İSTANBUL TECHNICAL UNIVERSITY ★ INSTITUTE OF SCIENCE AND TECHNOLOGY

DEVELOPING TECHNIQUES FOR REDUCING EMC EFFECTS ON MICROCONTROLLER BASED MEDICAL EQUIPMENT

M.Sc. Thesis by
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Programme: **Biomedical Engineering**

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

MİKRODENETLEYİCİ TABANLI BİYOMEDİKAL CİHAZLAR ÜZERİNDEKİ EMC ETKİLERİNİN AZALTILMASI İÇİN GELİŞTİRİLEN TEKNİKLER

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PREFACE

This thesis is based on working experience from August 2001 to April 2007 at the ROTA Electronics Company as a R&D Engineer and the Department of Avionics Engineering of the Engineering Directorate as an Avionics System Engineer in Turkish Airlines (THY) Technic.

I would like to express my sincere gratitude to my leading supervisor Adem HAYATSEVER in ROTA. Without his advise and unique support, this thesis would never been existed. Furthermore, I would like to thank my co-supervisors MSc. Murat ÖZ and MSc. Ömer AÇIKGÖZ for their great co-operation and help.

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May 2007 **Sedat KARAKAŞ**

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ABBREVIATIONS

AC : Alternative Current
A/D : Analog to Digital
AM : Amplitude Modulation
BCD : Binary Coded Decimal
CISPR : Internal Special Committee on Radio Interference
CMOS : Complementary Metal-Oxide Semiconductor
COP : Computer Operating Properly
CPU : Central Processing Unit
CRR : Recovery Routine
CSIC : Customer-Specified Integrated Circuit
DC : Direct Current
DIP : Dual Inline Package
DTMF : Dual Tone Multifrequency
DUT : Device Under Test
EEC : European Economic Community
EEPROM : Electronicaly Eraseable and Programmable Read Only Memory
EXTAL : External
EMC : Electromagnetic Compatibility
EME : Electromagnetic Emissions
EMI : Electromagnetic Interferance
EMS : Electromagnetic Susceptibilty
EN : European Norm
ESD : Electrostatic Discharge
ESL : Equivalent Series Inductance
ESR : Equivalent Series Resistance
FCC : Federal Communication Commission
FM : Frequence Modulation
FSK : Frequency Shift Keying
GND : Ground
GSM : Global System for Mobile Communications
GUI : Graphical User Interface
HCMOS : High-Density Complementary Metal Oxide Semiconductor
HF : High Frequency
I/O : Input / Output
IC : Integrated Circuit
IEC : International Electrotechnical Commission
IRQ : Inrerrupt request
ISP : In-System Programming
IRST : Internal Reset Signal
KBI : Keyboard interrupt
LCD : Liquid Crystal Display
LED : Light Emitted Diode
LVD : Low Voltage Detector
LVI : Low Voltage Inhibit

LVR	: Low Voltage Reset
MCU	: Microcontroller Unit
MHz	: Megahertz
ML-STD	: Military Standart
MR	: Manuel Reset
NOP	: No-Operation Instructions
OSC	: Oscillator
PCB	: Printed Circuit Board
PDIP	: Plastic Dual-In-line Package
PLL	: Phase-Locked Loop
POR	: Power On Reset
PTA	: PortA
PTB	: PortB
PTC	: PortC
PTD	: PortD
PWM	: Pulse Width Modulation
QFP	: Quad Flat Packages
RAM	: Random Access Memory
RF	: Radio Frequency
RFI	: Radio Frequency Interference
ROM	: Read Only Memory
RSR	: Reset Status Register
RST	: External Reset Pin
SEG	: Segment
SIM	: System Integration Module
SMC	: Surface-Mounted Components
SMD	: Surface-Mounted Devices
SMPS	: Switch Mode Power Supply
SO	: Small Outline
SOIC	: Small Outline Integrated Circuit
TCI	: Temperature Controlled Incubator
THY	: Turkish Airlines
TIM	: Timer Interface Module
TQFP	: Thin Quad Flat Pack
TTL	: Transistor Transistor Logic
TV	: Television
UME	: Ulusal Metroloji Enstitüsü
VDE	: Verland Deutcher Electro-Techniker
VGA	: Video Graphics Array
VLSI	: Very Large Scale Integration
VSWR	: Voltage Standing Wave Ratio
WDI	: Watchdog Input
WDPO	: Watchdog Pulse Output
WFI	: Waiting for Instructions
XTAL	: Crystal

