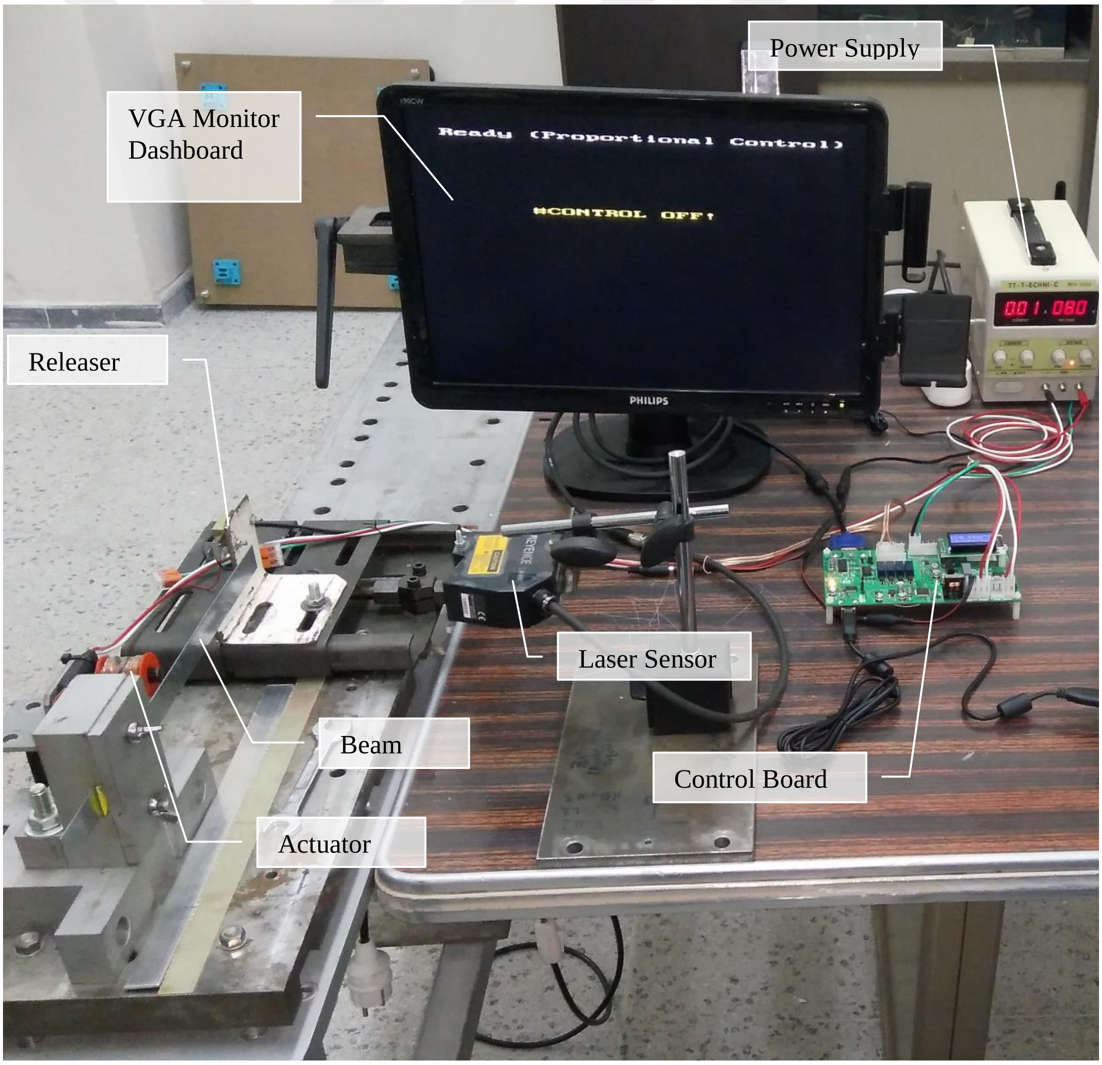

Figure 2.1 Experimental setup overview (Personal archive, 2019)

2.2 Actuator Design

Actuator is responsible for making mechanical movements on a mechanism or system. Basically an actuator uses an external energy source and transforms this energy in form of a mechanical movement. The mechanical movement can be linear, rotary. In some cases the profile of the movement can be in any form of a mathematical expression like sine function as the way crank based actuators behavior. The output of actuator can be a mechanical part like a linear rod or a rotary shaft. The designed actuator does not have an output device; in contrast to traditional actuators this design uses the body of the target mechanism as an output media. This property of the actuator allows making actuations without altering the dynamic properties of the beam that needs to be actuated.

2.2.1 Actuator Design Simulations

Prior to start actuator production, design verifications and if needed modifications need to me done primarily. Actuator is mainly constructed on U type electromagnet specially designed for this purpose. Design simulations including magnetic flux density, flux vectors distribution and electromagnetic energy transfer focal point analysis are done in ANSYS® software. The 2D simulation results are exported in figure form. Magnetic flux generated by the designed electromagnet is represented on Figure 2.2.

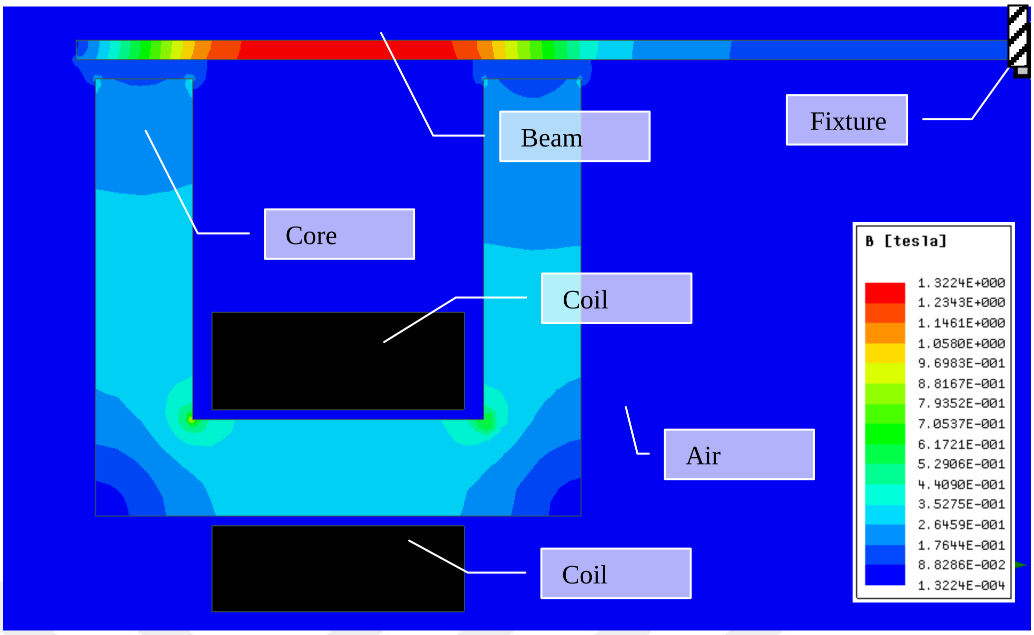

Figure 2.2 Magnetic flux density obtained by Ansys® simulation

Magnetic flux lines generated by the designed electromagnet are represented on Figure 2.3. As the flux travels across the beam and the core the lines become denser.

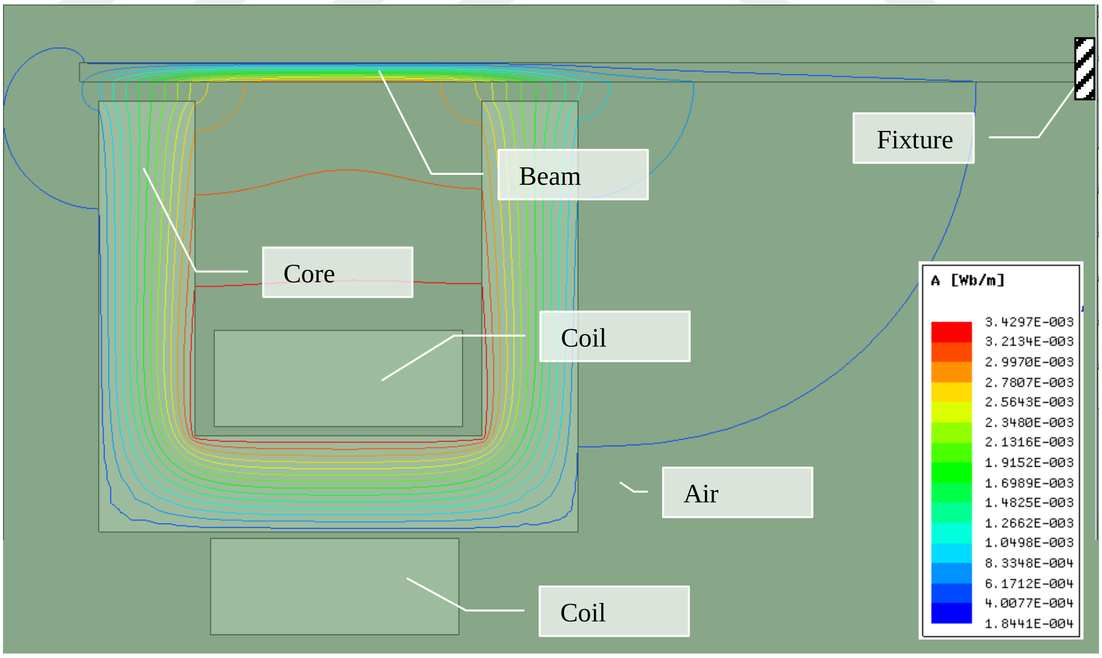

Figure 2.3 Magnetic flux lines obtained by Ansys® simulation

Magnetic field strength visualized on Figure 2.4. Most of the strength is accumulated on the beam.

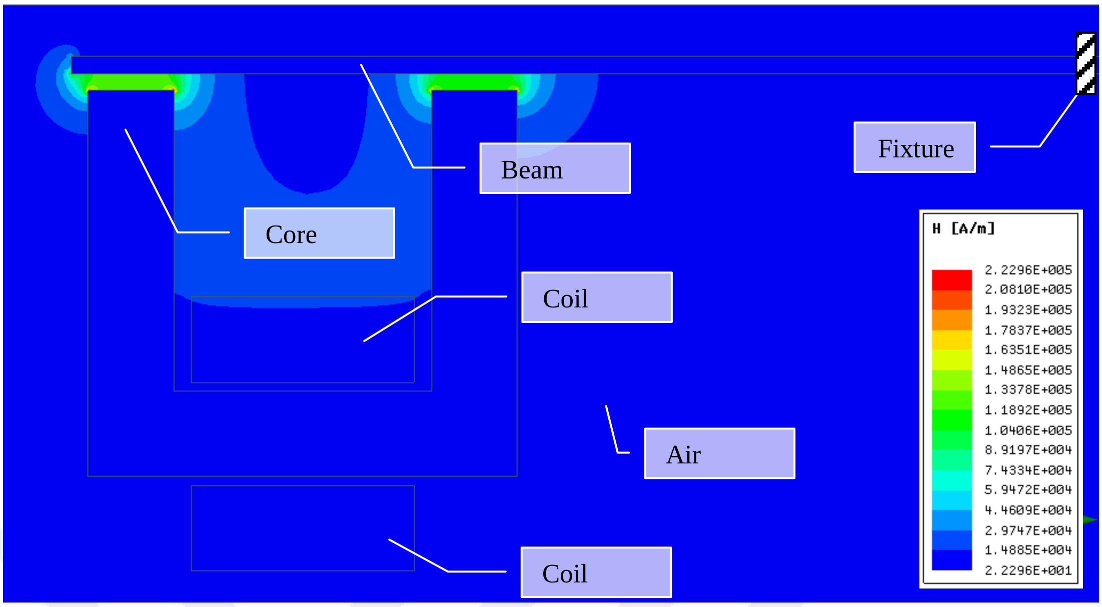

Figure 2.4 Magnetic field strength obtained by Ansys® simulation

Magnetic flux vectors generated by the designed electromagnet are represented on Figure 2.5. The vectors with biggest magnitude are directed on the beam.

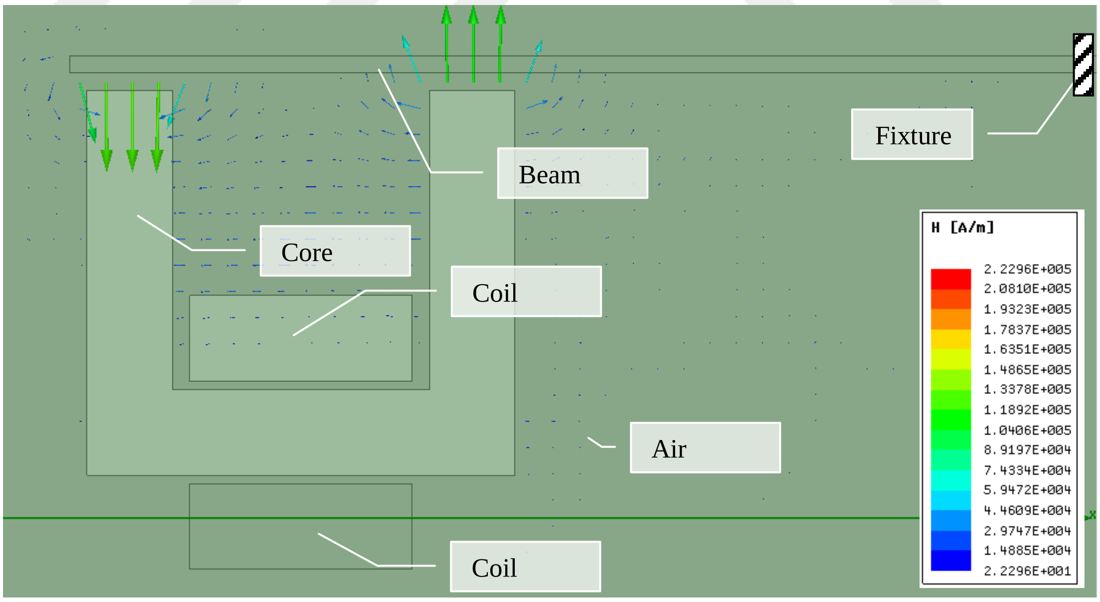

Figure 2.5 Ampere per meter flux vectors obtained by Ansys® simulation

Magnetic flux energy generated by the designed electromagnet are represented on Figure 2.6. The energetic focal volumes are focused on the beam. Thus the electromagnet is capable to direct the actuation energy to the beam without any major energy loss.

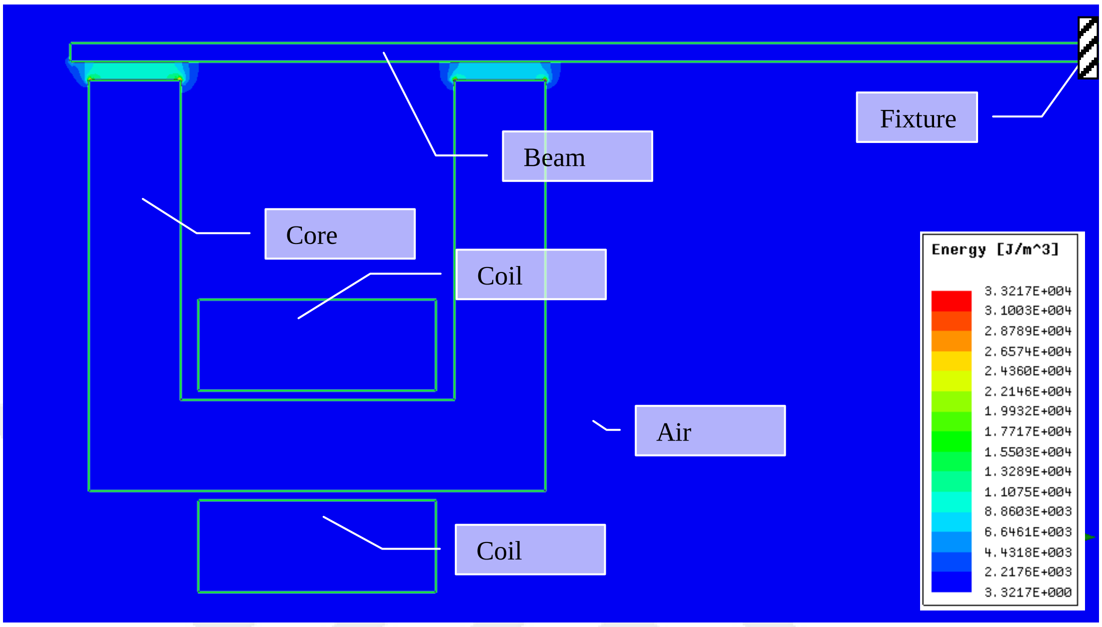

Figure 2.6 Energy Transfer focal points obtained by Ansys® simulation

2.2.2 Actuator Design Parameters

The desired parameters are determined after the simulation results. The parameters are listed in Table 2.1.

Table 2.1 Design parameters of coil.

Parameter	**Value**
Max DC Power	30 Watts
Magnetomotive Force	2x1100AmpTurn
Mechanical Force	1.7 Kg @ 1mm
DC Resistance	30 OHMs
Inductance	2.2H (Open Magnetic Loop In Air)
Core Type	Soft Iron “U” core
Core Diameter	10mm
Arm Length	50mm
Pole Distance	50mm
Turns	1100x2
Wire Diameter	0.8mm

2.2.3 Production of Actuator

Production of actuator can be divided into two main branches. Mechanical and electrical productions. After the simulation process the actual core materials are designed in SolidWorks® program. The 2D sketch of the core is given in Figure 2.7.

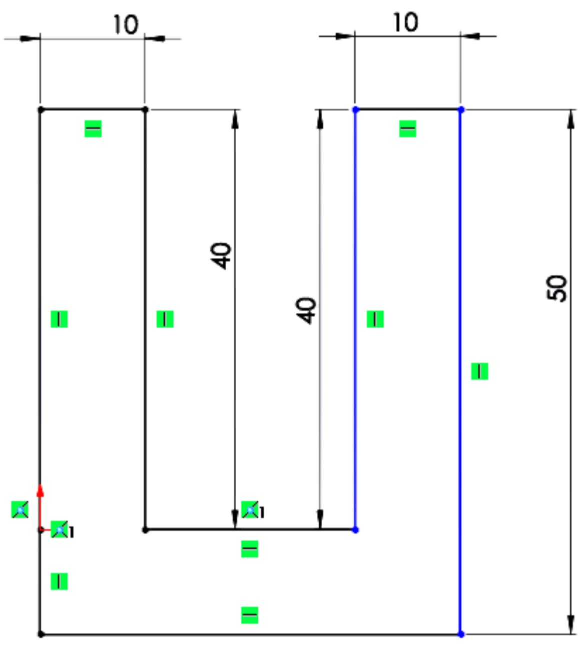

Figure 2.7 2D design of actuator core dimensions in mm

The 2D sketch is extruded and a 3D solid model is generated as seen on figure 2.8.

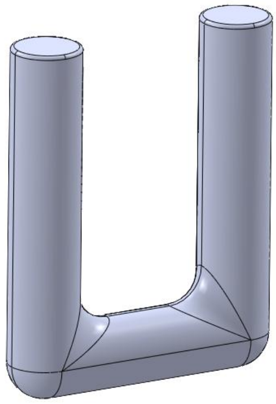

Figure 2.8 3D solid model of actuator core

After the core material design a bobbin holder slot is designed for housing 1100 turns of 0.8mm diameter enameled copper wire. 3D solid model of bobbin holder is shown on figure 2.9.

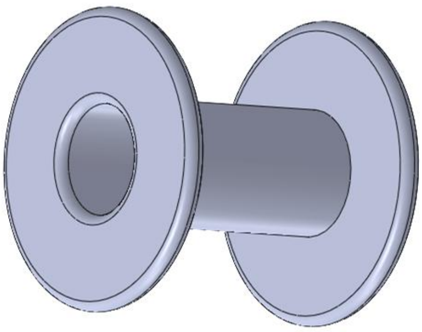

Figure 2.9 3D solid model of bobbin holder

Production of the bobbins of the actuator is done by an inductive sensor and a counter unit as shown on figure 2.10 and 2.11. Two bobbins are produced, each of them consist of 1100 turns of enameled wire as shown on figure 2.12.

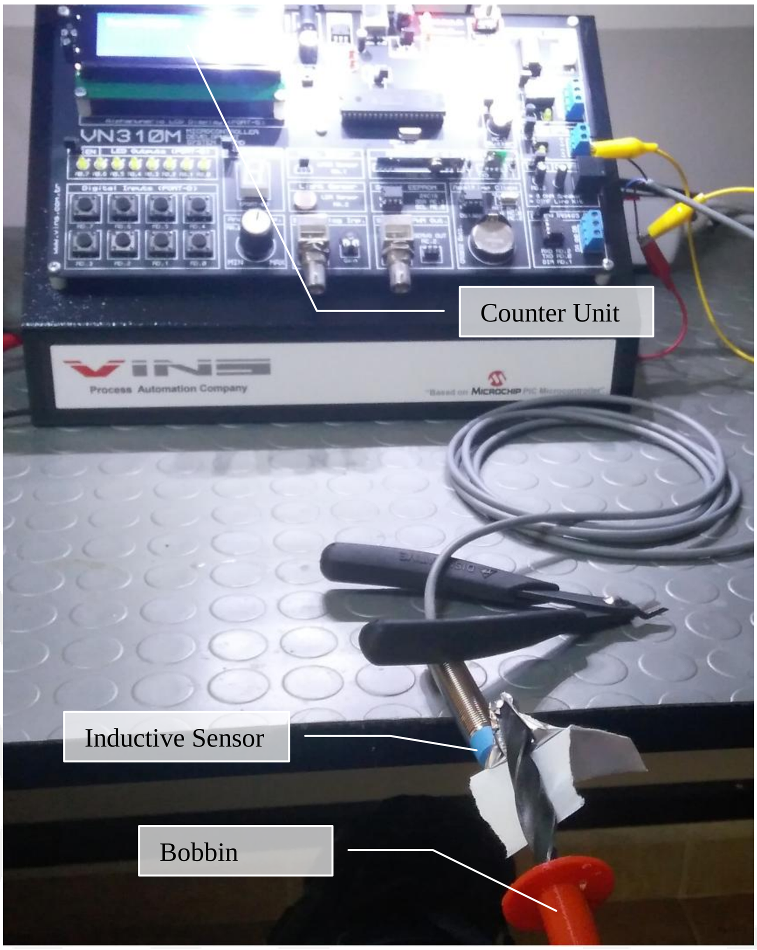

Figure 2.10 Bobbin winding bench (Personal archive, 2019)

Figure 2.11 Winding turns counter (Personal archive, 2019)

Figure 2.12 Finished single bobbin (Personal archive, 2019)

Finished bobbins are mounted on the core and electrical connections are made in serial form. Final look of the actuator electromagnet in figure 2.13 and its electrical circuit in figure 2.13.