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SYMBOL LIST

cm : Centimeter
Cs : Storage Capacity
Hz : Hertz
GHz : Gigahertz
I/O : Input/Output
Khz : Kilohertz
kV : Kilovolt
mA : Miliamper
Mhz : Megahertz
ms : Milisecond
M Ω : Megaohm
nF : Nanofarad
nH : Nanohenry
nS : Nanosecond
pF : Picofarad
Rd : Discharge Resistance
S : Switch
T1 : Timing value
T2 : Timing value
Vcc : Power Supply upper
Vdd : Power Supply upper
Vs : High Voltage Power Supply
Vss : Power Supply lower
V/M : Volt/Meter
Volt : Volt
Ω : Ohm
µF : Microfarad
µS : Microsecond

SUMMARY

The research in this thesis addresses the question of how Electromagnetic Compatibility (EMC) improvement on microcontroller-based medical devices can be developed from their corrupt environment and enhanced an application of medical device that allows to exchange information from this environment by means of those concepts which are hardware and software EMC techniques. A medical device is a system, in software or in hardware, that receives sensor input from the environment, selects actions, and may receive evaluative feedback reflecting the appropriateness of its actions. Communication is viewed as the transfer of information, in the sense that when a sender sends a message to a receiver, the amount of uncertainty in the receiver's knowledge about its environment decreases as a result of receiving the message because of the fact that Electromagnetic Interference (EMI) effects on medical devices have been increasing from day to day. For solving these bad effects from this device, some techniques will be explained and made a medical application.

Section 1, EMC introduces the concepts of electromagnetic compatibility and interference, why they need to be considered and how interference manifests itself. The present regulations are explained and any exceptions beetween these are noted. The frequency ranges, in which regulations test for EMC and typical solutions to EMI are examined, those available to the designer and techniques used by biomedical engineers. Then, EMI in a typical medical device discusses the ways in which EMI can occur. Then a closer look is taken to sources of emissions such as: natural interference, manmade interference, nuclear electromagnetic pulses and electrostatic discharge. Susceptibility and immunity of objects is examined such as the immunity to power supply irregularities.

Section 2, In this section, some hardware techniques will be explanied that medical applications in modern electronics, as component size continues to decrease and complexity to increase, electrostatic and magnetic fields and their interactions are becoming increasingly important. As problems have arisen, creative solutions have been developed. In this chapter, pulls together the latest tools and techniques for overcoming problems related to electrostatic and electromagnetic coupling. An understanding of the principles and recent developments in this growing field is essential to many individuals in both the commercial and medical electronics industries. This chapter is intended for individuals whose work requires an

understanding of the effects of interacting electrostatic and magnetic fields on electrical and electronic microcontroller-based medical equipment on hardware concept. Circuit designers, electronics packaging specialists and systems engineers will find this chapter helpful. Objectives to help engineers to understand grounding, shielding, PCB mounting and the other special concepts and terminology. To provide an overview of the newest and most effective techniques for overcoming EMC problems through the preventive hardware techniques.

Section 3, The software used on the medical equipment also has an impact on the EMC performance of the system. For the tests performed on the medical devices show that the hardened software used in medical devices decreases the EMC emissions in certain areas. The impact of software on immunity may prove greater than for emissions. In this chapter, some sofware techniques that are preventive and auto-recovery have been developed for safety of critical medical systems with regards to many potential threats. For instance, redundancy in software (e.g. securing the unused memory area, readings of input data, watchdog using correctly, using the reset flags to identify the reset sorce, etc.), diagnostic reporting, monitoring of critical/susceptible I/O pins, monitoring of memory are explained. In particular, examples have been developed for implementing software techniques with regard to EMC. These explained software techniques may provide additional immunity for harsh environments and when infrequent high level threats occur on biomedical devices.

Section 4, This chapter covers testing of medical equipment and systems. The explanation of the testing phase is in this chapter presented at the intermediate level, which is used to know general information about EMC test phase of the biomedical devices at the electronic/electrical engineering level. A brief review of basic EMI/EMC test stages that are ESD immunity test, fast transient burst immunity and emission tests principles are presented. The overall objective of this chapter is not only to develop a thorough practical understanding of EMI/EMC testing of microcontroller-based medical systems but also to understand which test equipment are used in the testing phase.

Section 5, In this chapter presents an application of medical device that is Temperature Controlled Incubator (TCI). The main aim of this thesis is to give not only theoretical aspects besides to show real application whatever the harware and software techniques are explained in before chapters. For that reason, all of the design phase of making hardened medical application towards EMC harmful effects are explained by means of this TCI application.

ÖZET

Bu tezdeki araştırmaların hedefi bozucu etkiler içerisinde bulunan mikrodenetleyici tabanlı medikal cihazların Elektromanyetik Uyumluluklarının (EMC) nasıl arttırılabilir sorusuna cevap vermek ve çevrebirimleri ile bilgi alışverişinde bulunan bir medikal cihaz tasarlayarak gelişmiş donanım ve yazılım tekniklerini de kullanarak EMC olarak daha gelişmiş bir uygulama gerçekleştirmektir. Medikal bir cihaz; yazılım veya donanımında çevresinden bilgi girişi alan, işlevsel seçimler yapabilen ve yaptığı seçimler sonucunda geri besleme alabilme özelliğine sahip bir sistemdir. Bilgi aktarımı esnasında gözlenen haberleşme, gün geçtikçe etkisi artmakta devam eden biyomedikal cihazlar üzerindeki Elektromanyetik Girişim (EMI) sonucu etkilenmekte, bunun sonucu olarak da iletilen bilgi alıcı tarafına ulaştığında değişmekte ve dolayısıyla çevresindeki bilgilerden daha az haberdar olan bir duruma doğru gidilmektedir. Cihazlar üzerindeki bu bozucu kötü etkileri azaltmak için bazı teknikler açıklanacak ve bir medikal uygulama yapılacaktır.

Bölüm 1, Bu bölümde EMC kavramını oluşturan elektromanyetik uyumluluk ve girişim konusu, niçin bu konunun düşünülmesi gerektiği ve bu girişimlerden nasıl etkilenildiği gibi konulara giriş yapılacaktır. Mevcut düzenleyici kurumların kuralları açıklanacak ve bunların dışında kalan kısımlarda not edilecektir. Biyomedikal mühendislerinin ve tasarımcılarının kullanabilecekleri ve ulaşabilecekleri EMC testleri için düzenleyici kurumların belirlediği frekans aralıkları ve tipik çözümler üzerinde çalışılacaktır. Daha sonra tipik bir medikal cihaz üzerindeki EMI etkileri hangi yollarla oluştuğu konusu tartışılacaktır. Ayrıca girişim oluşturan kaynaklara kısaca bir göz atılacaktır. Örnek olarak; bozucu girişim yapan doğal kaynaklar, suni kaynaklar, nükleer elektromanyetik darbeler ve elektrostatik boşalma konularından bahsedilecektir. Bağışıklık üzerinde, örnek olarak güç kaynaklarından oluşan bozucu etkilere karşı nasıl bağışıklık sağlanabilir konusunda çalışılacaktır.

Bölüm 2, Bu bölümde modern elektronik konusu olan biyomedikal uygulamalar için bazı donanım teknikleri açıklanacaktır. Sürekli olarak devam etmekte olan; komponent boyutlarındaki küçülmeler ve karmaşık yapılara dönüşüm gibi kavramlar, elektrostatik ve manyetik alan etkileşimlerinin önemini arttırmaktadır. Artan bu problemlere karşı ise çözümler geliştirilmektedir. Bu bölümde ise elektrostatik ve elektromanyetik kuplajlara karşı geliştirilen son ekipmanlar ve teknikler toparlanmaktadır. Ticari ve medikal elektronik endüstrisinde bulunan birçok kimsenin bilmesi gerekli bir konu olan ve her geçen gün gelişen bir alan haline gelen

bu tekniklerin temel prensipleri ve son gelişmeler bahsedilecektir. Bu bölümde mikrodenetleyici tabanlı elektrik ve elektronik medikal cihazların donanım konsepti üzerinde etkilerde bulunan, elektrostatik ve manyetik alanların etkilerini anlamaya ihtiyacı olanlara bilgi vermek amaçlanmıştır. Devre tasarımcıları, elektronik uzmanları ve sistem mühendisleri bu bölümden memnun olacaklardır. Amaç bu kişilere devre dizaynı esnasında EMC'ye karşı nasıl bir donanım gerçekleştirmenin anlatılmasıdır.