Figure 2.13 Finished electromagnet (Personal archive, 2019)

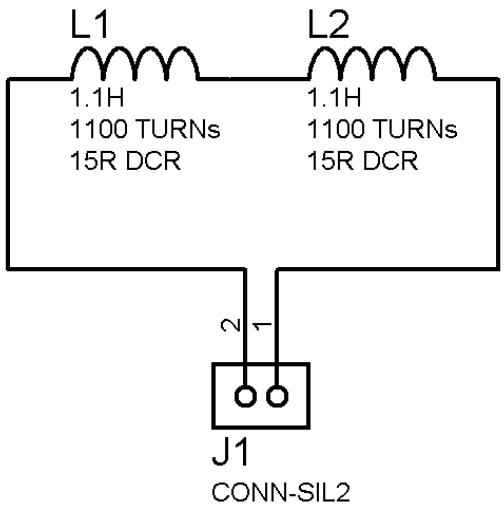

Figure 2.14 Electrical circuit of electromagnet

The produced electromagnet shown in Figure 2.13 needs to be tested in order to fulfill the requirements of the systems. The test setup of the electromagnet shown in Figure 8 and Figure 9 consists of a load cell, a ferromagnetic target, a power supply and a data acquisition and analysis system. A 30 kg full scale load cell with its parameters on Table2.2 shown in Figure 2.15 and VN830 data acquisition and analysis system shown in Figure 2.16 is used for data acquisition and analysis software shown in Figure 2.17.

Figure 2.15 Load cell

Table 2.2 Parameters of load cell

Combined error	%Emax	≤ ±0.05 ≤ ±0.02
Creep error over 30 min. (DR)	%Emax	0.012
Minimum load	%Emax	0
Maximum safe overload	%Emax	100
Maximum safe sideload	%Emax	100
Ultimate load	%Emax	150
Stretching (Emax)	mm	≤0.8
Maximum excitation voltage (Umax)	V	10
Rated output (Cn)	mV/V	2 ±0.1%
Zero balance	%Cn	≤ ±1.0
Input Resistance	Ω	409±6
Output Resistance	Ω	350 ±3.5
Insulation resistance	MΩ	≥500
Compensated temperature range	°C	-10...+40
Operating temperature range	°C	-40...+80
Load cell material		Aluminum
Sealing (EN60529)		IP55
Cable length	m	0.4±%3
Cable diameter	mm	4
Weight	kg	0.17
Package dimensions / weight	cm/kg	4x15x5 / 0.2

Figure 2.16 VN830 data acquisition and analysis system (Personal archive, 2019)

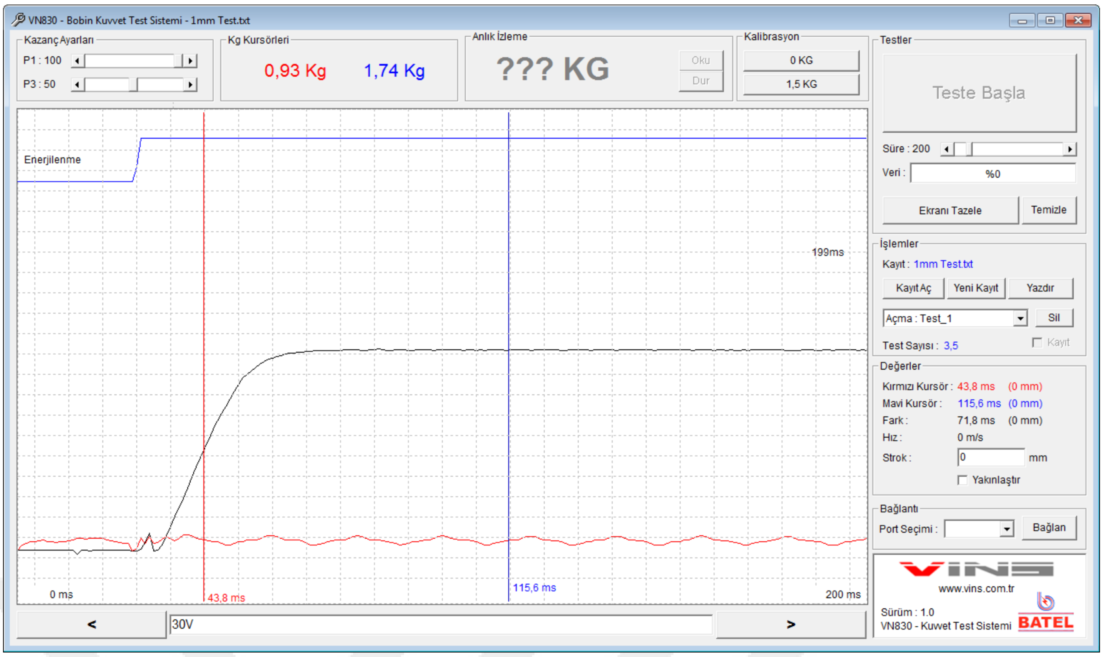

Figure 2.17 Data acquisition and analysis software

The electromagnet fixed to the test platform using a fixture and target plate is mounted on the load cell as shown in Figure 2.18. Using a complete test setup shown in Figure 2.19 measurements are done. In order to determine the behavior of the electromagnet voltage variation in constant distance and distance variation in constant voltage scenarios are evaluated.

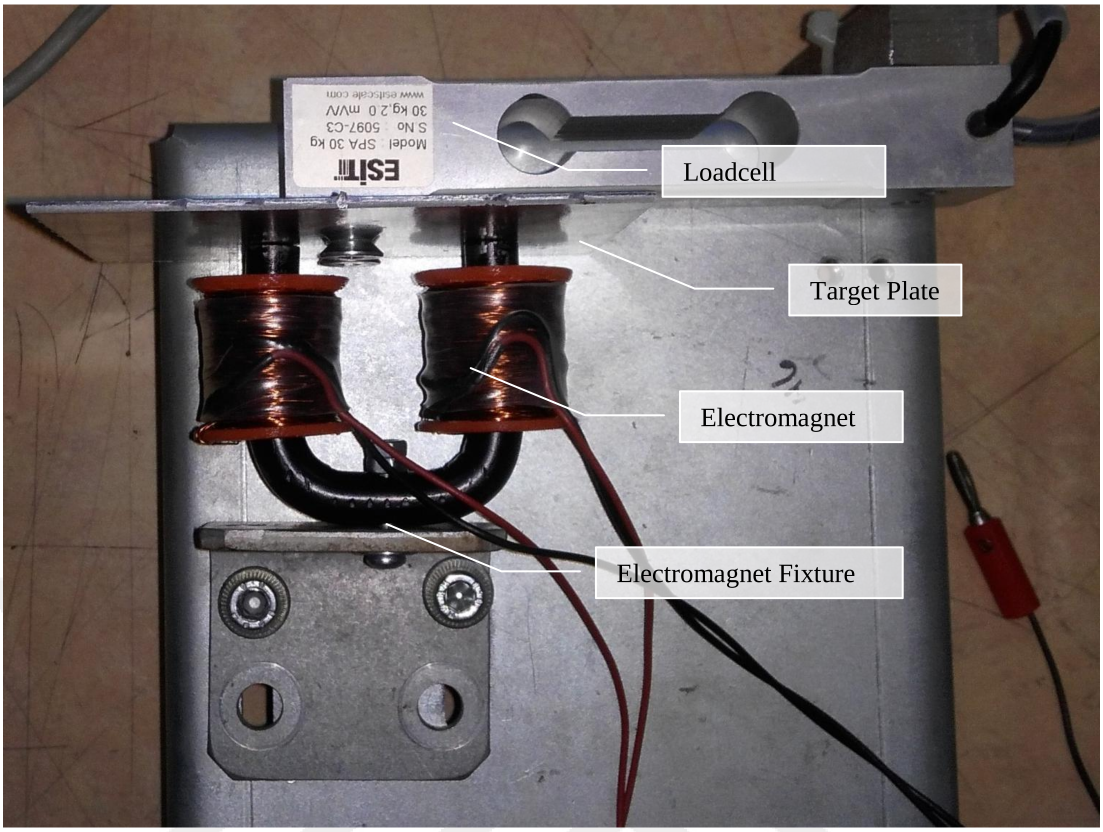

Figure 2.18 Load cell and electromagnet mountings (Personal archive, 2019)

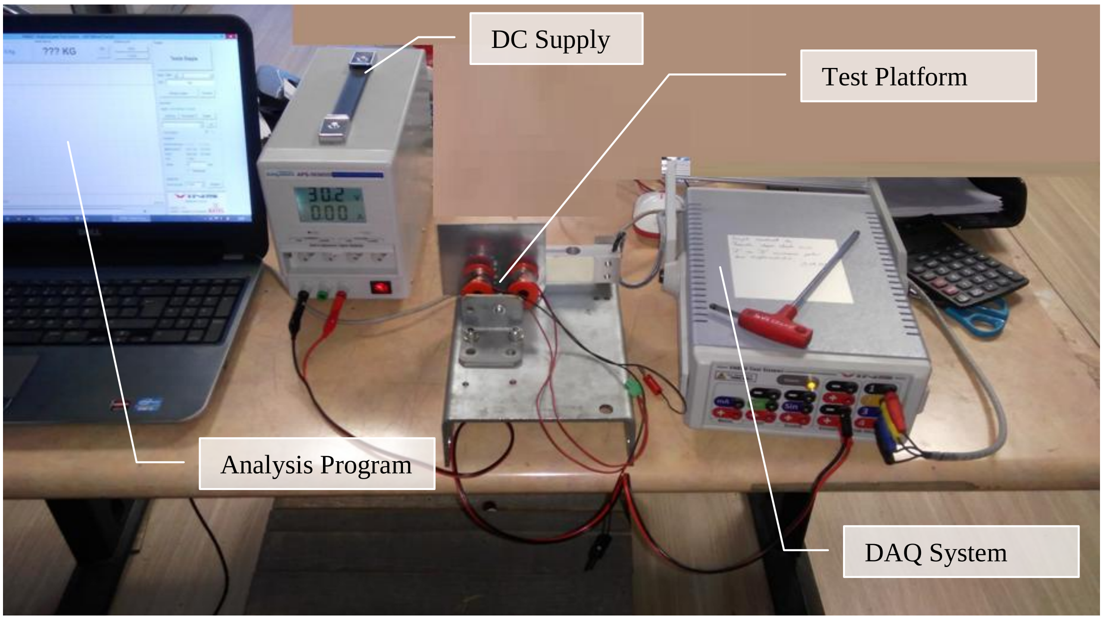

Figure 2.19 Complete test setup (Personal archive, 2019)

An approximate linear relation between force and applied voltage can be observed in the data plotted in Figure 2.20. The relation between target's distance and generated force is plotted in Figure 2.21.

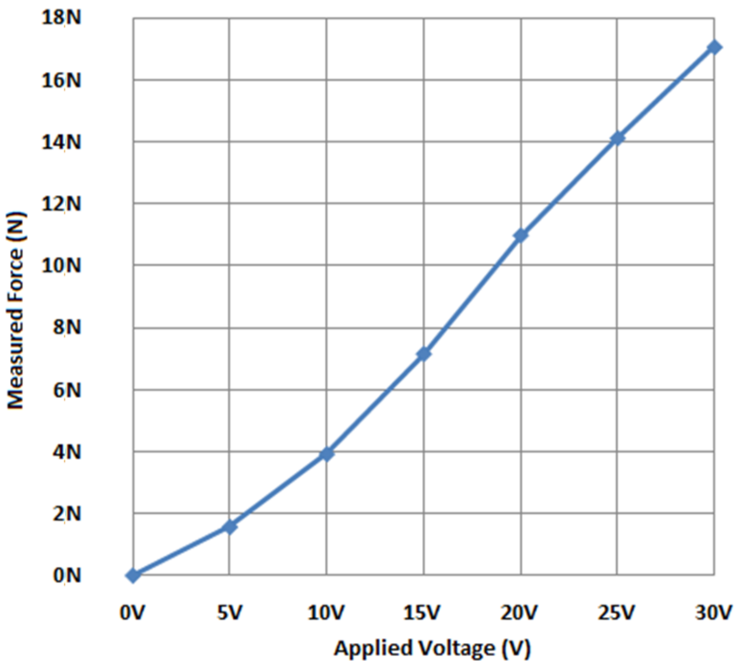

Figure 2.20 Voltage – force relation

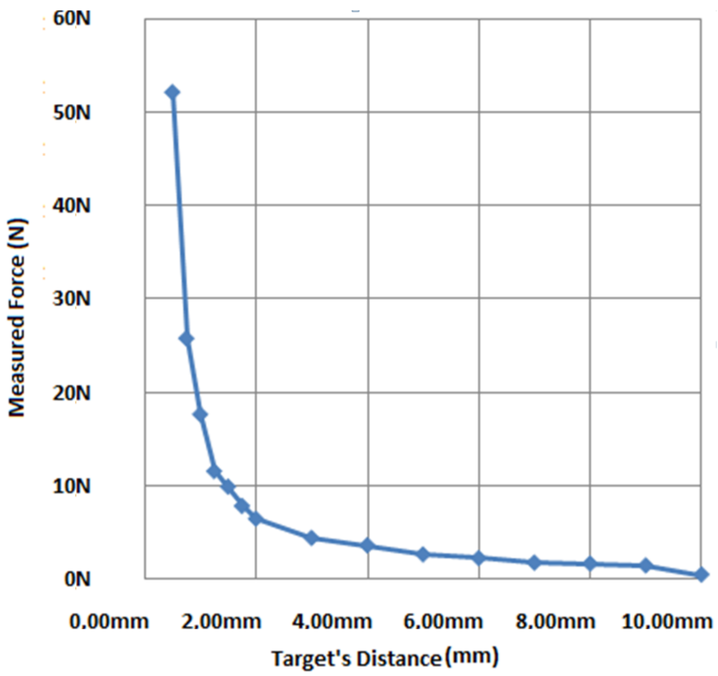

Figure 2.21 Distance – force relation

2.3 Electronic Control Unit (E.C.U.) Design

Realization of experimental setup is done by designing a special purpose end-to-end electronic circuit board and its firmware. By implementing this electronic circuit board, experiments become much more versatile and consistent. In classical approach of this kind of experiment shall consist of the followings;

- Data acquisition board (DAQ) for waveform capture.
- Releaser driver and power stage for releasing the beam.
- Actuator driver with advanced precise timing for controlling the power of the electromagnet actuator.
- Analog sensor front-end for reading data from the displacement sensor.
- DSP based analog signal processor to process data and create driving signals.
- USB data interface module to control the setup from PC.
- VGA driver system for visualization of dynamic values and system states.
- Relay and optically isolated I/O modules for interfacing setup with user in standalone mode.

Even collecting all those parts would not solve the problem immediately, further the experimenter shall make a huge effort to make this parts work in perfect harmony in order to serve a common purpose to realize the needs of the experiment. The designed circuit board hosts all of the hardware and software needed for experiments and standalone operation in its composition. First of all the expected capabilities of the ECU is listed as below.

- Single board end to end solution.
- 4 channel sensor interface (2 x Differential).
- 2 channel coil driver up to 180 watts of power delivery each coil.
- Analog front with onboard biasing and conditioning.
- Relay outputs and 4 optical inputs for galvanically isolated signalization.
- USB 2.0 full speed Interface.
- 10 MIPS microcontroller.

- VGA monitor output for dash boarding.
- EMC aware design.
- On-card referencing and biasing.
- 256Kbit Buffer for waveform capture.
- 2x8 Char LCD for local debug/info.

An overview of ECU is shown in Figure 2.22 as a fundamental units block diagram. Physical placement of the unit is also shown in Figure 2.23 with its realization is shown in Figure 2.24.

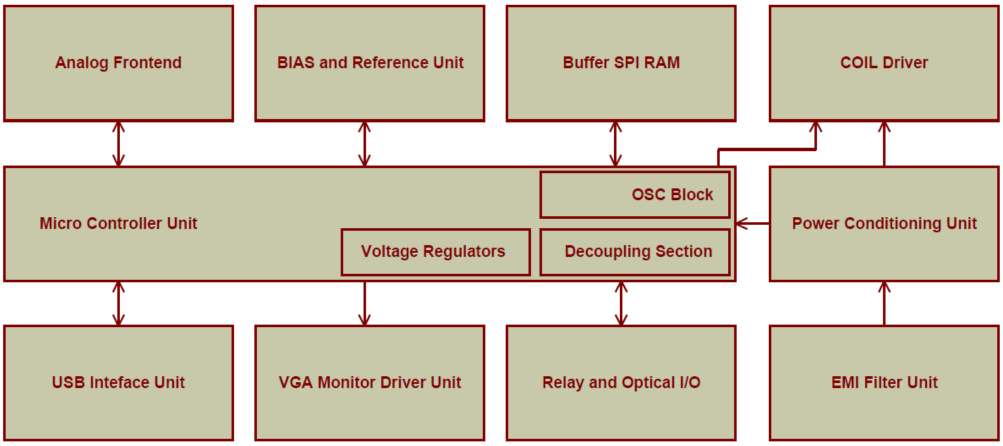

Figure 2.22 Functional block diagram of ECU

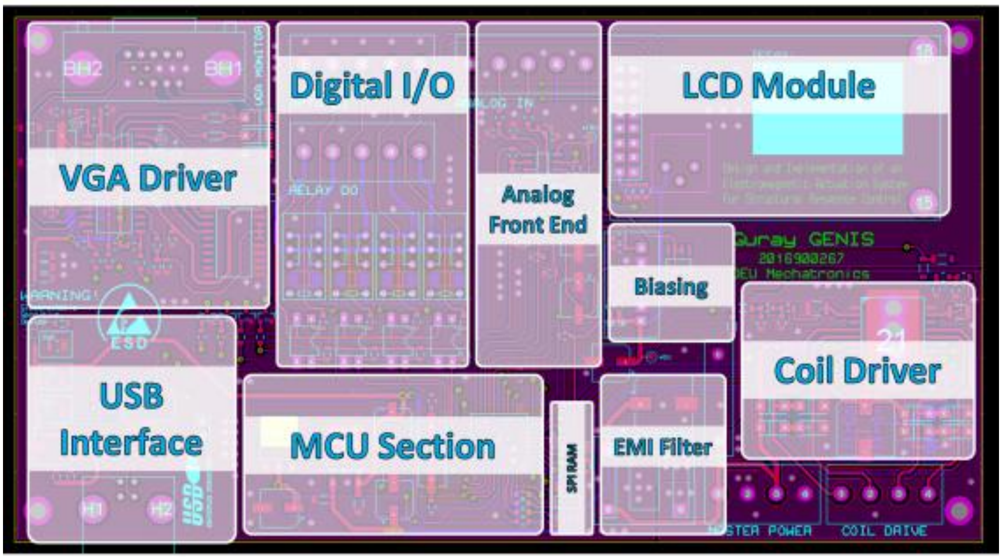

Figure 2.23 Physical locations of subunits on ECU

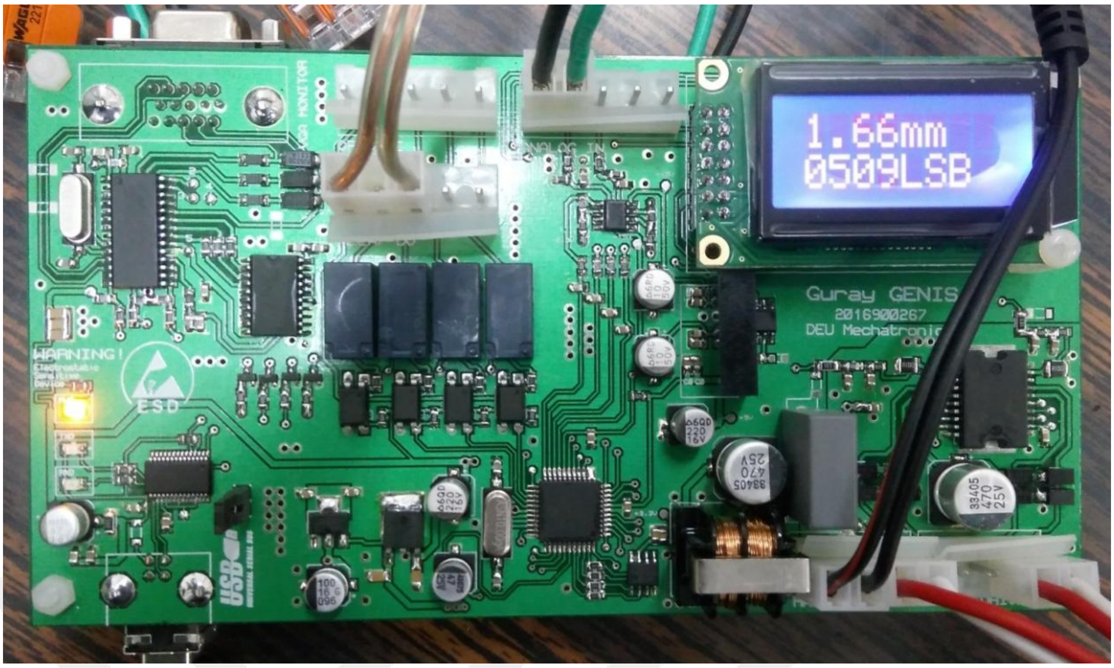

Figure 2.24 Finished outlook of ECU (Personal archive, 2019)

2.3.1 Power Conditioning Unit

This unit is responsible to deliver clean and ripple-free consistent power to the other units and peripherals of the board. An EMI capacitor and common mode inductive filter is used to eliminate EMI noise for the rest of the circuit. Input voltage range of the circuit is 9 to 30VDC. Total power consumption of the board is directly depends on the power delivering to the actuator. Thus there is no certain current requirement of the circuit. During experiments quiescent current is measured as 150mA when all peripherals including VGA monitor. Max measured current is 1.3Amperes. Power conditioning unit is designed using linear regulator topology via integrated temperature compensated reference based linear regulator ICs. The power conditioning unit capable of deliver required voltages to main +5V rail and +3.3V rail. Input of the circuit directly fed into a common mode EMI choke filter as in Figure 2.25 to eliminate high frequency conducted interference. Conjunction with a EMI capacitor module a input filter is constructed.

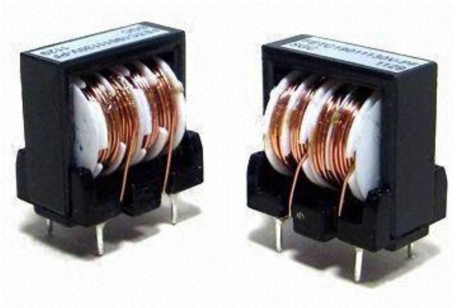

Figure 2.25 Commercial EMI common mode filters

An EMI filter is responsible to eliminate high frequency common mode signals like conducted interference. A typical common mode filter topology can be seen in Figure 2.26. As the same current passes through the single core double winding inductor they cancel out each other as stated in blue arrows in Figure 2.26.