Bölüm 3, Medikal cihazlar içerisinde bulunan yazılımlar, EMC performansı açısından önem arzetmektedir. Medikal cihazlar üzerinde yapılan testler sonucunda güçlendirilmiş yazılım kullanan cihazların EMC'ye karşı daha az etkilendikleri saptanmıştır. Bu bölümde potansiyel bozucu etkilere maruz kalan medikal cihazlar için bazı önleyici ve kurtarıcı yazılım teknikleri anlatılacaktır. Örnek olarak; kullanılmayan hafıza alanlarının güvenli hale getirilmesi, giriş bilgilerini okuma, zaman kontrollü resetleme, reset durum kontrolleri verilebilir. Açıklanan bu yazılım teknikleri bozucu etkiler barındıran ortamlarda bulunan medikal cihazlar için bağışıklığı arttıran tekniklerdir.

Bölüm 4, Bu bölüm medikal cihazlar ve sistemlerin testlerini kapsamaktadır. Anlatılan bu testler orta bilgi seviyesinde olmakla birlikte; elektronik-elektrik mühendisleri seviyesinde EMC test fazı hakkında genel bilgi amaçlı kullanılabilir. Temel olarak EMI/EMC testleri; ESD bağışıklık testleri, hızlı geçiş bağışıklık testleri ve yayınım test prensipleri olarak sunulmaktadır. Bu bölümün kapsamı mikrodenetleyici tabanlı medikal sistemlerin test fazını anlamakla birlikte test sırasında kullanılan cihazlar hakkında da genel bilgi sağlamaktır.

Bölüm 5, Bu bölümde bir medikal cihaz uygulaması olan sıcaklık kontrollü bebek küvözü (TCI) uygulaması sunulmaktadır. Bu tezin temel amacı sadece teorik bilgiler vermekten ziyade aynı zamanda daha önceki bölümlerde bahsedilen donanım ve yazılım tekniklerini de kullanarak gerçek bir uygulama göstermektir. Bu amaçla bozucu EMC etkilerine karşı geliştirilen bir medikal cihazın, TCI, bütün tasarım aşamaları açıklanmaktadır.

1. INTRODUCTION

This thesis discusses how to design a single-chip microcontroller application considering electromagnetic compatibility (EMC). Today almost every consumer, medical, automotive, and industrial application has a microcontroller (MCU) inside. More often than not, it will be a low-cost, single-chip MCU. Single-chip MCUs are ideal because of the flexibility and functionalty incorporated on one piece of slicon. Typical MCUs have their own CPU, RAM, ROM and input/output (I/O) ports and can have customized functions such as analog/digital modules, LCD drivers, on-screen display for television applications, dual-tone multifrequency (DTMF) generators for telephones, AC motor drive circuits, and EEPROM for non-volatile data storage.

As MCU functionality increases becoming more complex and with market costs being driven lower, MCU producers must reduce their manufacturing costs continually. Reducing the geometries of the on-chip transistors and gates achieves this, and also helps produce MCUs capable of functioning at higher operating frequencies.

As a transistor's gate size is reduced, the transition time decreases, and according to Fourier Analysis, fast edges on signals produce harmonic signals. These signals, if amplified, can cause emission problems. In a similar vein, if the devices have faster transition times, they can react to faster incoming signals, which can result in a gate being switched because of a high frequency noise spike and a false signal. Most modern MCUs operate with speeds ranging from 2 MHz to 40 MHz, with internal devices having switching speeds from a few nanoseconds to below a nanosecond, making them potential EMC problems.

EMC must be taken into account at the very beginning of a project as the cost of correcting an EMC problem encountered at the start of production can be far greater than the cost of a detailed EMC study during the development phase of an application [1].

Also, the use of microcontroller-based medical systems is increasingly wide-spread, the drive for cost reduction is the common trend. This emphasis on cost reduction and the increasing complexity of such systems requires the manufacturers of semiconductor components to develop highly integrated, single chip, high operating frequency microcontrollers using the highest density technology possible.

Unfortunately, for semiconductor structures, the higher the density and the faster the operation, intrinsically the higher the level of electrical noise generated, and the increased sensitivity to spikes induced from external noise. Therefore, the PCB layout, the software and the system must now apply EMC “hardening” techniques in their design. This thesis aims to provide guidelines for designers of microcontroller-based medical applications so that the optimum level of EMC performances can be achieved.

1.1 What is EMC?

Almost every electronic device emits some electromagnetic interference (EMI). These emissions can be transmitted as electromagnetic radiation or conducted through cables such as power cords. At the same time, most electronic devices are susceptible to emissions generated either internally or by other devices [2].