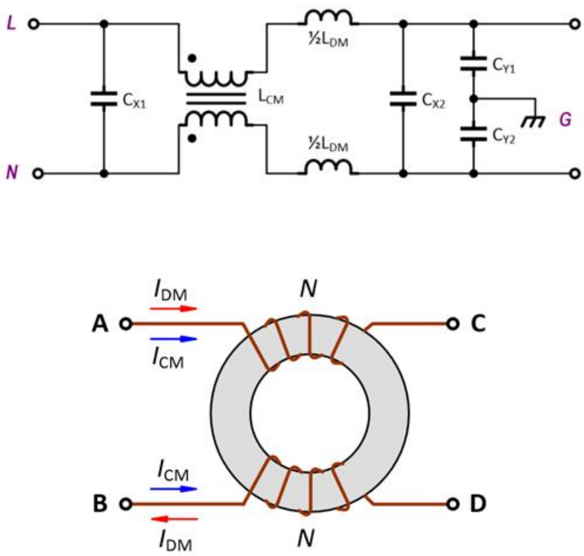

Figure 2.26 Typical common mode filter topology

After eliminating undesired signals from power supply the signal fed into capacitors in order to reduce ripple and make a reservoir for high power demand burst of the driver in the board. LM78M05 regulator IC is responsible for supplying +5VDC power rail up to 800mA on demand. LM78M05 that can be seen in Figure 2.27 is the surface mount DPAK version of traditional LM7805 regulator family that has been released first in 1969 (Atwell, 2018).

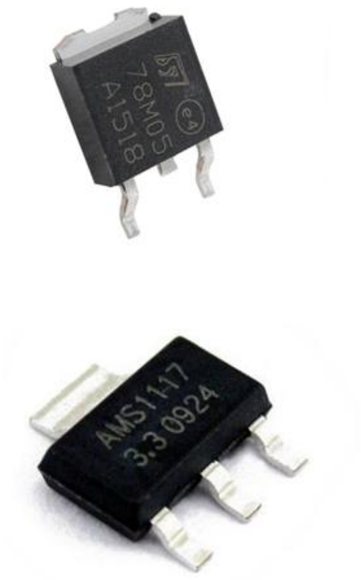

Figure 2.27 78M05 and AMS1117-3.3 IC in SMD packages

AMS1117-3.3 low drop out (L.D.O.) regulator IC is responsible for supplying +3.3VDC power rail up to 1A on demand. AMS1117-3.3 derives its power from +5VDC power rail. AMS1117 has 1.5V, 1.8V, 2.5V, 2.85V, 3.3V and 5.0V versions readily available. For our purpose 3.3V version is used. For the sake of integrity of the SMD design SOT223 version was chosen as seen on Figure 2.27.

2.3.2 Biasing and Voltage Reference Unit

This unit serves biasing purpose for the analog front end. The rail to rail voltage is 30VDC while positive rail is +15VDC and negative rail is -15VDC. This complies with symmetric supply voltage regulations required by analog frontend. An isolated DC/DC voltage converter MAU109 shown in Figure 2.28 is chosen to perform this purpose in the circuit. An isolated DC/DC converter is miniaturized form of a “DC Transformer”. It derives required power from +5VDC rail. It modulates the DC power in the form of AC power and drives a small transformer. Primary of the transformer is rated with the input voltage and the output is rated with the output voltage. In this configuration a center tapped transformer is used to generate symmetrical +/-15VDC analog power rails.

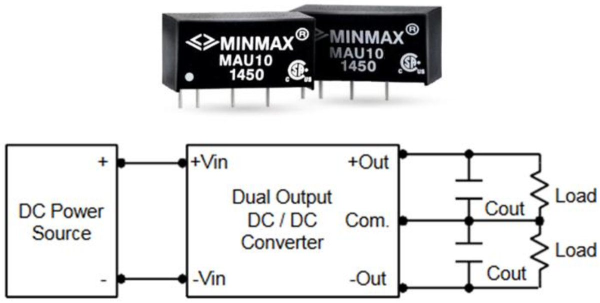

Figure 2.28 MAU109

Reference voltage is the key performance criteria in analog frontend designs. Reference voltage determines the offset, gain and amplification parameter of the analog circuit. Thus it has to be accurate, clean, ripple free, have low output impedance, and temperature independent. The analog frontend requires -2.5VDC reference voltage. TL431 IC is choosed to perform this duty. TL431 is a shunt voltage regulator designed to be forward biased. It uses internal bad-gap voltage reference to generate rock solid stable output voltage over in a wide temperature range with and output impedance as low as 0.2 Ω. TL431 is produced in three main grades. There are “Standard”, “A” and “B” grades. Standard grade has 2%, “A” grade has 1% and “B” grade has 0.5% error band. With this data “A” grade is chosen to fulfill the analog frontend requirements. TL431 in SO8 surface mount package can be seen in Figure 2.29 and its basic principle operation schematic in Figure 2.30.

Figure 2.29 TL431 in SO8 surface mount package

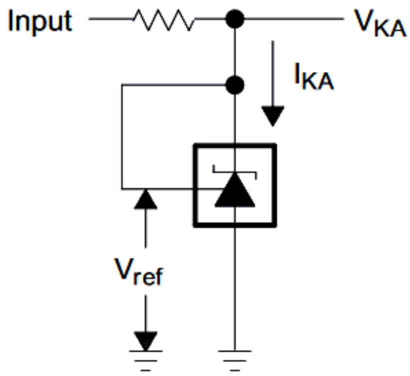

Figure 2.30 TL431 in basic principle operation schematic

2.3.3 Analog Frontend (A.F.E.)

Sensors output characteristics and microcontroller's input characteristics must meet for signal compliance. Otherwise an inter-circuit design may required. In this study sensors output signal and microcontroller input are matched using an analog frontend circuit. Sensor generates +/-10VDC bipolar signal and microcontroller accepts only 0 to 5VDC unipolar signal. Since the AFE's power rails are designed in span of -15VDC to + 15VDC the output can swing between +/- 10VDC even the LM358 op-amp in Figure 2.32 is not a rail to rail device. Thanks to the large headroom between rails. The AFE in Figure 2.31 works as an analog computer with time domain transfer function of;

$$V_{out} = \frac{V_{in} + 10}{4} \qquad (2.1)$$

Where V_{in} is output of the sensor and V_{out} is the input of the microcontroller. LM358 is a dual opamp IC. It consists of two independent opamp modules as seen in Figure 2.33 in one SO8 package. This eliminates using two ICs for dual channel AFE designs.

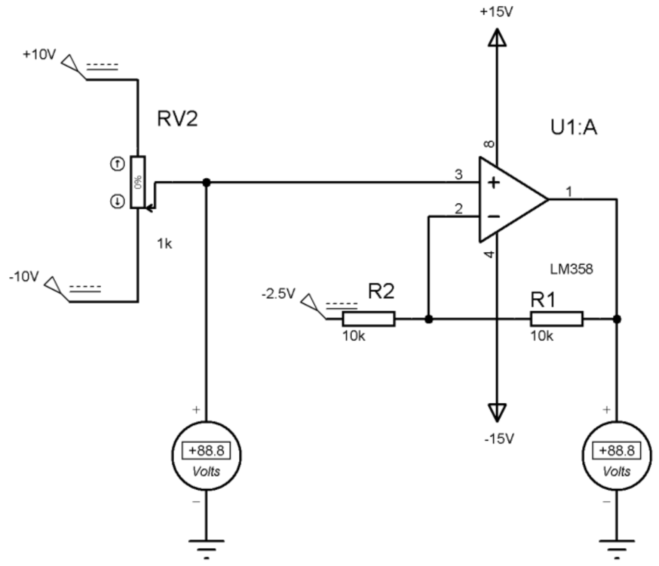

Figure 2.31 AFE unit without LPF

Figure 2.32 LM358 Opamp in SO8 package

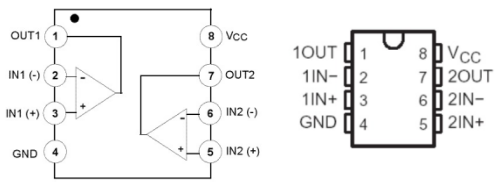

Figure 2.33 LM358 internal connections

Generated V_{out} signal includes high frequency noise that can cause undesired behavior of control algorithm must be filtered out using a low pass filter (L.P.F.). A low pass filter basically a RC network. A first order LPF consists of a series resistor connecting to a shunt capacitor. As the frequency goes higher the capacitor's impedance goes lower as stated in the formula below.

$$X_c = \frac{1}{2\pi fC} \tag{2.2}$$

The frequency response is also filtering characteristic of LFP is shown in Figure 2.34.

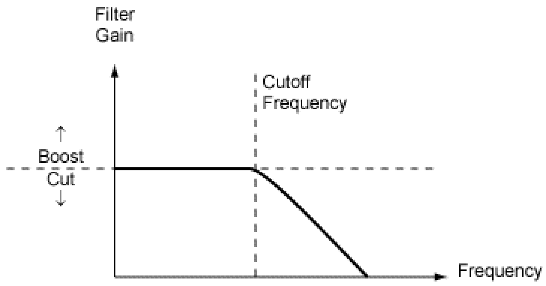

Figure 2.34 LPF frequency response graph

LPF's the cut off frequency can be formulated as follows;

$$f_c = \frac{1}{2\pi RC} \tag{2.3}$$

Where f_c is the cut-off frequency, R is the series resistance in ohms, and C is the shunting capacitance in farads. This yields the designed filter has 338.62Hz cut off frequency with R = 4.7kΩ and C = 100nF values. Resulting cut off frequency of 338.62Hz leaves very large headroom for our signal with noise elimination as the beam's natural frequency is measured as 12.7Hz.

2.3.4 Microcontroller Unit

A computer system basically requires a CPU, RAM, ROM, I/O, Control Unit and peripherals. These units are residing in separate chips and they need to be assembled in harmony to serve in the way of a purpose. Microcontroller is a derivation of units those were previously implemented by individual chips on a system board.

Microcontrollers are intended to make the real world demands easier to implement. A microcontroller can consists more than CPU, RAM, ROM, I/O, communication interfaces, timers, counters, interrupt handlers, oscillator block on their architecture.

2.3.4.1 Microcontroller

In This study a PIC18F4520 microcontroller in SMD package shown in Figure 2.35 and functional pin diagram is shown in Figure 2.36 is used as the main controller of the board. Every task applied on the board are in control of the MCU. This chip has a 10MHz crystal oscillator block. This frequency handled as base frequency for the PLL unit of the MCU. This frequency is multiplied by 4 in the PLL and 40MHz of instruction signal is fed into the core of the CPU of MCU. PIC microcontrollers need 4 clock cycles to perform one machine instruction. This causes CPU core to run at 10MIPS (Mega Instruction per Second.) The MIPS performed by microcontroller can be calculated as follows;

$$MIPS = \frac{f_{osc} . P_{LL}}{C_i} \tag{2.4}$$

Where MIPS is performed instruction executions per second, C_i is cycles required to perform a single instruction, f_{osc} is the external clock frequency in Hz, P_{LL} is the frequency multiplication coefficient performed by PLL module of microcontroller.

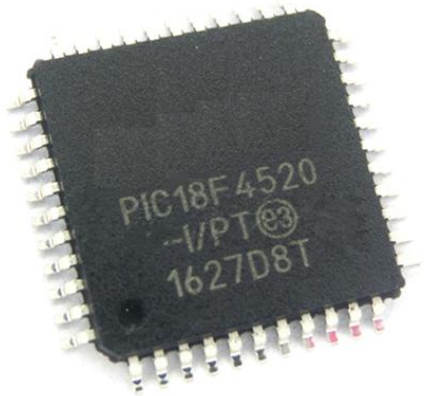

Figure 2.35 PIC18F4520 controller in TQFP44 package

PIC18F4520 microcontroller is very rich of peripherals and technologies such as modern PWM and ADC modules as entire chip organization is in Figure 2.37. Those features serve the following main functional advantages.

- High current I/O signalization up to 25mA
- Three programmable external interrupts
- Four input change interrupts
- 2 PWM modules
- Master Synchronous Serial Port (MSSP) module
- Enhanced Addressable USART module
- 10-bit, up to 13-channel Analog-to-Digital Converter

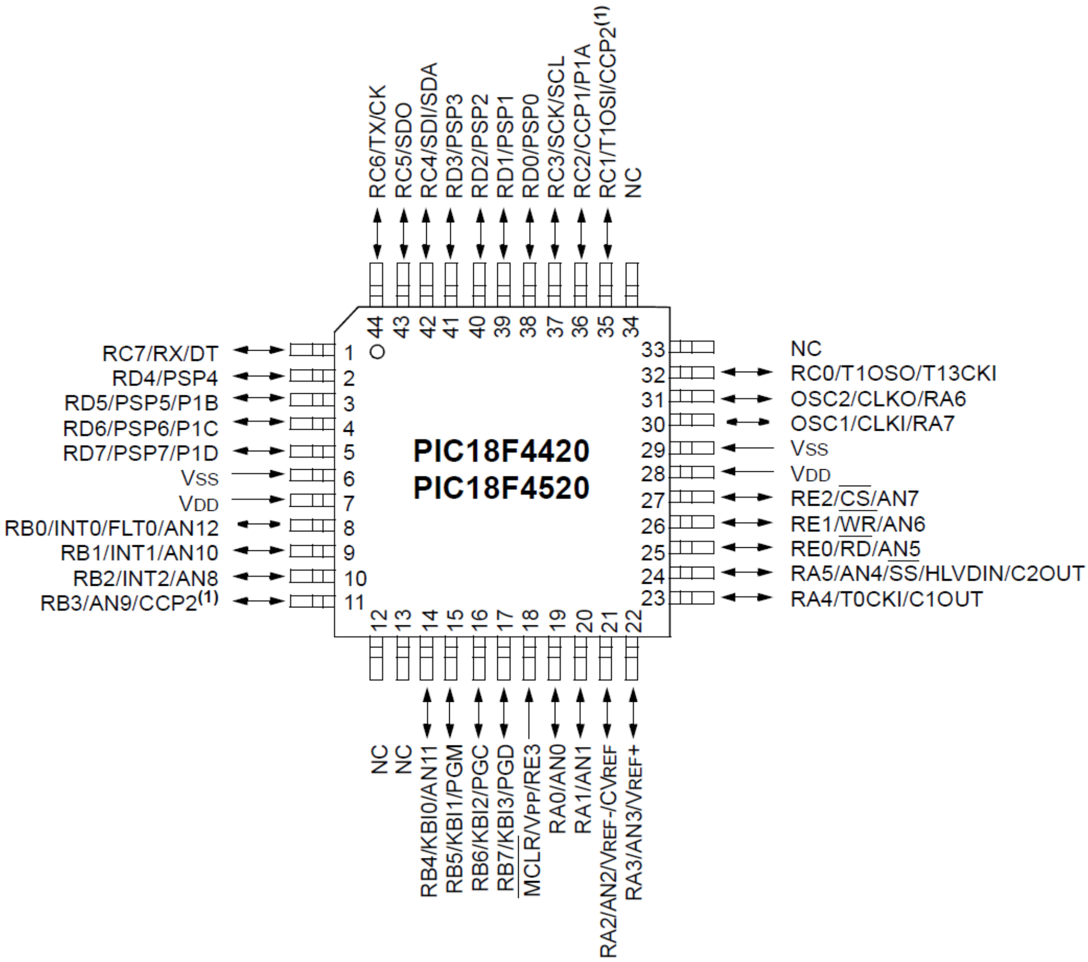

Figure 2.36 PIC18F4520 controller in TQFP44 package

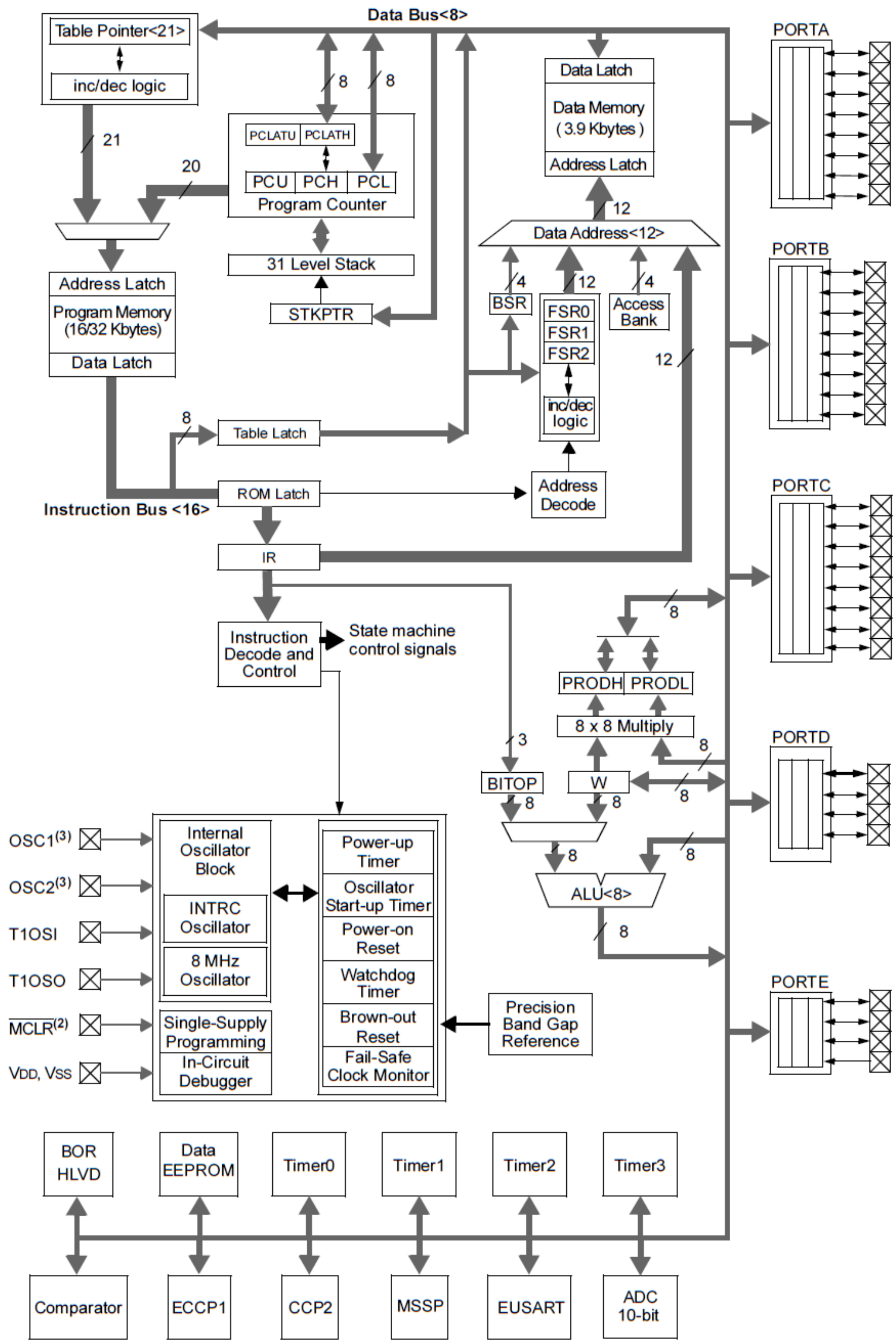

Figure 2.37 Internal blocks of PIC18f4520 controller

This microcontroller is responsible to perform the following duties in order to control the signal flow and decision makings required to run the system.

- Control algorithm implementation
- Data sampling and recording
- Analog to digital conversion
- PWM driving
- Local LCD driving
- SPI communication with VGA sub unit
- SPI communication with external RAM buffer
- Optical input reading
- Relay output driving
- USB communication over RS232 TLL

In order to perform those actions the microcontroller must be programmed in proper way. Out of the box the microcontrollers are shipped with an empty memories and the user need to program the memory in order to make the CPU perform the required actions. Microcontrollers have different architectures for programming. PIC18F4520 uses Reduced Instruction Set Computing (R.I.S.C.) based programming method. All command used to program PIC must be in assembly language form. In order to use a high level programming languages such as C or Basic compiler is required to translation to assembly language. In this study “Basic” language is used with “Proton” compiler and IDE in Figure 2.38 to compile the code.

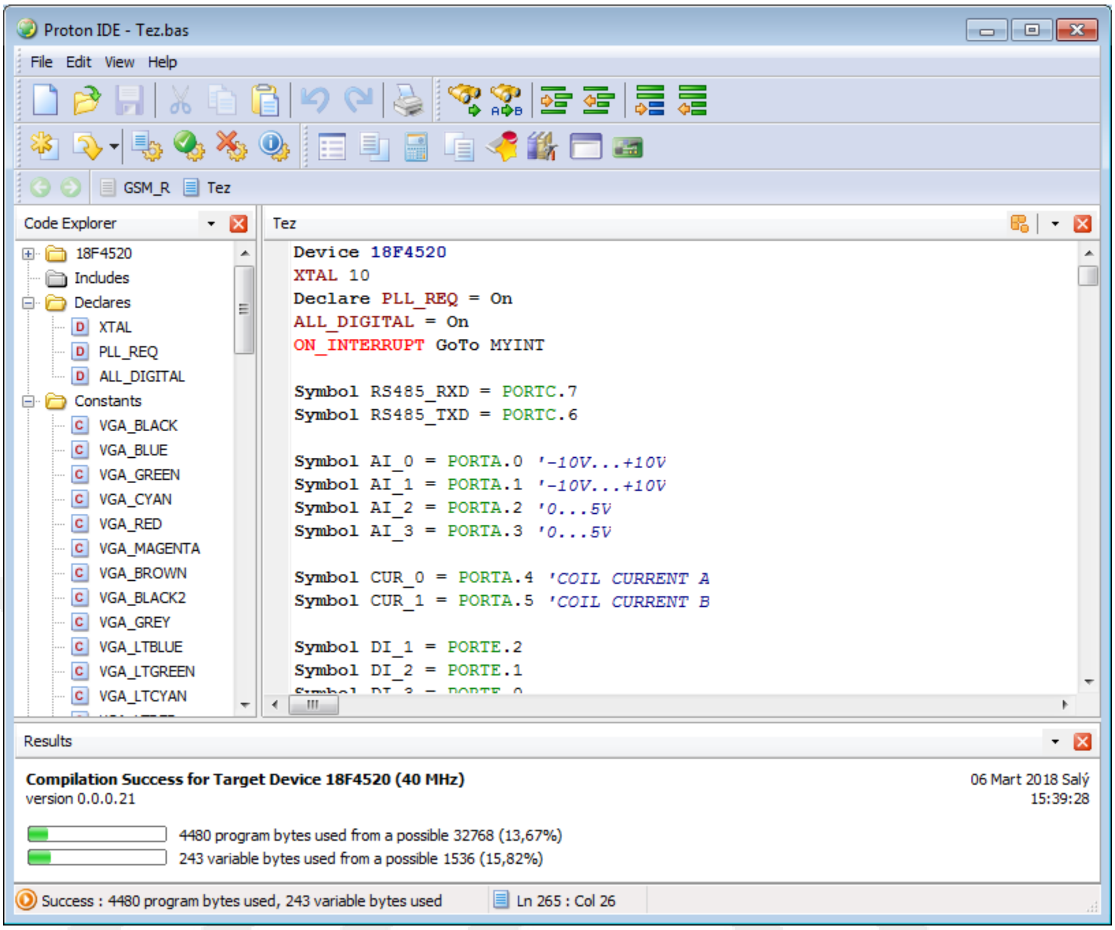

Figure 2.38 Proton IDE basic compiler for PIC microcontrollers

The compiled file generally will be in .hex format and this file needs to be transferred to the ROM of the microcontroller. For this purpose a flash program loader device such as PicKit3® is used. PicKit3 is an official development tool produced by Microchip Company which is also the vendor of the microcontroller. Pickit3 device and user interface can be seen in Figure 2.39 and Figure 2.40.