In other terms, it is the ability of any electrical or electronic equipment to operate without suffering any EMI from other electronic products. EMI may be described as an electronic form of pollution and its effects include causing radios to crackle and making sensitive medical equipment malfunction.

Because many electronic circuits are in proximity to each other, it is essential that their design is not affected by external noise sources and that the circuit itself is not a noise source affecting other circuits. This relationship is known as electromagnetic compatibility or EMC. Sources of electromagnetic noise are numerous and have both natural and man-made origins [2].

Natural sources below 10 MHz are dominated by the atmospheric noise generated by electrical storms. Above 10 MHz, natural sources consist primarily of cosmic noise and solar radiation [2].

Man-made noise include AM, FM, TV and other broadcast transmitters, mobiles radios but also computing devices, motors, appliances, power lines, auto ignition systems, GSM phones and many others. With the proliferation of these sources (particularly in urban areas), electromagnetic noise has reached important levels [1].

Receptors susceptible to electromagnetic radiation include communication receivers such as radio and television, radar and navigation devices or computing devices. The effect of the interference on the receptor depends on several parameters: strength of the source, transmission medium, distance from the source, coupling mechanisms and degree of susceptibility of the medium [2].

EMC can be split into two major fields which are Electromagnetic Interference (EMI) or Emissions (EME) and Electromagnetic Susceptibility (EMS) or Immunity shown in

Figure 1.1. EMI tests involve measuring the frequency and amplitude of undesirable signals emitted by the tested equipment. Signal radiated into free space are called radiated emissions, whereas signals travelling along power cords or other interconnecting cables are called conducted emissions [2].

EMS testing is a way to determine the ability of the device to operate properly in an undesirable electromagnetic environment. These tests use signal sources and power amplifiers to generate high level fields around a device. Conducted susceptibility measurements are performed by coupling an offending signal of a specified level onto cables to try to induce a malfunction into the tested device. Other forms of susceptibility tests include electrostatic discharge (ESD), transient burst, voltage surge testing [2] and the others.

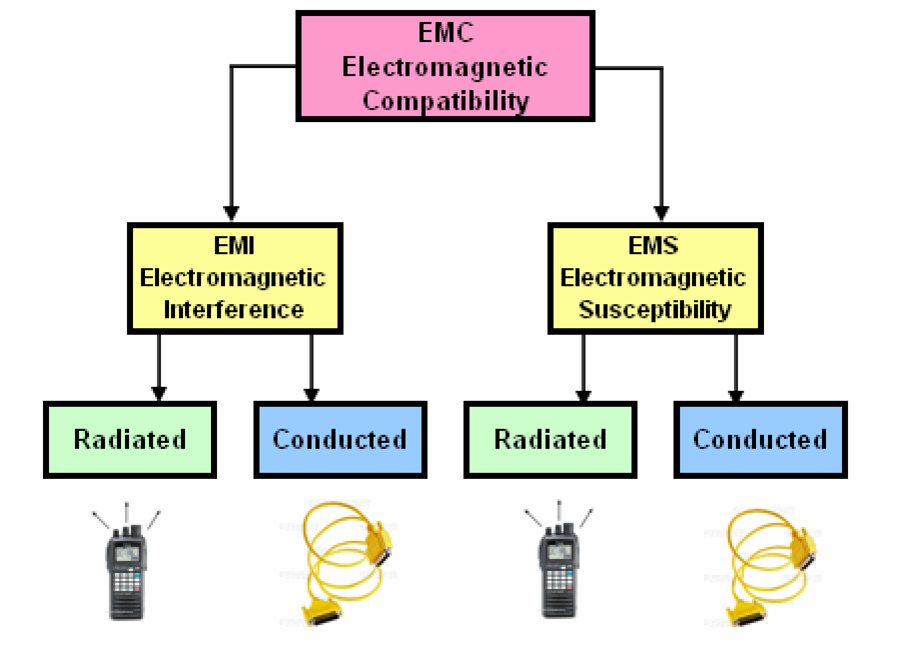


Figure 1.1: EMC Contents: EMI and EMS

1.1.1 Emissions

Emissions from any digital source are normally high frequency, coming from the harmonics produced by the high-frequency clock rates that make up a square wave. These emissions generally are radiated and created by the currents switching beetween the source and return paths of the digital signals and on the main power supply to the digital source. These fast switching currents flow in loops acting as small antennas, which radiate magnetic fields known as differential-mode radiation. Also, any resistive or inductive paths can cause voltage drops in the circuit, which will put some parts of the circuit at a common-mode potential relative to true ground.