Figure 2.39 PicKit3 flash tool

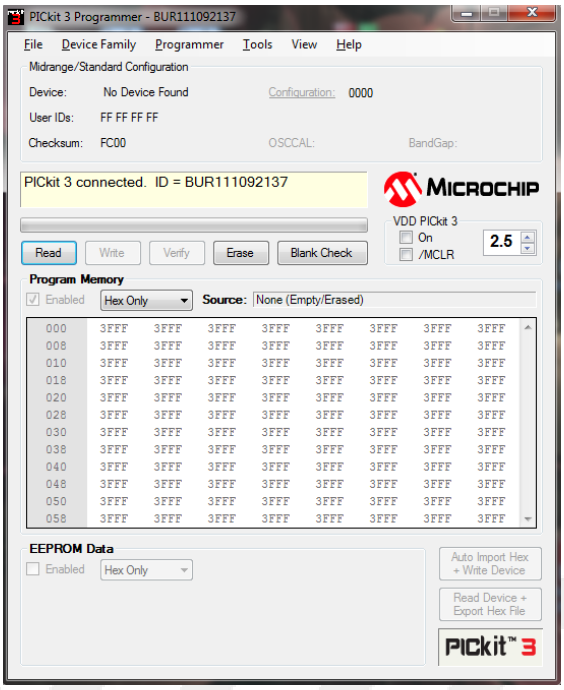

Figure 2.40 PicKit3 user interface

PicKit3 uses the generic In Circuit Serial Programming (I.C.S.P) method for flashing the microcontroller. This method uses a dedicated data and clock pins on the microcontroller. Data pin is named as PGD and clock pin in named as PGD. In order to put the microcontroller into programming mode the flash tool sends 13VDC to the controller via VPP pin. Thus programming can be done by using 3 pin as shown in figure excluding VDD and VSS.

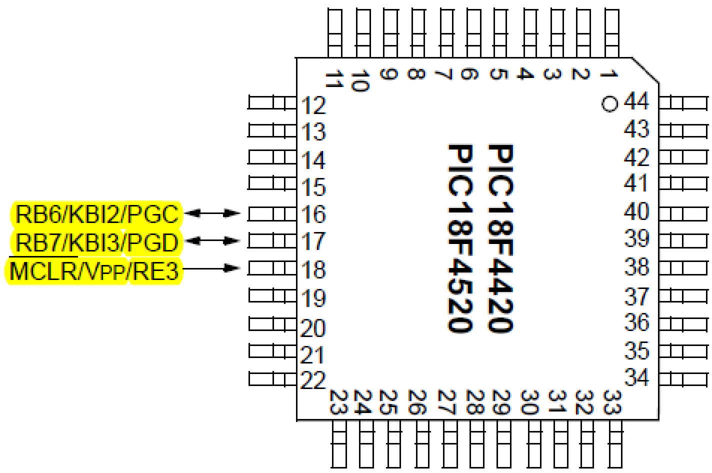

Figure 2.41 PIC microcontroller ICSP interface

In the prototyping phase of design programming the microcontroller via ICSP is not so easy and practical for everyday flashing. To overcome this obligation bootloader process is developed by the vendors of microcontrollers. A special program once needs to be loaded into the microcontroller. This is only one time action need to be done via ICSP. After this step program can be loaded into controller using RS232 connection, USB or if supported over Ethernet. Another software tool is needed to perform bootloading process for the controller is shown on Figure 2.43. A typical bootloader memory map is illustrated on Figure 2.42.

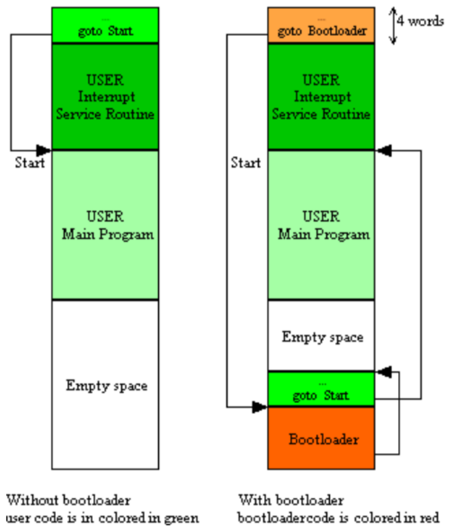

Figure 2.42 A typical bootloader memory map

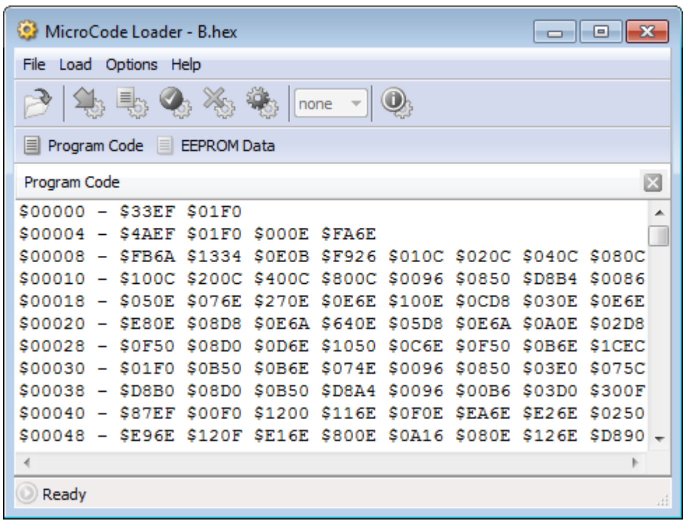

Figure 2.43 Bootloader programming interface

2.3.4.2 Decoupling Unit

Decoupling perform a very important role in digital electronics circuits. Basically decoupling a decoupling structure removes or reduces coupling of a specific component. If the decoupling structure is omitted on a circuit for a specific component it becomes vulnerable for the interferences sourcing from other on-board components. A decoupling capacitor is also having low pass filter property to protect the protected component from high frequency conducted interference. A decoupling network is shown on figure 2.44

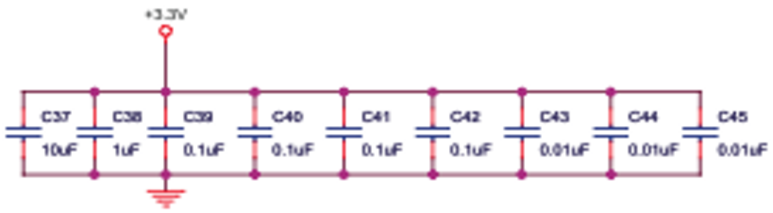

Figure 2.44 Sample decoupling network

Note that a decoupling structure generally is designed in form of network as seen in Figure 2.44. Using a large and single capacitor seems to be an ideal solution but in practice it is not. Because a real capacitor is not even close to an ideal capacitor. As it can be clearly seen in Figure 2.45 a real capacitor has a series inductance and resistance in series. At very high frequencies the impedance of Ls can be very high even it cause the capacitor behave like an open circuit component.

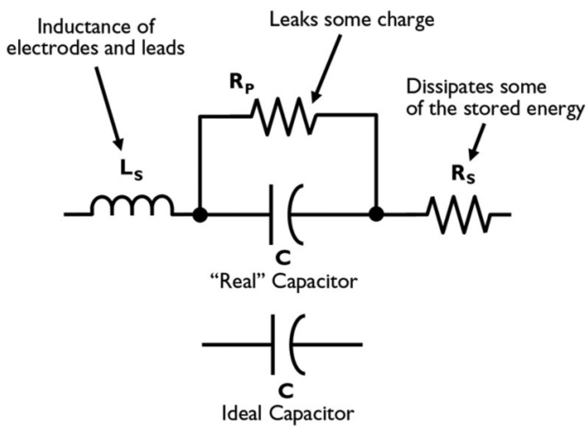

Figure 2.45 Real capacitor model

A decoupling capacitor also serves as an energy reservoir for the burst energy demands of an individual chip. Because of the nature of the CMOS design as the frequency goes higher, the current need to switch a MOS element goes higher. In order to fulfill the requirement of the burst energy demands of an individual chips, every chip is equipped with a decoupling capacitor. The decoupling capacitor must be placed very close to the chip. Otherwise it will not perform as an efficient energy reservoir.

Using the advantage of different capacitors in parallel helps to reduce the equivalent series resistance (E.S.R) of the equivalent capacitance. When using a bunch of capacitors in parallel their ESR is also connected in parallel as in Figure 2.46. Thus the design ends up with a lower ESR capacitance and high burst energy delivery capability.

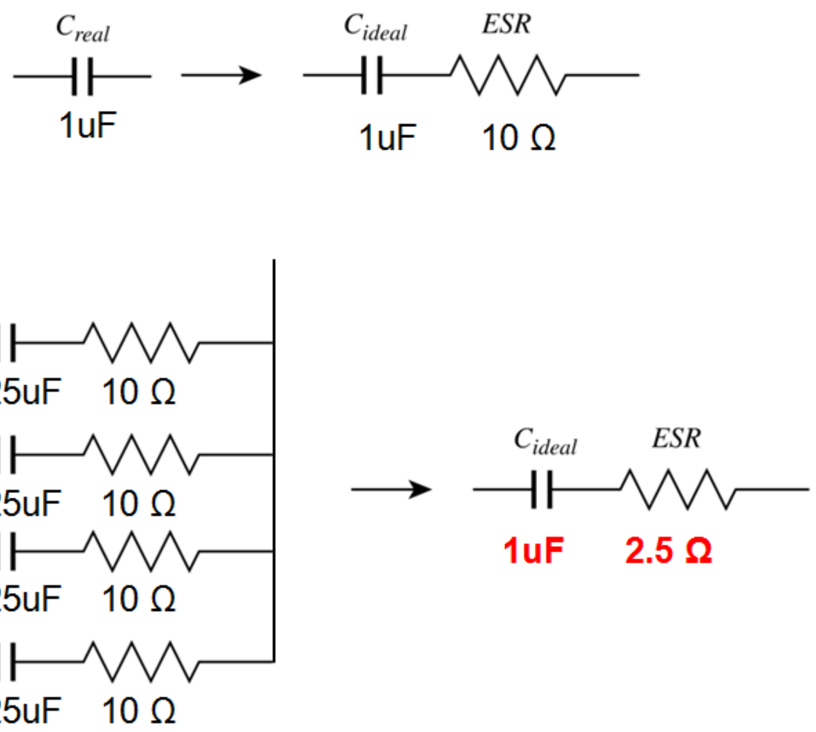

Figure 2.46 Effect of capacitor paralleling

Each capacitor construction is close to an ideal capacitor in means different parameters. Some capacitors have large capacitance for example electrolytic capacitors. Ceramic or multilayer capacitors serve low capacitance but they have very low ESR. With this information using different capacitor types in parallel is a way of achieving capacitor which is close to an ideal capacitor as shown in Figure 2.47.

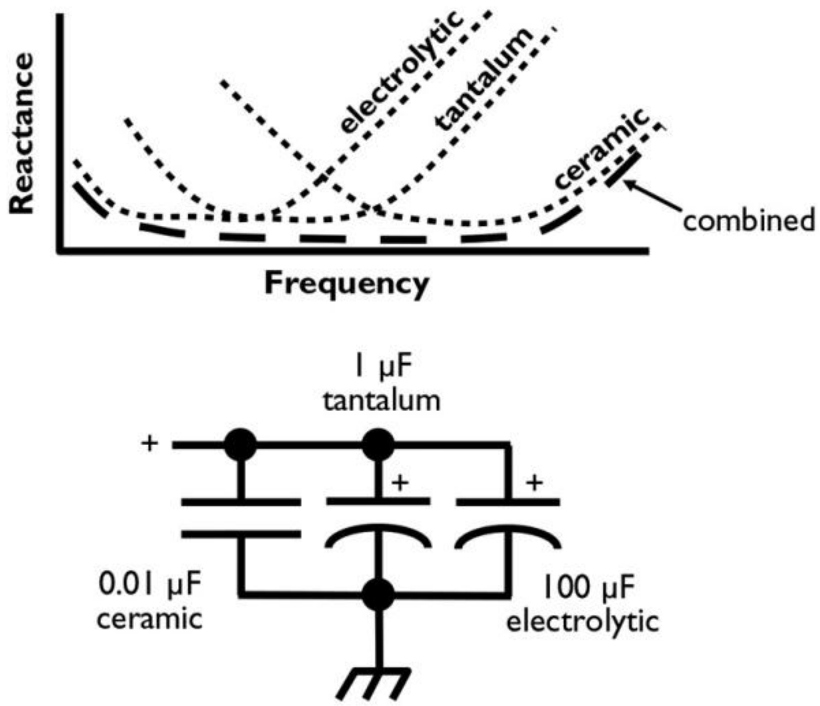

Figure 2.47 Effect of different types of capacitor paralleling

2.3.5 SPI Buffer RAM

This experiment uses sampling method to acquire the data from sensor units. Sampling a signal very frequently requires intensive amount of data to be stored on a media. The required media must be high speed and high capacitance. The sampling requirements of the experiment are listed in Table 2.3.

Table 2.3 Requirements of the experiment

Parameter	**Value**
Sampling Frequency	1000Hz
Sampling Resolutions	10 Bits
Sampling Interval	1ms
Allowable SPI Time	50uSec
Sampling Duration	10 Sec

Numbers of collected samples are calculated using the formula below;

$$n = f_s * T_s \qquad (2.5)$$

Where n the number of samples is collected, f_s the frequency of the sampling and T_s is the duration of data acquisition. As the control algorithm and the data acquisition process is running on the same controller sampling and storing time must be as fast as possible to leave CPU time for control algorithm and other housekeeping processes in the firmware. Because of this fact allowable SPI time is limited to 50uSec. After doing the math 10,000 sampled data needs to be stored on a RAM. The number of bits needed to store the data is calculated using the formula below;

$$n_{bits} = S_r * n \qquad (2.6)$$

Where n_{bits} is the calculated bits count to store, S_r is the bits for a individual sample, and it must be a times of 8 bit as the per memory cell is an 8 bit storage, n is the number of samples as derived from formula (2.5). With this calculation 16*10,000 = 160,000 bits 160,000/1024 = 156.25 Kbit) need to store. PIC18F4520 used in this system has only 12,288 bits of user RAM and it’s not suitable to store this much of data. To overcome this limitation an external SPI RAM chip is used. 23A256 SPI RAM chip in Figure 2.48 has capacity of 256Kbit storage with high speed data bus up to 20MHz.

Figure 2.48 23A256 SPI RAM chip

The 23A256 has the following advantages for the systems performance;

- Max. Clock 20 MHz
- Low-Power CMOS Technology:
- Read Current: 3 mA at 1 MHz
- Standby Current: 4 μA Max. at +85°C
- 32,768 x 8-bit Organization
- 32-Byte Page
- HOLD pin available
- Flexible Operating modes
- Byte read and write
- Page mode (32 Byte Page)
- Sequential mode
- Sequential Read/Write
- High Reliability
- -40°C to +125°C Temperature Ranges Supported

With the specified capacity of RAM chip there is still enough room for additional data storage for future use.

SPI protocol is a very common protocol for usage in electronic circuit board. It was first designed by Motorola Company in mid 80’s. It is generally intended to use as between the chip sharing the same board. Since it can be used on this purpose SPI is not mainly designed as a Board to board communication standard. SPI uses minimum 4 signalization connection for a basic communication when only one slave with one master. The basic signalization can be seen on Figure 2.49.

Figure 2.49 SPI basic communication connection diagram

As SPI protocol is a synchronous type of protocol, SCLK signal is always driven from master side. Master Out Slave Input (M.O.S.I.) signal carries master’s signal to the slave device. Master Input Slave Output (M.I.S.O.) signal is used to receive data from master as it carries slave’s data to master. Slave Select (S.S.) signal is for selecting the slave chip in multi slave configurations. Also it is used for data latching purposes for the registers residing on slave device memory areas. If the configuration using more than one slaves on the SPI bus two different configurations are used. Daisy chain and independent slave in Figure 2.50 can be seen. Daisy chain has advantage of using less pins on master side with disadvantage of slow reaching capability to the last slave. In independent slave configuration every slave can be reached with the same speed without any access time variation with the order of the slaves.

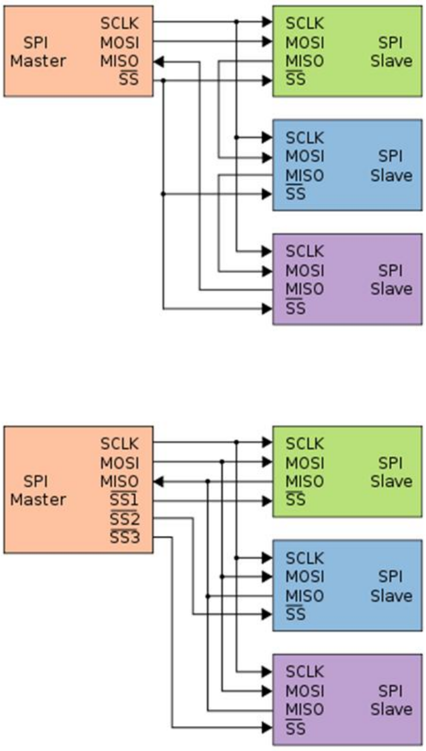

Figure 2.50 Independent slave and daisy chain SPI configuration

23A256 SPI RAM Chip uses 3.3V signalization on SPI bus, in contrast PIC18F4520 is supplied with 5VDC and also uses 5VDC signalization levels on SPI bus. This signal level must be matched in order to maintain systems stability. A resistor-diode based level shifter is used for matching the levels. The designed level shifter is in Figure 2.51.

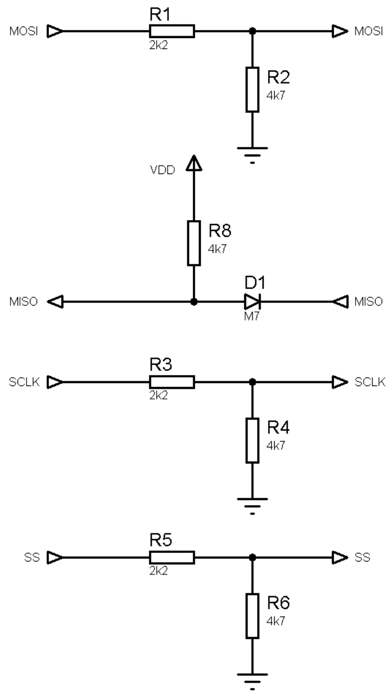

Figure 2.51 SPI level shifter

When MOSI drives the output to 5VDC the R1 and R2 resistors divides the voltage. R1 = 4k7 and R2 = 2k2. Resulting series resistance is 6k9. This causes 0.72mA of current passes to the circuit. As the slave takes the voltage level on R2 the voltage drop on R2 is 0.72mA causes to drop of 3.38VDC on R2 which is a sufficient voltage level for driving SPI RAM chip. The MOSI level shifting process is the same for SCLK and SS signal levels. For the MISO slave's 3.3VDC signal must be boosted to 5VDC. Thanks to push pull output structure of SPI RAM chip when the MISO signalization line is taken high by the slave, the master's input is pulled high by the pull up resistor which is connected between MISO and VDD. Because the diode prevents current flow from master to slave this makes the signal high. When the MISO signalization line is taken low by the slave, the master's input is pulled very close to zero volts by the diode which is connected between master and slave.

2.3.6 USB Interface

USB stands for Universal Serial Bus which is an industry standard connecting the external devices to computers. The specifications of the standard first released in 1996. It has several versions including USB2.0. This version uses 4 wires for power delivery and signalization. It uses single differential twisted pair media as seen on Figure 2.52 to transfer data. This makes USB2.0 half duplex in the point of hardware design layer.

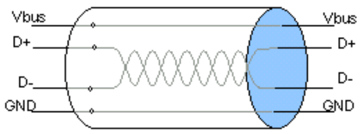

Figure 2.52 USB2.0 signalization media

Data transmission and command interface is realized over USB with compliance of USB 2.0 Full Speed specifications as shown in Figure 2.53 and Figure 2.54. PIC18F4520 microcontroller itself does not have embedded USB transceiver. It has an UART for serial data communication. To close the gap between USB and PIC a famous USB UART chip FT232RL is used. FT232RL is USB2.0 full speed device with full compliance of USB2.0 standard. It has on-chip oscillator and EEPROM which is only required a few external components to operate as an USB transceiver.

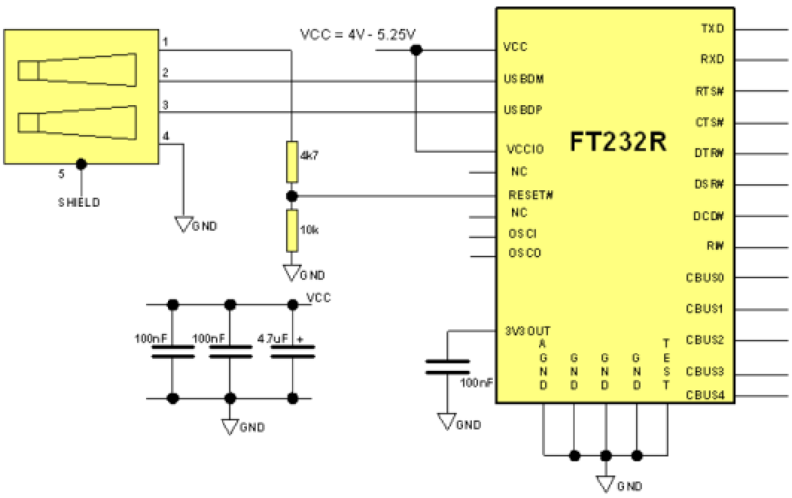

Figure 2.53 Basic configuration of FT232R

FT232R creates and operates a VCP (Virtual COM Port) as seen on on Windows® operating system; this enables easy integration of legacy and and modern scientific data processing software into the system.

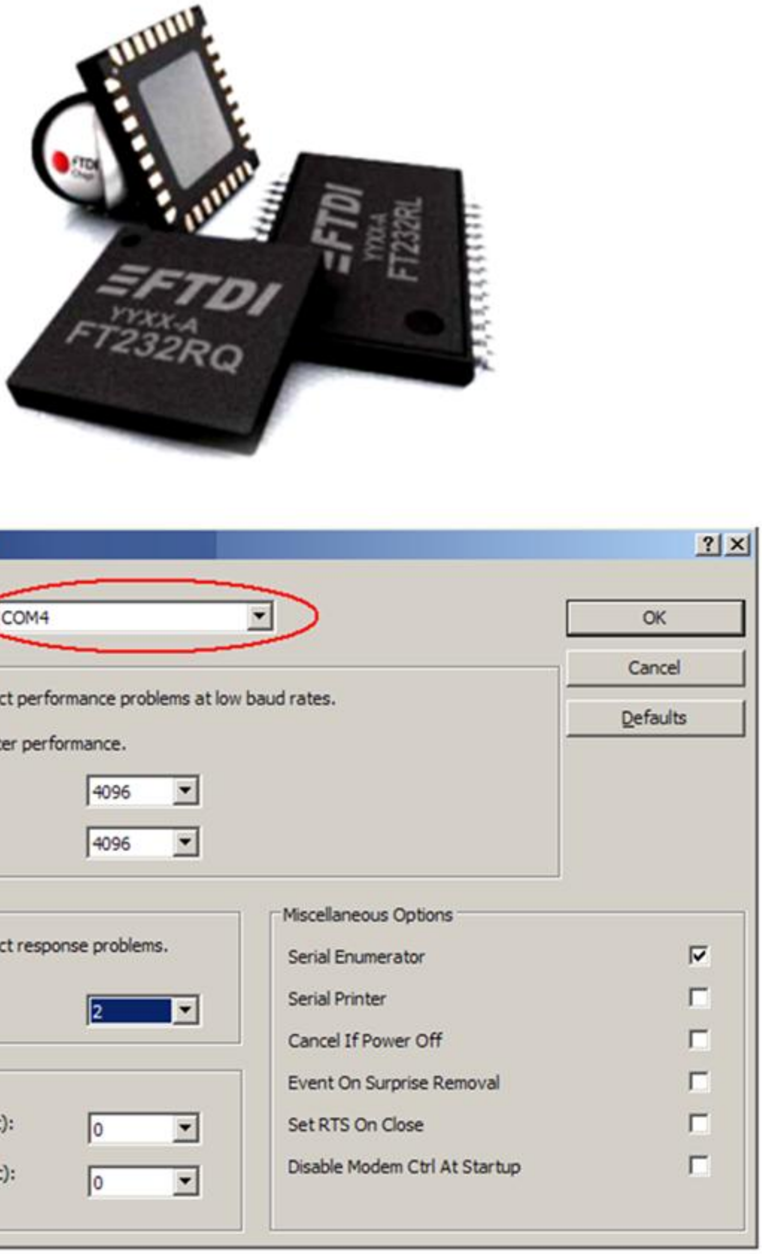

Figure 2.54 SMD packages of FT232R and VCP Window

2.3.7 Actuator Driver

Actuator coils are can be considered as purely inductive loads (Pithadia, 2013). This causes considerably large back EMF strike to the driver circuitry. Special precautions are taken into account in the design phase. L298 shown in Figure 2.55 and Figure 2.56 dual full bridge driver is chosen as coil driver with appropriate diode based snubber network. L298 shown in Figure 2.55 and Figure 2.56 is capable of handling voltages as high as 45 volts and current ratings of 4A. This makes L298 very suitable for the purpose as designed coil is rated as 30V and 1A. For higher output currents outputs of L298 can be paralleled for 8 Amps of current. This results with total 360 watts of total controllable power.

Figure 2.55 Outlook of “PowerSO20” SMD package of L298

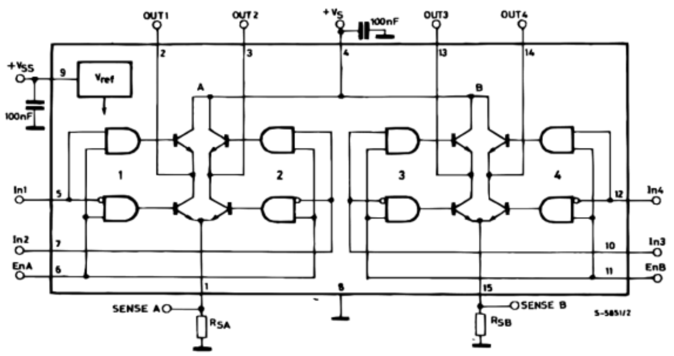

Figure 2.56 Internal principal schematic of L298

Special low impedance sensing resistors are placed in SENSE A snd SENSE B pins to the ground for future ready system capable of actuator current measurements.

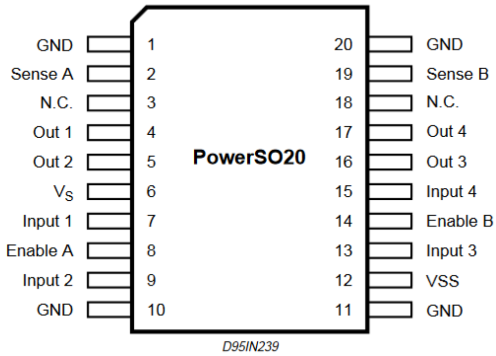

Figure 2.57 Pin diagram of L298 for PowerSO20 package

2.3.8 Local LCD Display

On-card information and user indications and user interface is implemented by embedding a LCD module on the card in the design phase. WH0802-TMI-ET module shown in Figure 2.58 is capable of displaying two lines of ASCII text with 8 characters on each line, 16 chars in total. Very low power consumption of module helps to comply with the low power requirements. Internal principal schematic of the module is show in Figure 2.59 in detail. This module has a LED backlight which consumes less than 4mA as expected. Interfacing of LCD module is done by half width 4bit parallel interface for a balanced trade-off between MCU I/O count and CPU time for LCD refresh routines.

Figure 2.58 Local LCD display (Personal archive, 2019)

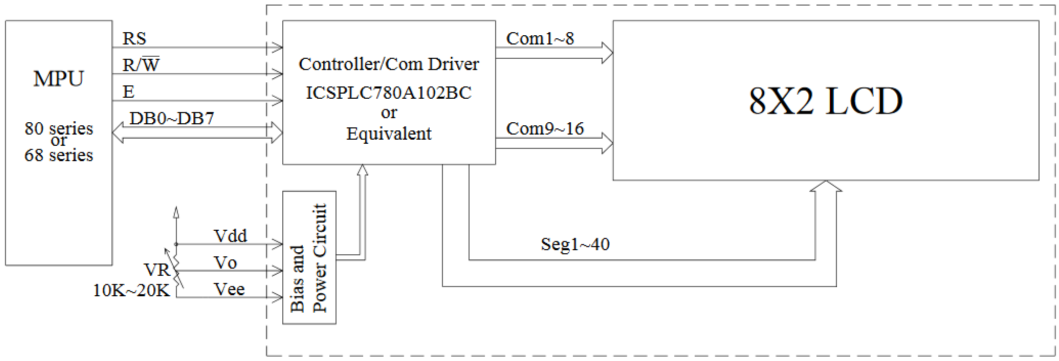

Figure 2.59 Internal principal schematic of WH0802

2.3.9 VGA Monitor Driver

During the experiment phase and standalone working phase data dash boarding on a large display is needed when there is no PC. In order to achieve a PC free solution large display ability must be embedded into design. For this purpose a VGA unit is placed into the design. This unit allows system to put data on a standard VGA monitor/TV/projector for observing real-time system parameters when working in standalone mode. This unit acts like a graphic card in a PC (Singh, & Ahuja, 2013). It has its own display memory, horizontal and vertical scanning & signalization algorithm, color generation and SPI interface for data exchange between MCU and VGA unit. The created images are in 640x480 pixel resolution and with a refresh rate of 60Hz. The unit has its own controller chip, this eliminates to use the CPU time of the main MCU for the refreshing of the display while maintaining complex control algorithm executions.

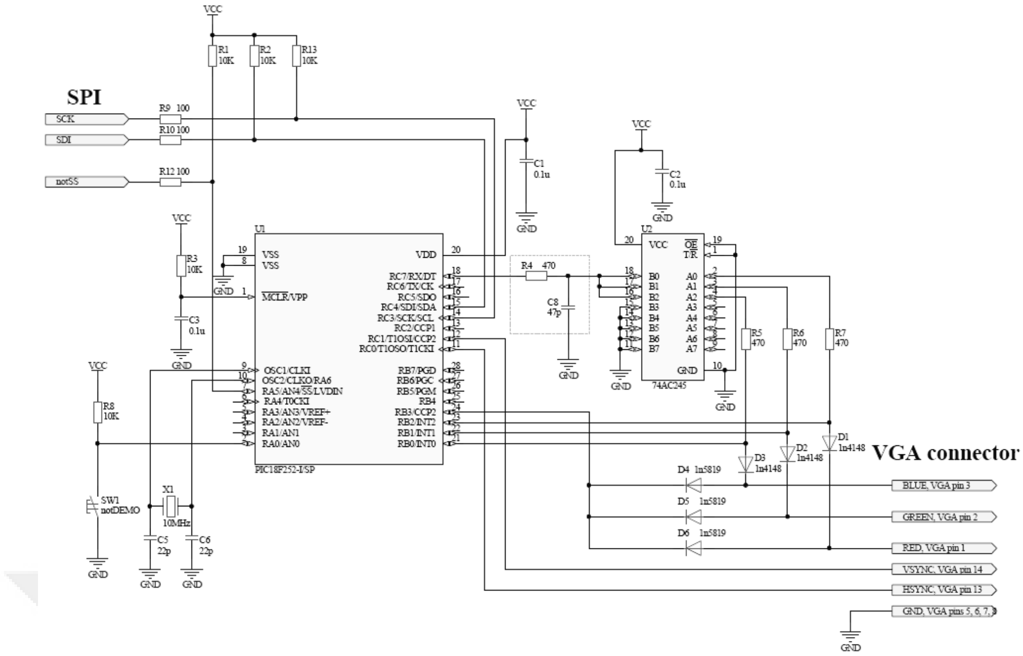

Figure 2.60 VGA unit detailed schematic

The VGA unit is capable of the following features;

- 30x30 chars text positioning
- 240x480 graphics resolution
- 8x16 pixels char size
- 15 Colors
- Cursor emulating
- SPI Interface, up to 250 kbits per second

2.3.10 Input and Output Interface

As a standalone system the application needs user interactions without PC requirement. Also different kinds of loads need to be driven such as releasing mechanism. For this purpose 4 input and 4 outputs are equipped on the system. The inputs and outputs I/Os are the door of the system opening to the real world. Real world is the source and sink of the signals. In addition real world is the source of noise and interference. This forces the design to be robust against these interferences and noise sources. So the inputs and outputs must be galvanically isolated. There is no electrical connection between the I/Os and the rest of the board.

Input isolation is done by using optical couplers, in other word optocouplers. Basically optocouplers are consisting of two optical transducer, one LED and one photo transistor. The LED is generally choosed an infrared type. The LED and photo transistor is coupled optically in a PC817 single package as seen on Figure 2.61 so there is no electrical coupling between them. This optical coupling enables 5,000VRMS isolation between input and output.

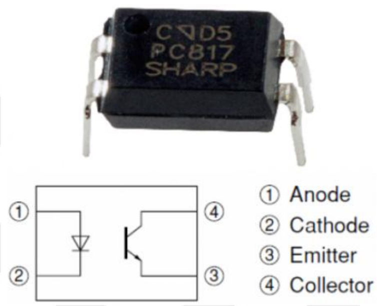

Figure 2.61 PC817 optocoupler component

Output isolation is done by using electromechanical components, in other word relays. Basically relays are consisting of one electromagnet and one contact set. The electromagnet and contact set is coupled mechanically in a TX2 relay single package as seen on Figure 2.62 so there is no electrical coupling between them. This mechanical coupling enables 2,000VRMS isolation between input and output.

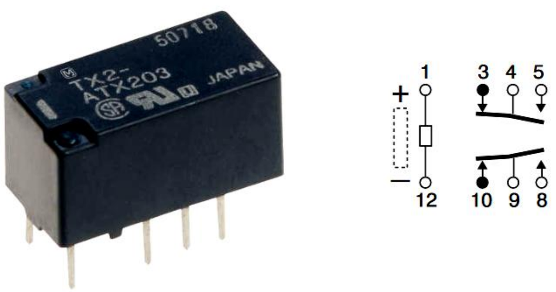

Figure 2.62 TX2 Relay

2.3.11 Printed Circuit Board

Making connections between advanced and complex electronic circuit components requires a versatile technique. PCB (Printed Circuit Board) technique is the most common, even more the unique technique all over the world. There are mainly two types of components are produced to use on the PCBs. Through hole components are designed to be placed via their pins through the holes of the PCB and soldered from relatively bottom side of the component. THDs (Through Hole Device) are generally bulky and needs relatively more area and volume on the design. In contrast with THDs, SMDs (Surface Mounted Device) are soldered directly on the surface of the PCB as seen on Figure 2.63 and Figure 2.64.

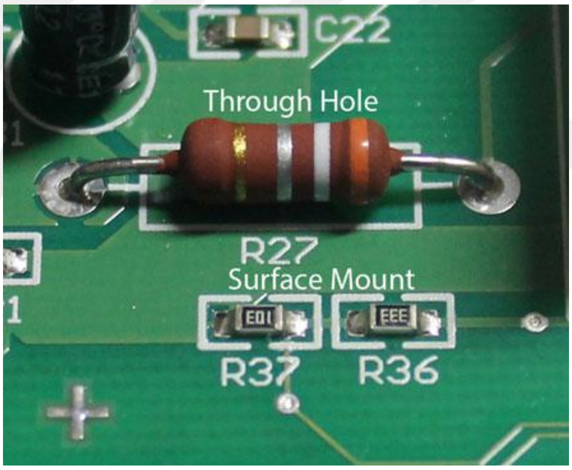

Figure 2.63 THD and SMD devices placed on the same board (Personal archive, 2019)

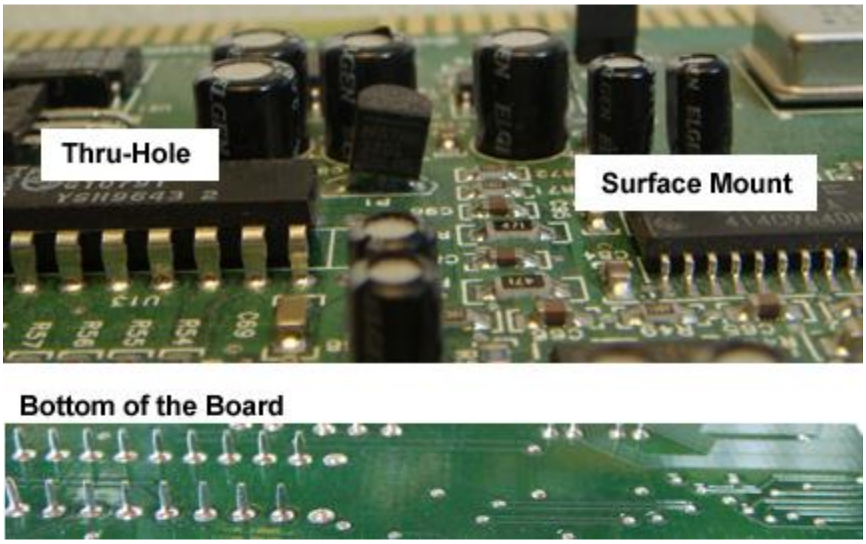

Figure 2.64 Comparison of THD and SMD device’s bottom view (Personal archive, 2019)

This saves too much space which is very valuable when designing a PCB. SMDs are considerably small devices in comparison with THDs. Also SMD design shown in Figure 2.65 helps to use both sides of PCB without mechanically interfering to the other side of the PCB layer resulting with highly populated and thermally stable PCB based circuits. The PCB used in this ECU is designed as double layer and mostly SMD except high power components. ARES software from Proteus Design Suite is used for CAD process of PCB as shown in Figure 2.65 and 3D view in Figure 2.67.

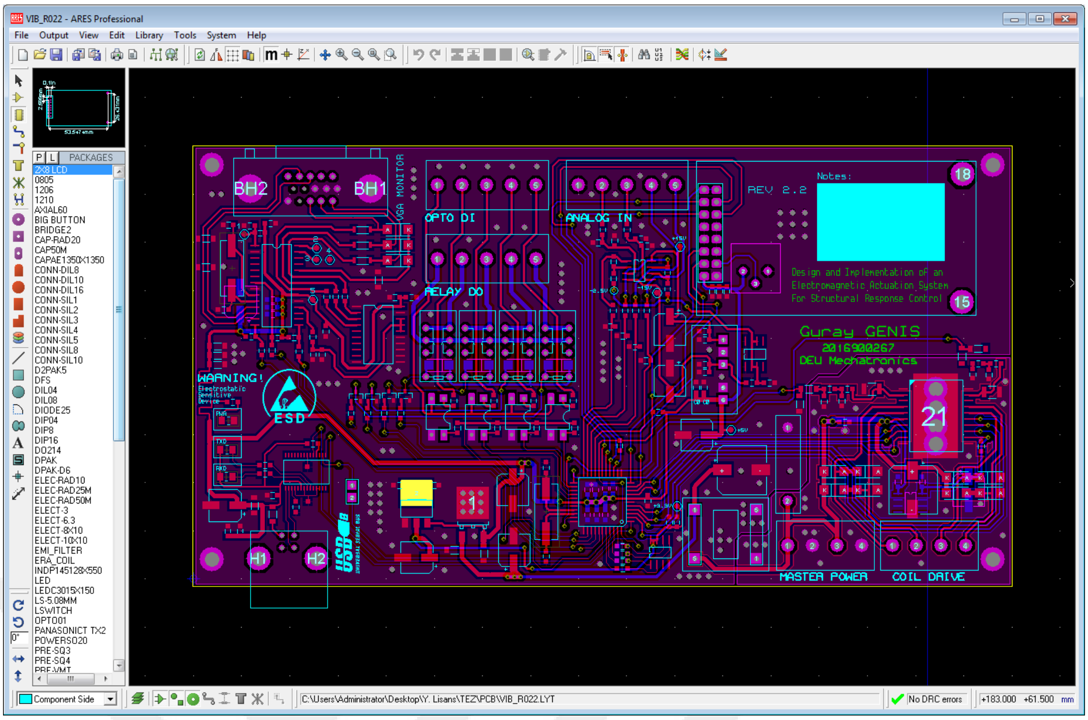

Figure 2.65 ARES PCB CAD software

The voltage regulator, low drop-out regulators and power drivers generates heat and this heat must be taken away from the component, otherwise the component can become too hot resulting with unstable behavioral or damage of the component can occur (Brizoux, Grivon, Maia, & Monier, 2010). Using SMD technology allows the designer to use the surface of copper are as a heatsink for the power components as seen on Figure 2.66. This is very useful when space constraints are very limited and strict. In addition to this avoiding using bulky, floppy and heavy aluminum heatsink structures makes the circuit more resistant to vibration and pulls the circuit mass lower.

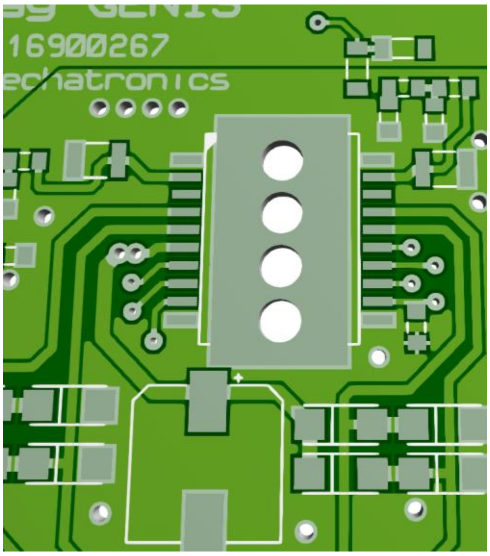

Figure 2.66 PCB area as heatsink for SMD power component

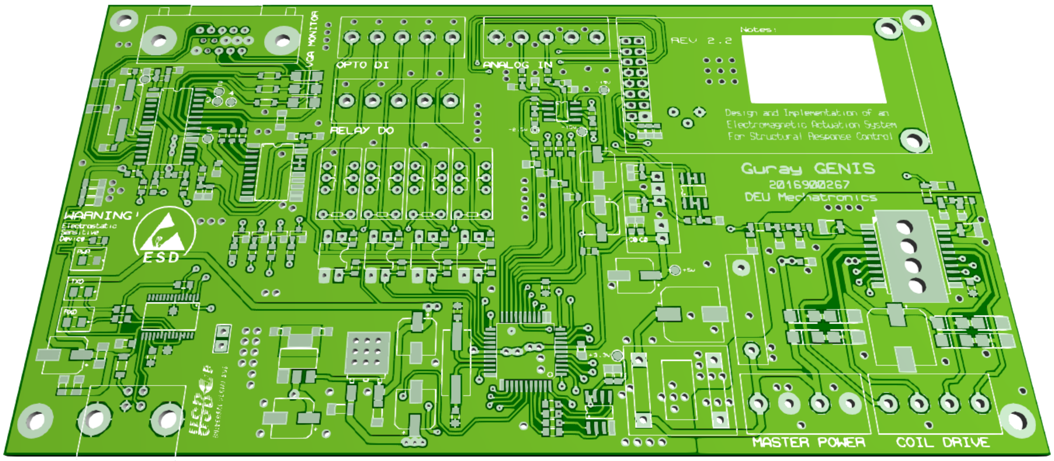

Figure 2.67 ARES PCB CAM software 3D visualization output of PCB

Assembly of components on the PCB is done by handwork using tweezers, solder paste, soldering iron and hot air gun. This board is also capable of assembling in serial production line by having appropriate CAM data. After assembly is done cold tests are done by writing test bench program to check basic functionalities of the board.

2.4 Control and Data Acquisition Program

A VB6.0 application shown in Figure 2.68 is designed to control the board and transferring data from the system those captured during the experiments.