If an emission problem exists with single-chip MCU applications, the PCB design most likely will be the major contributing factor, as loop areas within the silicon are several magnitudes smaller than those created on a PCB. Emissions are likely to come from the power supply (GND and Vdd), since the sum of all currents in the digital chip pass through here. Port pins are designed with higher drive capability than internal gates and, therefore, generally are larger in size, resulting in increased capacitance ensuring that the transitions of the digital signal are slower than the transition times of internal gates. Since port pins are controlled normally by software, they will switch at the lower frequencies than those of internal MCU circuits, meaning that port pins are not usually problematic areas in emissions. The exception is when the port pins drive or source high currents, where the magnetic field strength is proportional to the switching current and also proportional to the loop antenna area. The solution is either to reduce the current or reduce the loop area. In most cases, the loop area is altered.

The fastest fundamental external frequency to the MCU is the oscillator circuit. This is normally a signal which is nearly sinusoidal, if a crystal-based circuit is used. Because the oscillator circuit normally is very small and sinusoidal, the higher order harmonics are attenuated greatly and, consequently, should not upset other circuits. Again, if the clock comes from an external, take care that the path for this signal is kept as close as possible to the return ground path/plane to reduce the loop area to a minimum.

For MCUs with external memory peripherals and even microprocessors, emissions can be more problematic. For instance, the main noise source is the clock/strobe that enables the external memory, which is switching very fast, has been routed without thought, and has a very long ground return path. This ensures that the clock signal acts as a strong antenna which radiates the clock and its higher harmonic signals. The lower address lines and the data bus also will be problematic if not laid out correctly, but reducing the current loop as described here will help significantly.

1.1.2 Susceptibility

Most MCUs are designed using CMOS technology and work on the principle of latches and flip-flops to generate more complex functions. Because of their synchronous nature, clocking a bad level can easily cause malfunction. Any CMOS device will have a noise threshold that if exceeded will cause failure.

The failure usually will occur in these four categories:

1- MCU fails momentarily, then corrects itself.

2- MCU fails and interrupt or reset recovers the MCU.

3- MCU fails. Powering OFF then ON recovers the failure.

4- MCU fails and latch-up occurs, resulting in permanent damage.

If the failure occurs in categories 1 and 2, then it may go unnoticed and the end user may either never see the failure or accept it due to its irregular occurrence.

However, if the failure is in categories 3 or 4, then it definitely will be seen as an immunity problem and will be unacceptable by any manufacturer. A category 4 failure will need to happen in the field for the first time, since the product release would have been halted had the failure happened during the design phase. This failure would have gone undetected only if no EMC testing had been carried out in the product's design phase.

1.2 Importance of EMC in recent years

With advances in technology, electronic products become more common and the problems caused by EMI have caused concern. Some reported incidents of EMI include:

- arc welders affecting medical equipment
- mobile telephones affecting readings on petrol pumps
- in-car cigarette lighters causing car park barriers to operate

These problems are the reason for the drafting of this legislation.

Electromagnetic compatibility is a subject most designers did not have to worry about a few years ago. Today, every designer putting a product on the global market has to consider this. There are two main reasons for this: [3]

- The electromagnetic environment is getting tougher.
  High-frequency radio transmitters, like mobile telephones, are found everywhere. More and more systems are using switching power supplies in the power circuit, and the overall number of electronic appliances is increasing every year [3].
- Electronic circuits are becoming more and more sensitive. Power supply voltages are decreasing, reducing the noise margin of input pins. Circuit geometries get smaller and smaller, reducing the amount of energy required to change a logic level, and at the same time reducing the amount of noise required to alter the logic values of signals [3].

From an electronic designer's point of view, EMC phenomena have to be considered in two different ways:

- How the environment may affect the design (immunity or susceptibity).

- How the design may affect the environment (emission or interferance) [3].

1.3 EMC Regulations

The Federal Communications Commission (FCC) has a set of standards to regulate EMI in electronic equipment and systems for use in the United States. Compliance with the appropriate sections of these regulations is mandatory to market or sell a product except for certain subclasses of digital devices that are temporarily exempt. Engineering models (including field-trial prototypes which are not sold) are also exempt; however, the display of a product at an electronics show is considered a marketing function subject to regulations [4].