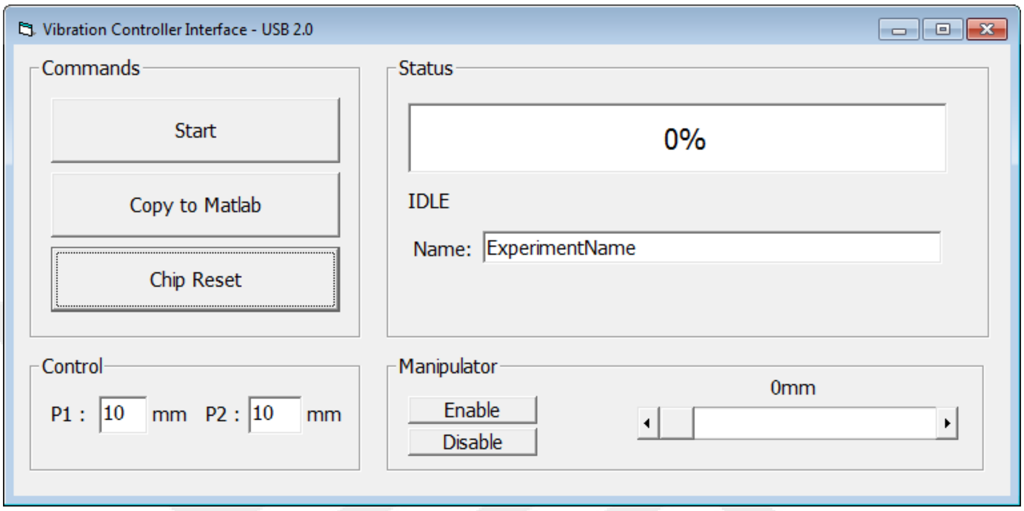

Figure 2.68 User interface of control and data acquisition software

After the data has been downloaded from board to PC the sampled values are stored in a *.m file in the same folder with MatLab® software for further analysis. There are several fields and buttons on the program their functions as follows;

- “Start” Button: Releases the trigger and starts data sampling.
- “Copy to MatLab” Button: Creates a MatLab vector and copy it into clipboard.
- “Chip Reset” Button: Resets the main board’s controller.
- “Status”: Shows the data transfer progress.
- “Name” Field: Specifies the name of the .m file to be created.
- “P1” Field: Sets the first displacement position.
- “P2” Field: Sets the second displacement position.
- “Enable” Button: Enables continuous manipulator operation.
- “Disable” Button: Disables continuous manipulator operation.
- “mm” Slider : Controls the displacement

CHAPTER THREE

VIBRATION SUPPRESSION

3.1 Bang – Bang Control

Control of a system can be made under different approaches. The most basic one is Bang-Bang control algorithm. It uses single decision logic with full on or full of control of output power. Before proceeding with the algorithm the mechanical model is simulated in a simulation environment in order to verify the design itself.

Free vibration simulation is done in simulation environment by using the finite element method in SolidWorks software and the first mode shape is given in Figure 3.1. The first fundamental free vibration is obtained as 12.649 Hz and this result is in a good harmony with the experimental result which is obtained as 12.7Hz given in Figure 3.2.

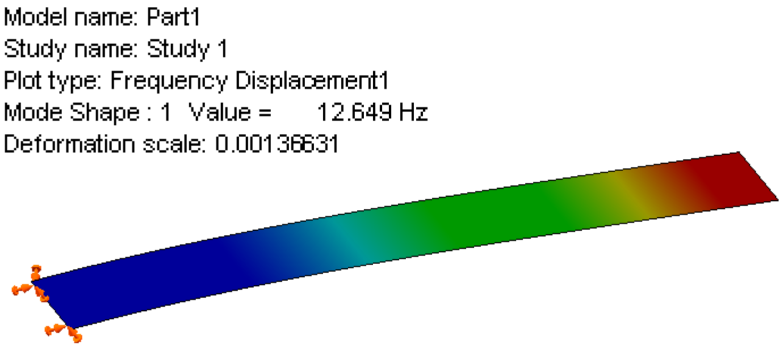

Figure 3.1 SolidWorks free vibration simulation

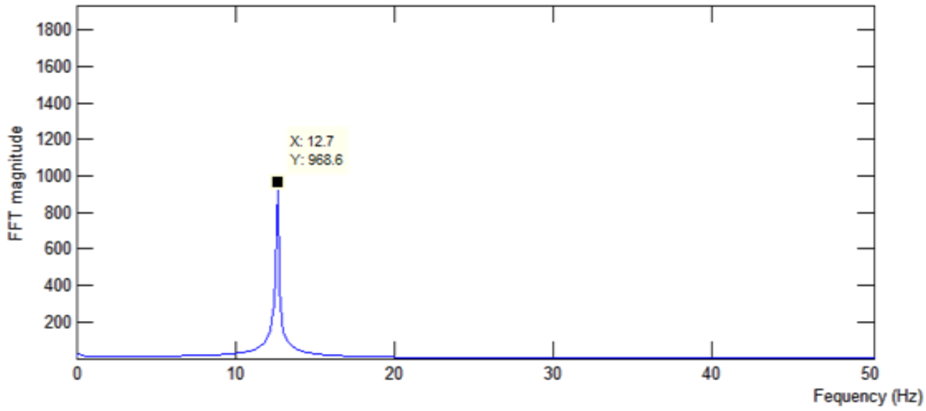

Figure 3.2 Measured natural frequency of the beam

Industrial applications based on high production rates need a base algorithm to perform the desired actions (Liu, & Liu, 2006). Primary experiments are based on “Bang-Bang” control algorithm shown in Figure 3.3 which relies on full drive of output or totally shutting down of the drive power.

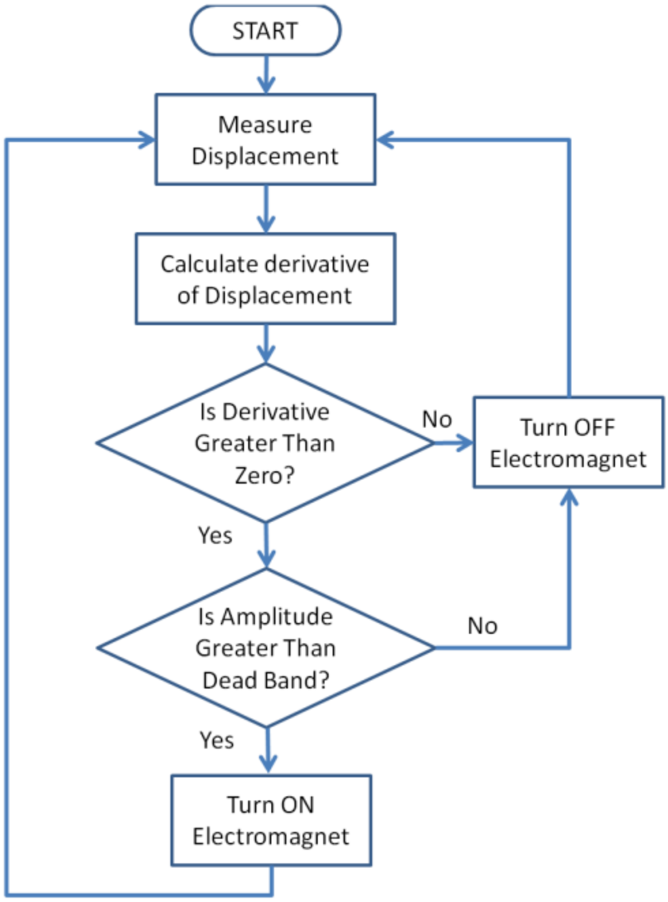

Figure 3.3 “Bang-Bang” control algorithm flow chart

Main control loop program for bang-bang loaded into the controller is shown below. Only main control loop is given, actual entire program is much complex and detailed.

```
For i = 1 To 10000 'Create a 10sec control loop
      Here:
      If IntBit = 0 Then GoTo Here 'Interruppt occurs every 1 msec, wait for
 it
      IntBit = 0 'Clear interrupt flag
      AI_0_RAW = ADIn 3 'Read the displacement

      SHOut RAM_SDI, RAM_CLK, msbfirst, [ AI_0_RAW\16] 'Store it in SPI RAM

      If i > 0  Then 'Control ON @ t+0

            If AI_0_RAW - OLD_AI < 50000 Then 'If derivative less than zero

                  If AI_0_RAW > 505 Or AI_0_RAW<485 Then'If error greater than
 dead band
                    High EN_B 'Energize the actuator
                 EndIF

            Else
                 Low EN_B 'If not de energize the actuator
            EndIf

      OLD_AI = AI_0_RAW 'Store previous measurement for derivative
 calculation
      EndIf
Next 'Repeat the loop
```

Because of the nature of the control algorithm as the derivative stays in positive region the output stays on. This “ON” time is directly proportional with the amplitude of the oscillations. As the beam travels in the positive direction the output power tracks with the motion. This algorithm results with PWM like controlled output power and only required amount of power fed in to the system while maintaining a trade-off between consumed energy and suppression time.

Control of the system can be turned on or off and the difference can be seen in Figure 3.4 and Figure 3.5. Control ON is enabled at t+0 second on the in this response.

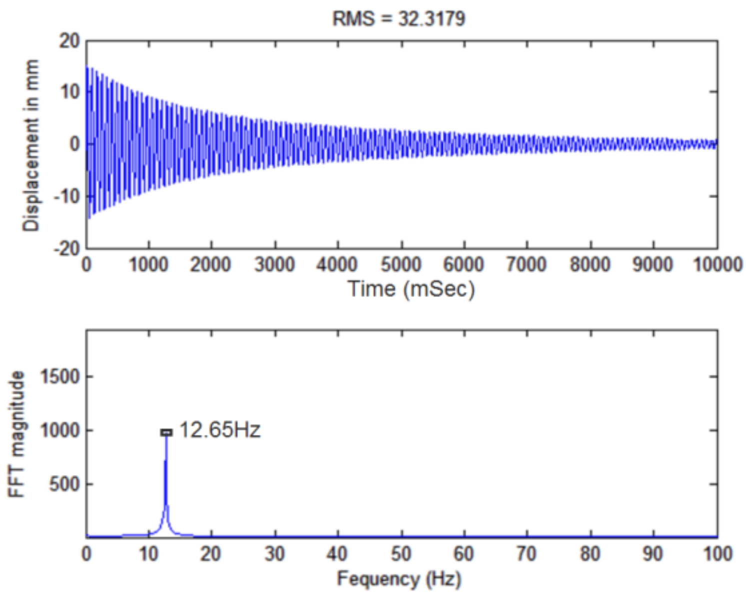

Figure 3.4 Control OFF

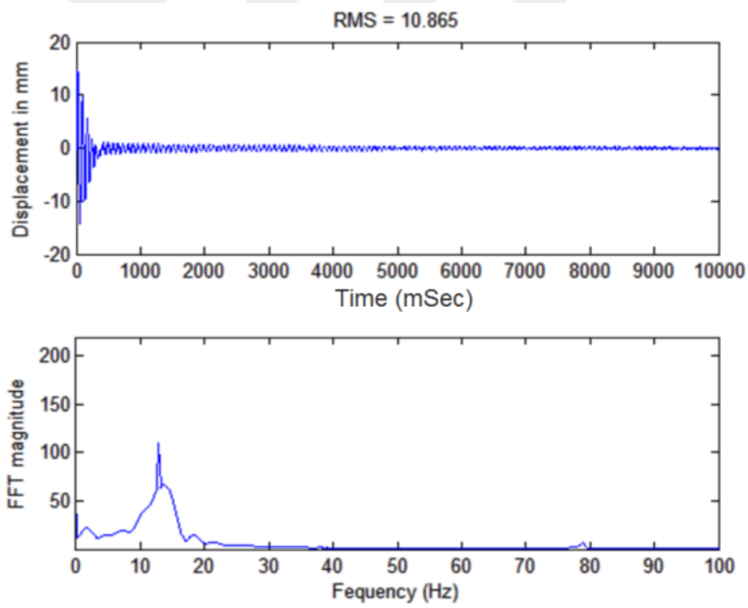

Figure 3.5 Control ON

The suppression can be numerically measured by computing the RMS value of vibration displacement (Liu, & et al., 2006). The RMS value when the control off is 32.3179. When the control is turned on RMS value dramatically reduced to a value of 10.865 under the action of closed loop control.

Control can be enabled at any time of vibration (Liu, & et al., 2006). In Figure 3.6 system freely oscillated until t+1000 mSec, after this time control is enabled and the oscillations are suppressed less than 400mSec after the activation of the control loop.

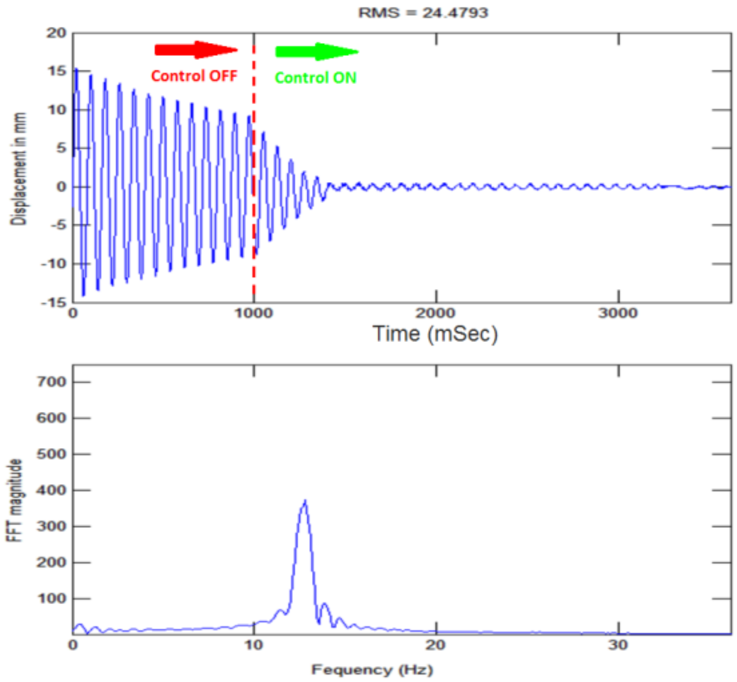

Figure 3.6 Control ON @ t+1000mSec

In the bang-bang control experiments different scenarios are tested and the results are recorded systematically via MatLab® and Microsoft® Excel™ software. In the first phase of experiment the power of the electromagnet coil is varied in steps to examine the effect of actuation power on vibration suppression. The control algorithm has a dead band parameter to determine the stopping criteria for the suppression algorithm. In this experiment 2.22mm dead band is used. Dead band concept is shown in Figure 3.7 Different dead band settings are lead to different results when suppressing the unwanted vibration.

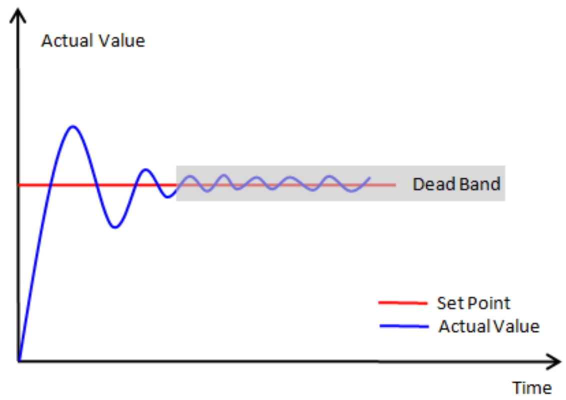

Figure 3.7 Dead band concept

Different levels of power have impact on the suppression time and RMS values. High values of applied power result with lower RMS value and lower settling times as shown in Figure 3.8 and Figure 3.9.

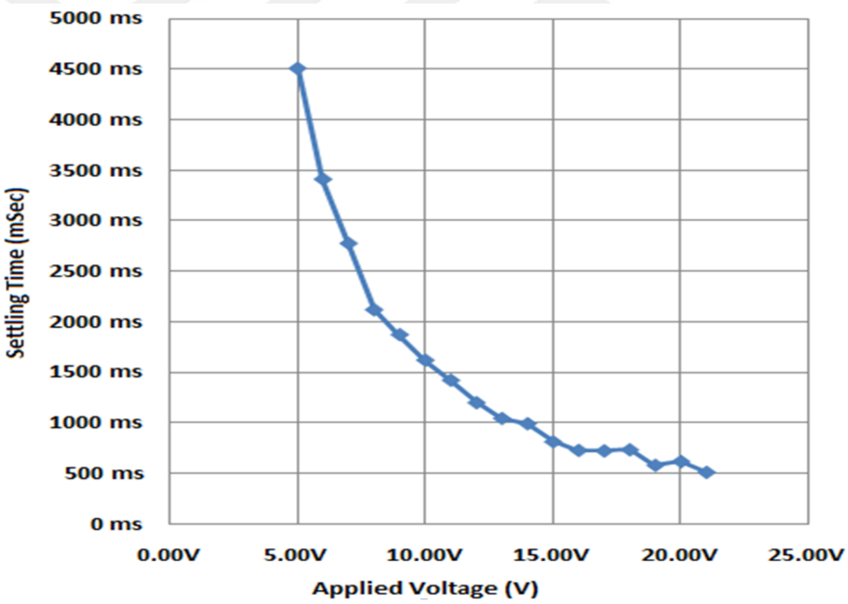

Figure 3.8 Settling time vs. actuator voltage

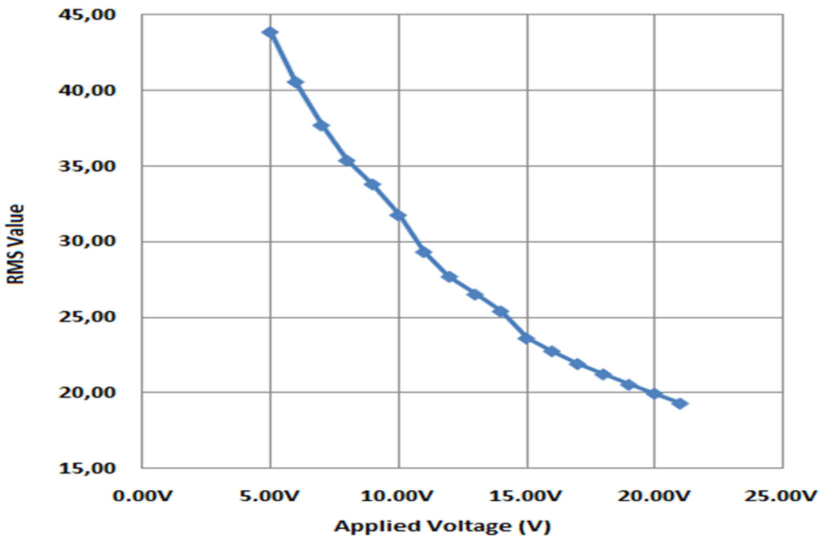

Figure 3.9 RMS value vs. actuator voltage

3.2 Proportional Control

Even though bang-bang control seems to be solving the vibration problem it is not a perfect solution. It has a significant dead band and long settling time as seen on Figure 3.10. Basically proportional control calculates the speed of displacement and the output power is controlled proportional to this data as seen on Figure 3.12. The FVS (Free Vibration Suppression) response of proportional suppression system is given in Figure 3.11. As it can clearly seen on the figures proportional control has less settling time and less steady state dead band vibrations.

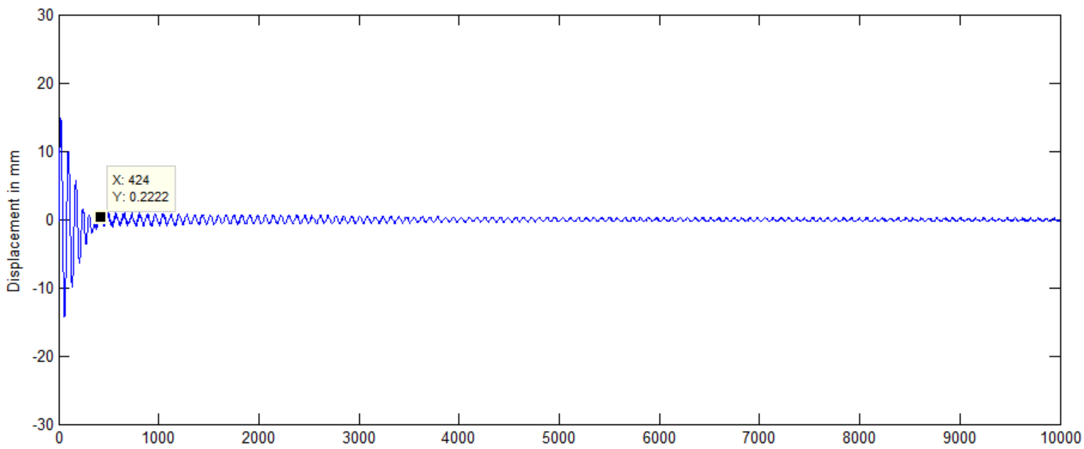

Figure 3.10 Bang-Bang control response

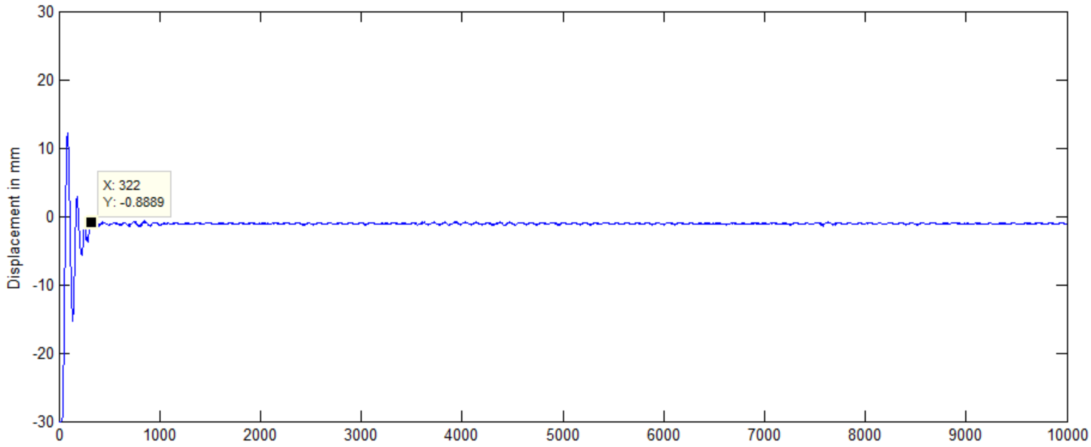

Figure 3.11 Proportional Control Response

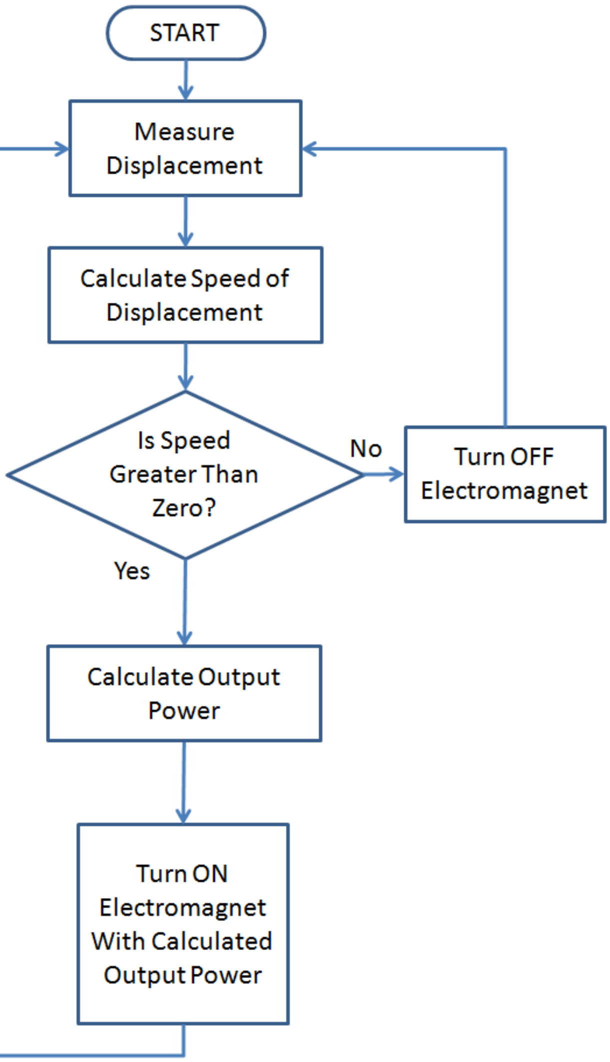

Figure 3.12 Proportional control algorithm flow chart

Main control loop program for proportional control loaded into the controller is shown below. Only main control loop is given, actual entire program is much complex and detailed.

```
For i = 1 To 10000 'Create a 10sec control loop
      Here:
      If IntBit = 0 Then GoTo Here 'Interruppt occurs every 1 msec, wait for
 it
      IntBit = 0 'Clear interrupt flag
      AI_0_RAW = ADIn 3 'Read the displacement

      SHOut RAM_SDI, RAM_CLK, msbfirst, [ AI_0_RAW\16] 'Store it in SPI RAM

      If i > 0  Then 'Control ON @ t+0

            If AI_0_RAW - OLD_AI < 50000 Then 'If derivative less than zero

                        PWM_Word = AI_0_RAW - OLD_AI 'Calculate the instant.
speed

                  PWM_Word = PWM_Word * 100 'Calculate output using gain value
                  If PWM_Word > 255 Then PWM_Word = 255 'Saturate the output
                  PWM_Val = PWM_Word 'Word to byte conversion
                  HPWM 1,PWM_Val,10000 'Drive the actuator
            Else
                  Low EN_B 'If not de energize the actuator
            EndIf

      OLD_AI = AI_0_RAW 'Store previous measurement for derivative
 calculation
      EndIf
Next 'Repeat the loop
```

Because of the nature of speed change of an object the output power driven to the actuator is modulated for proportional control. Different levels of power have effect on the suppression time and calculated RMS values. If applied power is high this results with lower RMS value and less settling times as shown in Figure 3.13 and Figure 3.14.

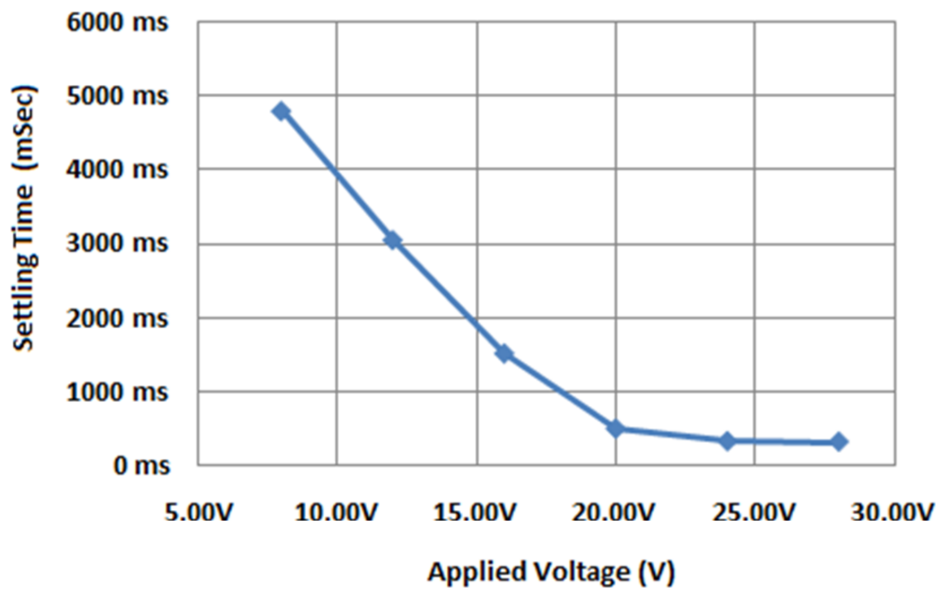

Figure 3.13 Settling time vs. actuator voltage

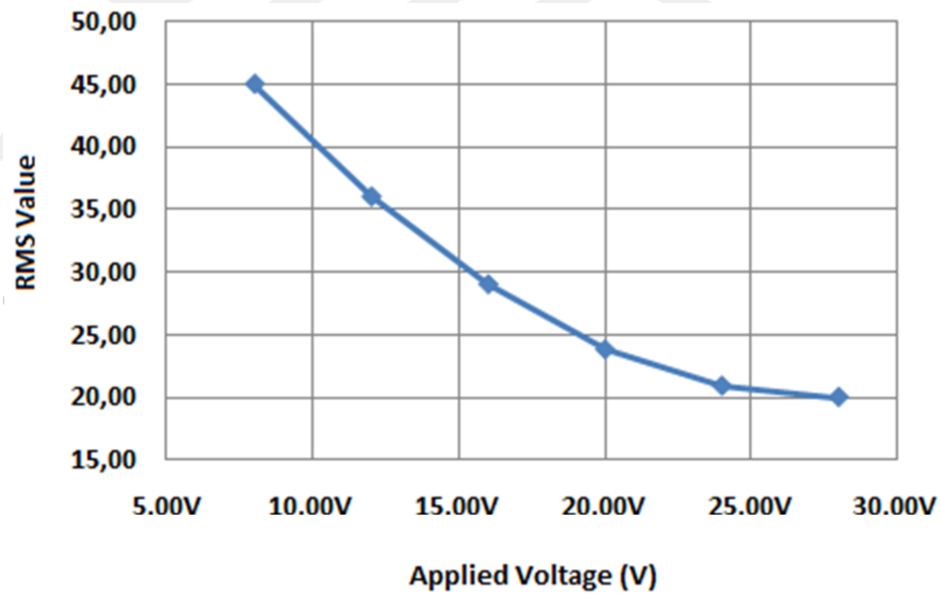

Figure 3.14 RMS value vs. actuator voltage

Two algorithms generate different responses in different regions of application. As the settling time the of two algorithm shows close responses bang-bang algorithm has better settling time for low voltages given in Figure 3.15. RMS value comparison states that bang-bang control algorithm shows better performance at low voltages but show unpredictable behavior at high voltages due to resonance issues given in Figure 3.16. Proportional control algorithm serves better stability and predictable response and very low steady state vibrations.

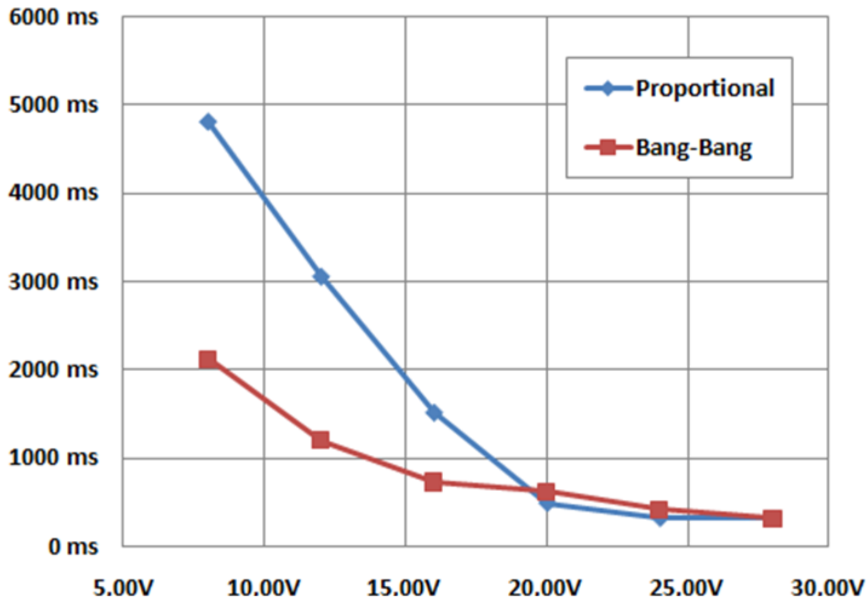

Figure 3.15 Settling time comparison between two algorithms

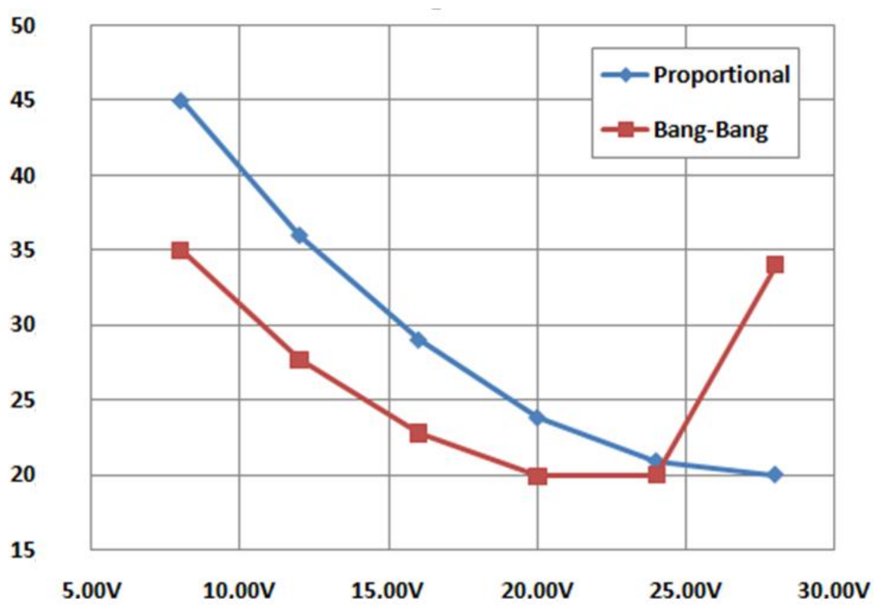

Figure 3.16 RMS Value comparison between two algorithm

Proportional control offers the advantage of using different gain values for the vibration suppression control given in Figure 3.17. In proportional mode both released mechanism free vibration suppression and impulse driven vibration suppression can be performed. Impulse driven results are given in Figure 3.18.

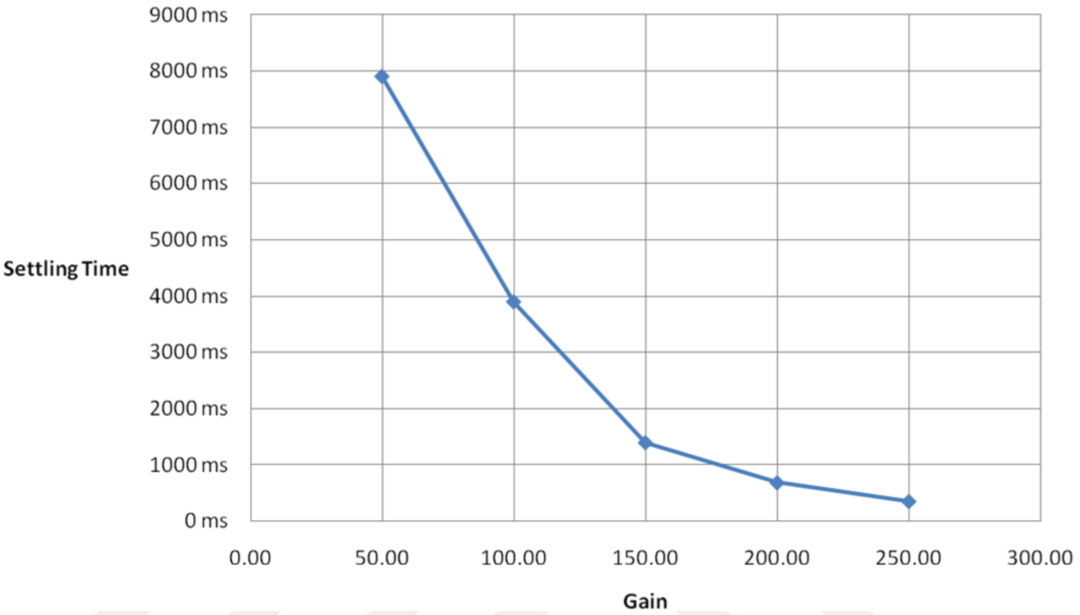

Figure 3.17 Free vibration suppression with different gain values

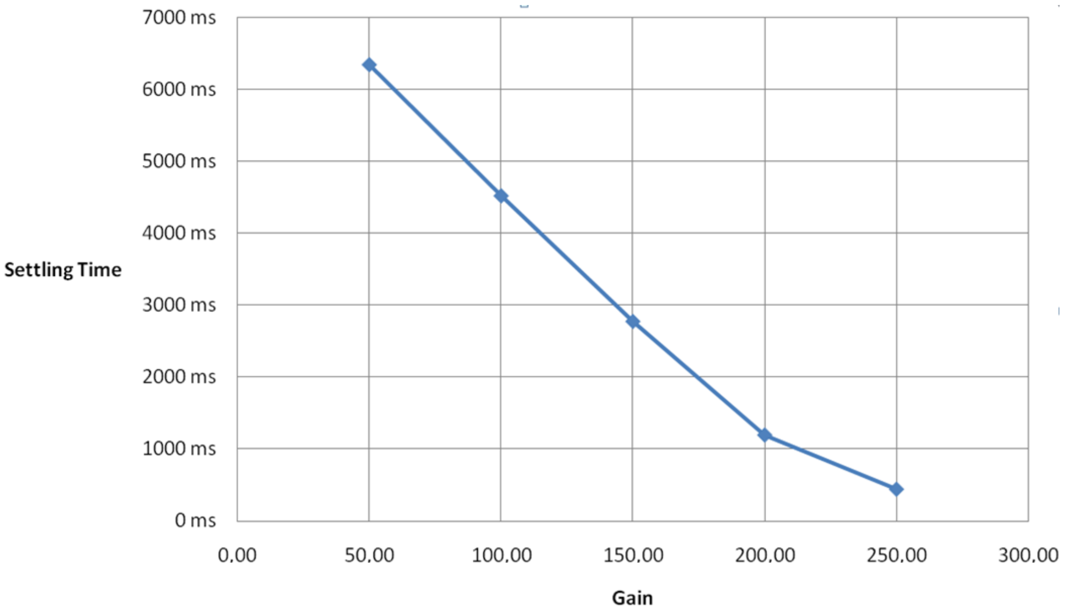

Figure 3.18 Impulse driven free vibration suppression with different gains

CHAPTER FOUR
DISPLACEMENT MANIPULATION

4.1 Displacement Manipulation

As a composite application this study includes vibration suppression and displacement manipulation in the same system. Displacement manipulation is done under the closed loop control in conjunction with vibration suppression. In general the result of vibration suppression promises to set the displacement to zero position. In this study vibration is suppressed plus the steady state displacement of cantilever beam is manipulated given in Figure4.1.

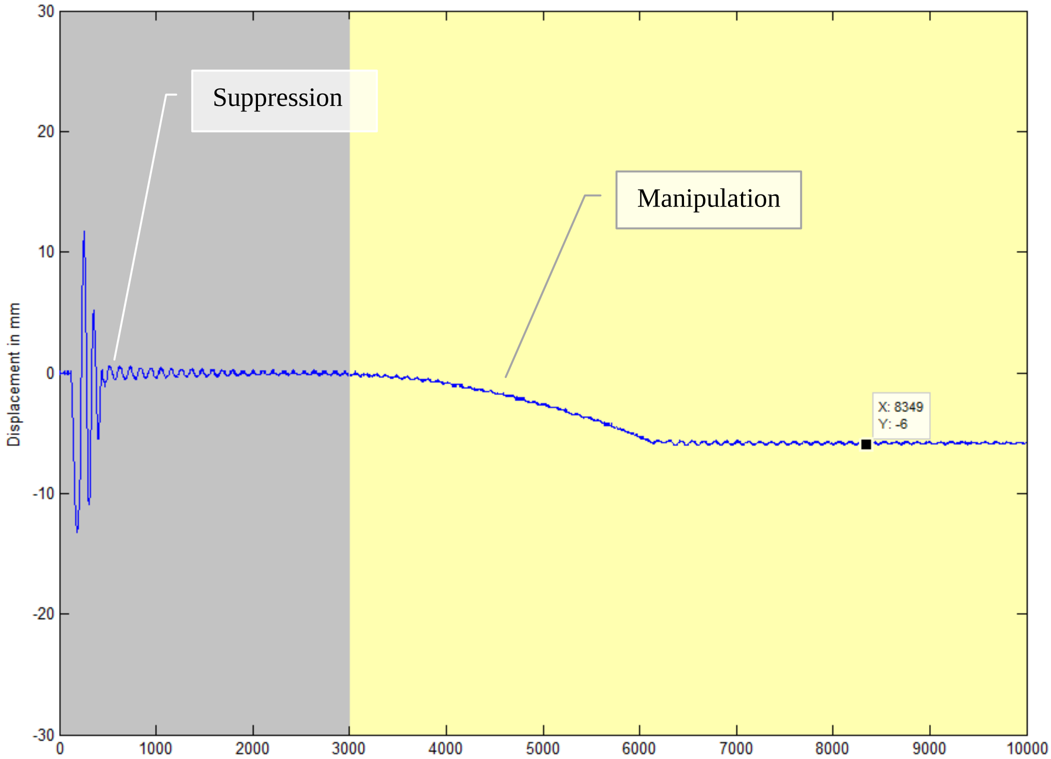

Figure 4.1 FVS & -6mm manipulation gain : 250, no load

Beyond manipulating the steady state displacement of the beam an additional mass can be fixed on the tip of the cantilever beam. Figure 4.2 show the system response of free vibration suppression and displacement manipulation of loaded cantilever beam with an additional mass. And the effect of proportional gain on manipulation performance can be seen with comparison of Figure 4.2 and Figure 4.3.

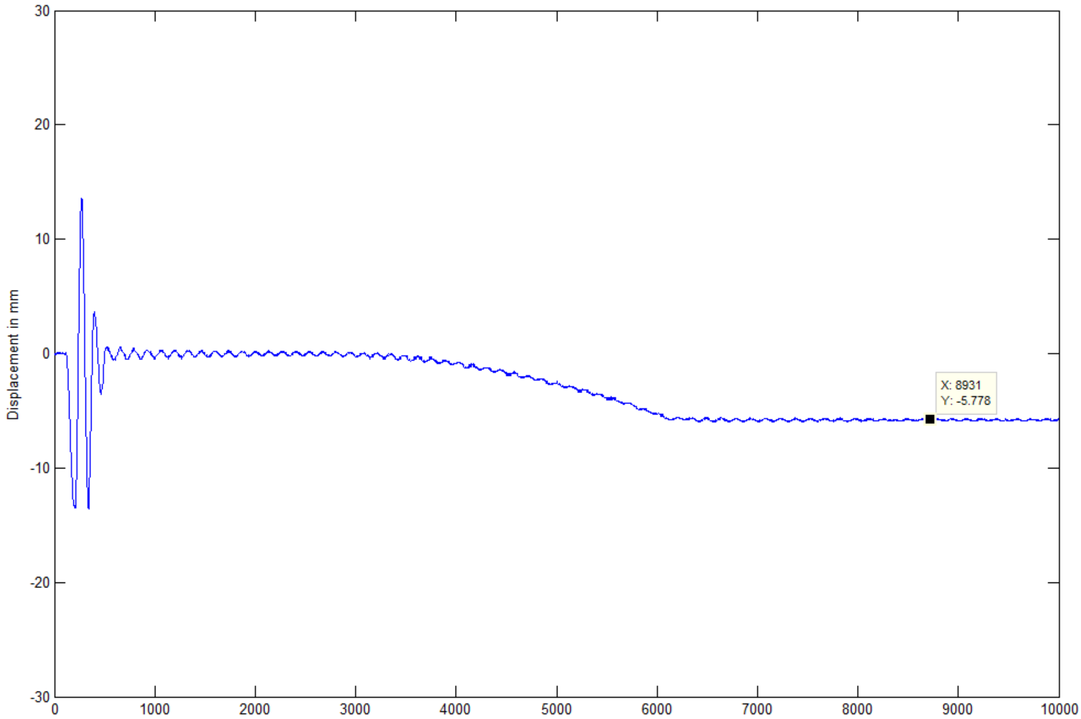

Figure 4.2 FVS & -6mm manipulation gain : 250, load 5 grams

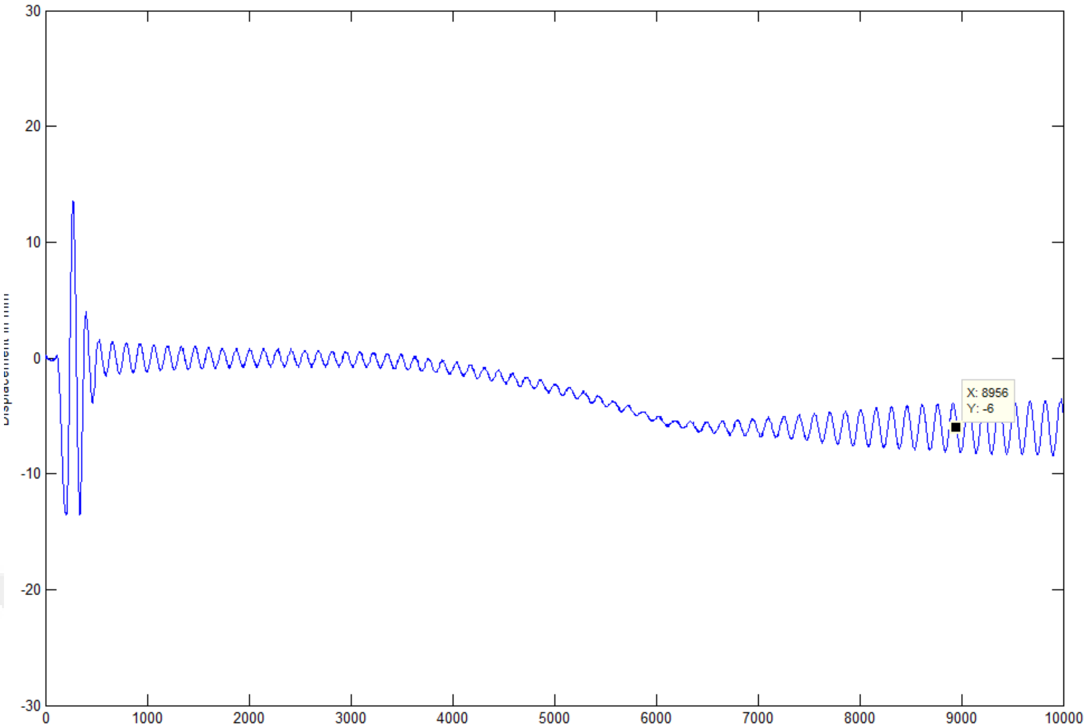

Figure 4.3 FVS & -6mm manipulation gain : 200, load 5 grams

The system allows controlling the displacement of cantilever beam without the presence of free vibration or impulse driven vibration. Figure 4.4 and Figure 4.5 show different manipulation commands and the system response in conjunction with the commands.