FCC rules and regulations (part 15, subpart J of title 47 of The Federal Regulations) apply to almost all digital devices (seen Figure 1.2), defining standards and operational requirements for all devices capable of emitting radio frequency (RF) energy within the range 450 kHz to 1 GHz [4].

Equipment for use within Germany must comply with a different set of standards defined and administered by the Verland Deutcher Electro-Techniker (VDE). Digital equipment is generally required to meet both VDE0871 standards. In other countries, compliance to a standard is not always mandatory; however, the European Economic Community (EEC) member states intend to introduce a mandatory RFI performance standard after January 1, 1992. The current proposal is based on Internal Special Committee on Radio Interference specification CISPR22 and is referred to as European norm EN55022. As the FCC is a member of the CISPR, and has voted in favor of the CISPR22 standard, it is likely that the FCC will ultimately adopt the same standards. CISPR22 is somewhat more stringent than FCC part 15, subpart J, in the 88-MHz to 230-MHz frequency range, though it is less stringent than some aspects of the VDE0871 [5].

Regulations are one of the primary reasons when products can be tested for EMC. Therefore, it can be looked at some of the important organizations that develop and enforce EMC regulations. Failing to comply with EMC regulations can result in forced removal of a product from the market place or even monetary fines [2].

EMC regulations cover the entire spectrum of electrical products, from computing or medical equipment to microwave ovens to aircraft. As shown in Figure 1.2, the frequency ranges of interest for EMC testing extend from 30 Hz to 40 GHz (9 orders of magnitude), depending on the agency and the type of measurement. The frequency range over which regulations exist varies, depending on the device and its intended use [2].

While individual EMC requirements vary widely from one another, one common aspect is the goal of achieving valid, repeatable results. Therefore, most regulations specify the test environment, receiver and transducer characteristics. Antenna height and polarization is usually varied, and the tested equipment is rotated to find the maximum response from the device. All these actions help insure that the worst-case emissions are found [2].

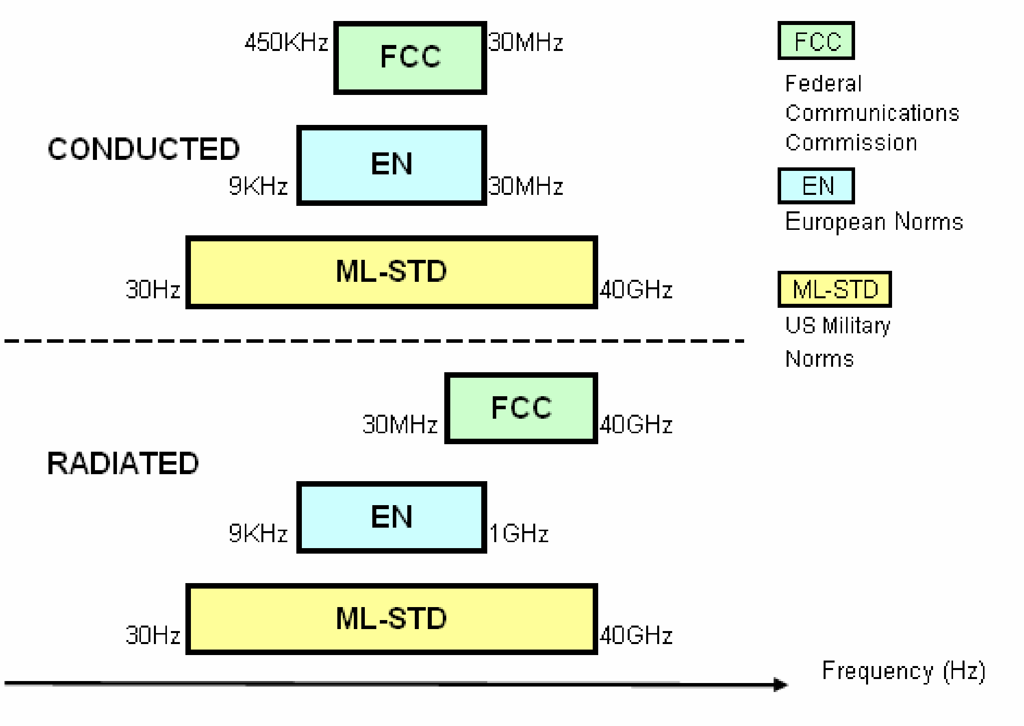


Figure 1.2: Conducted versus radiated Regulations [4].