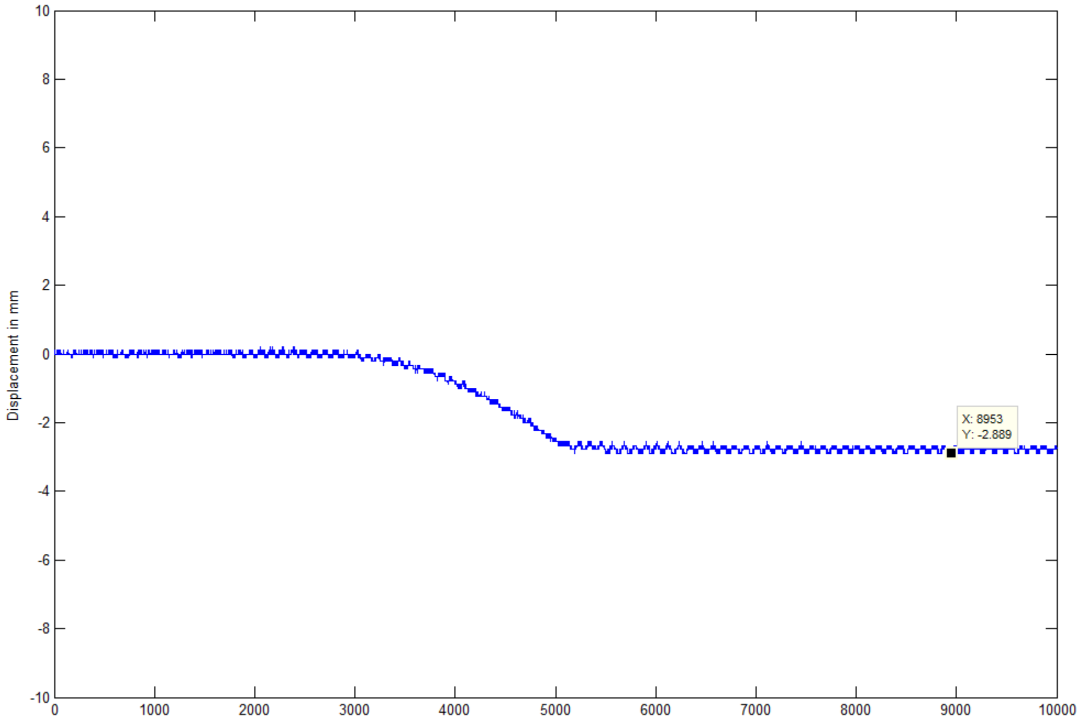

Figure 4.4 Direct -3mm manipulation

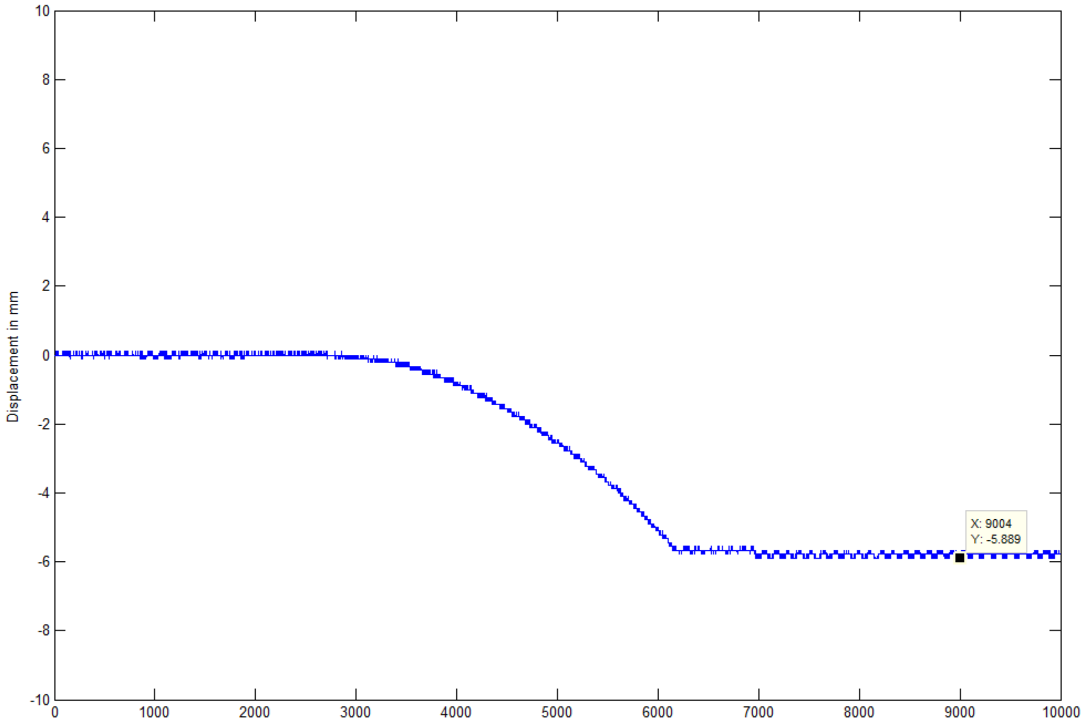

Figure 4.5 Direct -6mm manipulation

CHAPTER FIVE
CONCLUSIONS

In this study free vibration of a cantilever beam is suppressed using magnetic field generated under the control of a closed loop control system. An application specific end to end hardware is implemented in order to solve the problem with extreme flexibility. Two different algorithms are used and their performances are compared. Their strong and weak properties are studied and a tradeoff between two algorithms is observed in terms of vibration suppression characteristics.

In addition to vibration suppression, displacement manipulation is implemented successfully. The developed composite control system is capable of suppressing beam vibrations and manipulates cantilever beam displacement successfully. Thus composite system makes the design simpler. Besides a versatile solution for vibration suppression and displacement manipulation system can be realized. In the further phases much more advanced control algorithm can be applied on the experiment.

The main advantage of the designed system is its flexibility in terms of technical resources. This design can be called a tailor-made design. This advantage allows the experimenter to directly change every part of hardware, firmware and software.

This system can be used in very wide application areas from household appliances to aerospace applications as an end-to-end standalone design. As a future study this design can be improved by adding a second counter electromagnet while preserving the existed electromagnet bidirectional actuation can be done. Additionally implementing a moving actuator system can be used for suppression of higher mode vibrations and to obtain more efficient single mode vibration suppression performance.

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APPENDICES

APPENDIX 1 : Firmware Program of Mictrocontrolller

```
Device 18F4520
XTAL 10
Declare PLL_REQ = On
ALL_DIGITAL = On
ON_INTERRUPT GoTo MYINT

Symbol RS485_RXD = PORTC.7
Symbol RS485_TXD = PORTC.6

Symbol AI_0 = PORTA.0 '-10V...+10V
Symbol AI_1 = PORTA.1 '-10V...+10V
Symbol AI_2 = PORTA.2 '0...5V
Symbol AI_3 = PORTA.3 '0...5V

Symbol CUR_0 = PORTA.4 'COIL CURRENT A
Symbol CUR_1 = PORTA.5 'COIL CURRENT B

Symbol DI_1 = PORTE.2
Symbol DI_2 = PORTE.1
Symbol DI_3 = PORTE.0

Symbol DO_1 = PORTD.5
Symbol DO_2 = PORTC.1
Symbol DO_3 = PORTC.0

Symbol PH_1 = PORTB.1
Symbol EN_A = PORTB.0
Symbol PH_2 = PORTD.7

Symbol PH_4 = PORTD.4
Symbol EN_B = PORTC.2
Symbol PH_3 = PORTD.6

Symbol RAM_CS = PORTD.3
Symbol RAM_SDO = PORTD.2
Symbol RAM_SDI = PORTC.4
Symbol RAM_CLK = PORTC.5

Symbol VGA_BLACK = 0
Symbol VGA_BLUE = 1
Symbol VGA_GREEN = 2
Symbol VGA_CYAN = 3
Symbol VGA_RED = 4
Symbol VGA_MAGENTA = 5
Symbol VGA_BROWN = 6
Symbol VGA_BLACK2 = 7
Symbol VGA_GREY = 8
Symbol VGA_LTBLUE = 9
Symbol VGA_LTGREEN = 10
Symbol VGA_LTCYAN = 11
Symbol VGA_LTRED = 12
```

```
Symbol VGA_PINK = 13
Symbol VGA_YELLOW = 14
Symbol VGA_WHITE = 15

Dim StringTemp As String * 128
Dim StringIndex As Byte
Dim ASCII As Byte
Dim Color As Byte
Dim Row As Byte
Dim Col As Byte
Dim i As Word
Dim BarChar As Byte
Dim TIMER1 As TMR1L.Word                    ' Access 16 bits of TIMER1
Dim IntBit As Bit
Dim Envelope As Word

Dim OUT As Float
Dim ErrorE As Float
Dim IN As Float
Dim SETVal As Float


Dim Buff[20] As Word
Dim k As Byte

Dim B0 As Word
Dim B1 As Word
Dim B2 As Word
Dim B3 As Word
Dim B4 As Word
Dim B5 As Word
Dim B6 As Word
Dim B7 As Word
Dim B8 As Word
Dim B9 As Word
Dim RamStats As Byte

Dim Serdata As Byte

Dim PWM_Val As Byte
Dim PWM_Word As Word

Dim AI_0_RAW As Word
Dim AI_1_RAW As Word
Dim AI_2_RAW As Word
Dim AI_3_RAW As Word

Dim AI_0_VOLT As Float
Dim AI_1_VOLT As Float
Dim AI_2_VOLT As Float
Dim AI_3_VOLT As Float
Dim OLD_AI As Word
Dim SampleEnvelope As Bit

Dim RMS As Word
Dim RMS_SUM As Word

DelayMS 100
Dim ManData As Byte
```

```
Dim ManData2 As Byte
Dim IntTester As DWord

Input DI_1
Input DI_2
Input DI_3

Low DO_1
Low DO_2
Low DO_3

Low PH_1
Low EN_A
Low PH_2

Low PH_4
Low EN_B
Low PH_3


High PH_3



T1CON = %10000001        ' Turn on Timer1, prescaler = 1
INTCON      = $C0              ' Enable global interrupts, peripheral
interrupts
PIE1 = $01                     ' Enable TMR1 overflow interrupt
Clear
TIMER1 = 55536

GoTo MAIN   ' jump over the interrupt handler and sub



MYINT:
    TIMER1 = 55536
    bsf IntBit
      bcf      PIR1, 0

retfie fast




MAIN:


 '******* RAM INITIALIZE *******
 Output RAM_SDI
 Output RAM_CLK
 Output RAM_CS
 Input RAM_SDO
 RAM_CS = 0
 SHOut RAM_SDI, RAM_CLK, msbfirst, [$01, 64]  ' Enable sequential
mode
 RAM_CS = 1
 DelayMS 200
 RAM_CS = 0
```

```
 SHOut RAM_SDI, RAM_CLK, msbfirst, [$05]        ' Send read command
and address
 SHIn RAM_SDO, RAM_CLK, msbpre, [RamStats]    ' Read data
 RAM_CS = 1

 RAM_CS = 0
 SHOut RAM_SDI, RAM_CLK, msbfirst, [$01, 64]  ' Enable sequential
mode
 RAM_CS = 1
 DelayMS 200
 RAM_CS = 0
 SHOut RAM_SDI, RAM_CLK, msbfirst, [$05]        ' Send read command
and address
 SHIn RAM_SDO, RAM_CLK, msbpre, [RamStats]    ' Read data
 RAM_CS = 1

 '******* RAM INITIALIZE *******
Low PORTD.0
SHOut PORTC.3 , PORTD.1 , msbfirst , [6]  'Clear VGA
High PORTD.0
DelayMS 10

Low PORTD.0
SHOut PORTC.3 , PORTD.1 , msbfirst , [3,0]  'Set cursor zero
High PORTD.0


ADCON1 = %10001010  'ACTIVATE Analogue Input
ADCON2.7 = 1        'RIGHT Justified



Cls

Print At 2,1,"Proporti"

StringTemp = "Ready (Proportional Control)"
Row = 2
Col = 2
Color = VGA_WHITE
GoSub PrintTextVGA



 MainLoop:
    Inc k
    AI_0_RAW = ADIn 3



    AI_0_VOLT = AI_0_RAW
    AI_0_VOLT = AI_0_VOLT - 494
    AI_0_VOLT = AI_0_VOLT / 9



    Print At 1,1, DEC2 AI_0_VOLT,"mm     "
```

```
    If k.2 = 1 Then
        StringTemp = "#CONTROL OFF!"
        Row = 10
        Col = 8
        Color = VGA_YELLOW
        GoSub PrintTextVGA
    Else
        StringTemp = "             "
        Row = 10
        Col = 8
        Color = VGA_YELLOW
        GoSub PrintTextVGA
    EndIf



     SerIn PORTC.7, 6, 100, NODATA,
[Wait("XYZ"),Serdata,ManData,ManData2]
     Print At 2,1,DEC3 ManData," ",DEC3 ManData2
     NODATA:

     If Serdata = "M" Then
        Cls
        Print At 1,1,"Manipl."
        Serdata = 0
        High PH_3
        PWM_Val = 0
        While PWM_Val < 130
            Inc PWM_Val
            HPWM 1,PWM_Val,10000
            DelayMS 10
        Wend


        GoTo Manip
     EndIf

     If Serdata = "Q" Then
        OUT = 0
        PWM_Val = 0
        SETVal = ManData * 9
        SETVal = 494 - SETVal
        'Print At 2,1,DEC1 SETVal
        Serdata=0
        Print At 1,1, "Busy    "

        StringTemp = "Sampling...                                 "
        Row = 6
        Col = 0
        Color = VGA_WHITE
        GoSub PrintTextVGA

        StringTemp = "#CONTROL ON! (@ t+0 mSec)"
        Row = 10
        Col = 0
        Color = VGA_LTRED
        GoSub PrintTextVGA
```

```
        High DO_2 'Release trigger







        RAM_CS = 0

        SHOut RAM_SDI, RAM_CLK, msbfirst, [$02, 0\16] 'Start storing
data to RAM


        PWM_Val = 255
        For i = 1 To 10000
            Here:
            If IntBit = 0 Then GoTo Here
            IntBit = 0
            AI_0_RAW = ADIn 3
            SHOut RAM_SDI, RAM_CLK, msbfirst, [ AI_0_RAW\16]


            If i = 1000 Then Low DO_2    'Trigger OFF


            If i > 0 And i < 2000 Then  'Start time of suppression
in mseconds.


                If AI_0_RAW - OLD_AI < 50000 Then

                    High PH_3


                    PWM_Word = AI_0_RAW - OLD_AI
                    If PWM_Word < 1 Then PWM_Word = 0


                    PWM_Word = PWM_Word * 100


                    If PWM_Word > 255 Then PWM_Word = 255

                    PWM_Val = PWM_Word

                    HPWM 1,PWM_Val,10000

                Else
                    'Low PH_3
                    HPWM 1,0,10000
                EndIf

                OLD_AI = AI_0_RAW
```

```
    EndIf


    '**********************************
    '********** MANIPULATOR CODE ******
    '**********************************



    If i >= 2000 And i < 2500 Then
        OUT = OUT + 0.01
        PWM_Val = OUT
        If OUT > 130 Then OUT = 130
        HPWM 1,PWM_Val,10000
    EndIf


    If i > 6000 Then
        SETVal = ManData2 * 9
        SETVal = 494 - SETVal
    EndIf

    If i >= 2510 Then
        IN = AI_0_RAW

        ErrorE = SETVal - IN


        If ErrorE > 3 Then OUT = OUT - 0.03
        If ErrorE < -3 Then OUT = OUT + 0.03

        If OUT > 250 Then OUT = 250
        If OUT < 130 Then OUT = 130


        PWM_Val = OUT
        HPWM 1,PWM_Val,10000


    EndIf





Next


While PWM_Val > 0
    Dec PWM_Val
    HPWM 1,PWM_Val,10000
    DelayMS 10
Wend

HPWM 1,0,10000


RAM_CS = 1
```

```
        DelayMS 100
        HPWM 1,0,10000
        DelayMS 100

        StringTemp = "Uploading:"
        Row = 6
        Col = 0
        Color = VGA_WHITE
        GoSub PrintTextVGA


        RAM_CS = 0

        StringTemp = "#CONTROL OFF!"
        Row = 10
        Col = 0
        Color = VGA_LTRED
        GoSub PrintTextVGA

        StringTemp = "Sending...                           " : GoSub
PrintTextVGA

        StringTemp = "Progress:"
        Row = 6
        Col = 0
        Color = VGA_WHITE
        GoSub PrintTextVGA



        SHOut RAM_SDI, RAM_CLK, msbfirst, [$03, 0\16] 'Start reading
data from RAM

        For i = 1 To 1000
            SHIn RAM_SDO, RAM_CLK, msbpre,
[B0\16,B1\16,B2\16,B3\16,B4\16,B5\16,B6\16,B7\16,B8\16,B9\16]
            SerOut PORTC.6,
6,["A",B0,B1,B2,B3,B4,B5,B6,B7,B8,B9,"B"]
            SerIn PORTC.7, 6, 100, No_Conn, [Serdata]
            If i // 50 = 0 Then Low PORTD.0 : SHOut PORTC.3 ,
PORTD.1 , msbfirst, [$AD] : High PORTD.0
        Next

        RAM_CS = 1


        Low PORTD.0
        SHOut PORTC.3 , PORTD.1 , msbfirst , [6]  'Clear VGA
        High PORTD.0
        DelayMS 10

        Low PORTD.0
        SHOut PORTC.3 , PORTD.1 , msbfirst , [3,0]  'Set cursor zero
        High PORTD.0

       StringTemp = "Uploading finished, IDLE!                  "
: GoSub PrintTextVGA
        DelayMS 1000
```

```
            GoTo MAIN
        EndIf



      Serdata=0

  GoTo MainLoop

 End

 No_Conn:
     Cls
     Print At 1,1,"TimeOUT"
     DelayMS 1000

 GoTo MainLoop

 Dim Q As Word

 Manip:
     SerIn PORTC.7, 6, 100, AData, [ManData]
     Print At 2,1,DEC3 ManData,"mm"

     If ManData = 255 Then HPWM 1,0,10000: GoTo MainLoop
     AData:

     For Q = 0 To 1000
         AI_0_RAW = ADIn 3
         SETVal = ManData * 9
         SETVal = 494 - SETVal

         IN = AI_0_RAW

         ErrorE = SETVal - IN


         If ErrorE > 3 Then OUT = OUT - 0.02
         If ErrorE < -3 Then OUT = OUT + 0.02

         If OUT > 250 Then OUT = 250
         If OUT < 130 Then OUT = 130


         PWM_Val = OUT
         HPWM 1,PWM_Val,10000
         DelayUS 950
     Next

 GoTo Manip
```

```
PrintTextVGA:
    Low PORTD.0
    SHOut PORTC.3 , PORTD.1 , msbfirst , [2,Row,1,Col,4,Color]
    High PORTD.0

    StringIndex = 0
    Low PORTD.0
    While StringTemp[StringIndex]<>0
        ASCII = StringTemp[StringIndex]
        Inc StringIndex
        SHOut PORTC.3 , PORTD.1 , msbfirst, [ASCII]
    Wend
    High PORTD.0
Return
```

APPENDIX 2 : Windows Application Program for Data Acquisition

```
Dim DataArray(0 To 9999) As Long
Dim LowByte As Byte
Dim HighByte As Byte
Dim PaketVeri As String
Dim Adres As Double
Dim MATLAB As String



Private Sub Command1_Click()
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    Adres = 0
    MSComm1.Output = "XYZQ" & Chr(Val(Text2.Text)) &
Chr(Val(Text3.Text))
    Label2.Caption = "Sampling for 10 seconds."
     Beep 1200, 750
End Sub

Private Sub Command2_Click()

    MATLAB = "A = ["

    For Adres = 0 To 9999
        MATLAB = MATLAB & Val(DataArray(Adres)) & " "
    Next

    MATLAB = MATLAB & "];"
    'Clipboard.Clear
    'Clipboard.SetText (MATLAB)

End Sub

Private Sub Command3_Click()
    MSComm1.DTREnable = True
    MSComm1.DTREnable = False
End Sub

Private Sub Command4_Click()
```

```
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    Adres = 0
    MSComm1.Output = "XYZM"
    Timer1.Enabled = True


End Sub

Private Sub Command5_Click()
    Timer1.Enabled = False
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    Adres = 0
    MSComm1.Output = Chr(255)

End Sub

Private Sub Form_Load()

    Label2.Caption = "IDLE"
End Sub

Private Sub HScroll1_Change()
    Label6.Caption = HScroll1 & "mm"
End Sub

Private Sub MSComm1_OnComm()

    PaketVeri = MSComm1.Input

    'If Len(PaketVeri) <> 22 Then Me.Caption = "HATA":
    'Me.Caption = Len(PaketVeri)


    For k = 0 To 9

        LowByte = Asc(Mid(PaketVeri, k * 2 + 2, 1))
        HighByte = Asc(Mid(PaketVeri, k * 2 + 3, 1))
```

```
        DataArray(k + Adres) = (LowByte + HighByte * 256)



        'Text1.Text = Text1.Text & DataArray(k + Adres) & " "

    Next

    Adres = Adres + 10
    MSComm1.Output = "."
    Label1.Caption = Round(Adres / 100) & "%"
    Shape1.Width = 6135 * Adres / 10000
    Label2.Caption = "Downloading data..."

    If Adres = 10000 Then
        Label2.Caption = "IDLE"
        Command2_Click
        FilePath = "C:\Users\Administrator\Desktop\Y.
Lisans\TEZ\Matlab\sampling.m"
            Open FilePath For Output As #3
                Print #3, MATLAB;
            Close #3



            FilePath = "C:\Users\Administrator\Desktop\Y.
Lisans\TEZ\Matlab\" & Text1.Text & ".m"
            Open FilePath For Output As #3
                Print #3, MATLAB;
            Close #3
            Beep 1200, 300
            Beep 1200, 300
            MSComm1.PortOpen = False
    End If



End Sub

Private Sub Timer1_Timer()
```

```
    If MSComm1.PortOpen = False Then MSComm1.PortOpen = True
    MSComm1.Output = Chr(HScroll1)
End Sub
```