Because so many factors affect emissions, an environment with known characteristics must be used when measuring electromagnetic interference. Testing within a known environment is critical in order to assure meaningful and repeatable results that can be compared to other measurements performed on other devices [2].

Traditionally, the only government regulations have been on the emission side: An electronic device is not allowed to emit more than a certain amount of radio frequency energy to avoid disturbing radio communication or operation of other electronic equipment. Most countries in the world have regulations on this topic.

Additional demands on noise immunity earlier were found only for special applications, like medical equipment, avionics and military applications. From 1995, Europe introduced regulations on immunity for all electronic products, known as the EMC directive. The purpose of this directive is:

- To ensure that no product emits or radiates any disturbances that may interfere with the function of other equipment.
- To ensure that all products withstand the disturbances present in their operating environment [3].

At the same time, enforcement of EMC requirements was strengthened: every product made in or imported to Europe must prove to fulfill both emission and immunity requirements before it can be put on the market. Countries in other parts of the world are also about to introduce similar legal requirements [3].

The limits for acceptable emission and immunity levels for different product classes and environments are given in various international standards. A more detailed description of these is found in the related reference literature [3].

The EMC directive applies to finished products, but not to components. As a component will not work without being put into a system, the demands are put on the finished system. How the problems are solved internally is left to the designer [3].

There are also some International EMC standarts for EMI and EMS in Table 1.1 and Table 1.2. [1]

Table 1.1: Electromagnetic Emissions [1].

STANDARD	EQUIVALENT INTERNATIONAL STANDARD	DESCRIPTION
EN50081-1		Generic emissions standards – Residential
EN50081-2		Generic emissions standards – Industrial
EN55011	CISPR 11	For industrial, scientific and medical equipment
EN55013	CISPR 13	For broadcast receivers
EN 55014	CISPR 14	For household appliances/tools
EN 55022	CISPR 22	For data processing equipment
	SAE 1752/3	American Measurements Proc. for susceptibility

Table 1.2: Electromagnetic Susceptibility [1].

STANDARD	EQUIVALENT INTERNATIONAL STANDARD	DESCRIPTION
EN50082-1		Generic immunity standards – Residential
EN50082-2		Generic immunity standards – Industrial
EN50140	IEC 1000-4-3 (old nb: IEC 801-3)	RFI (radiated test) (80 MHz - 1 GHz at 1 to 10 V/m)
EN50141	IEC 1000-4-6 (old nb: IEC 801-6)	Induced RF fields (conducted test) (150 kHz - 80 MHz at 1 to 10V (80% AM, 1 kHz))
EN50142	IEC 1000-4-5 (old nb: IEC 801-5)	Surge
EN???? TBD	IEC 1000-4-4 (old nb: IEC 801-4)	EFT / Burst (250V - 2kV I/O lines; 0.5 - 4kV AC/DC mains)

As a result of this, the test procedures required for marking such as CE are well suited for testing finished products, but they cannot be used directly for testing components like microcontrollers. The same applies for the test procedures required for FCC approval. The test boards the components are mounted on during test will influence EMC test data for components. These results should therefore only be regarded as informative [3].

On the other hand, there are test standards (military, automotive and others) that are made to test components directly. These standards specify standardized test boards to make sure that measurements on different manufacturer's components can be compared. These tests are not a requirement according to the EMC directive [3].

1.4 Dealing with EMC Phenomena

For most engineers, EMC design is a relatively new subject. Before Europe introduced the EMC directive, it was possible for a company to build and sell their products without paying too much attention to the problem. As long as the products worked as intended and did not interfere with broadcast stations, everything was basically fine [3].

The three-year transition period from the time the directive was effective in 1992 until it was a requirement in 1995 did not do much to change this. In many companies, the real work did not start until there was no longer a choice. And then, the only option was the hard, expensive way: take an existing product, which perhaps was designed without any thoughts of EMC at all, and try to add the necessary filter, protectors, shielding and whatever to make it EMC compliant. This is the worst possible approach; the cost is high and the results are usually poor [3].

When designing a new product, it is very important to start thinking EMC from the beginning. This is when all the low-cost solutions are available. A good PCB layout does not cost more in production than a bad one, but the cost of fixing a bad one can be high. One of the most expensive mistakes a designer can make is to believe that EMC is something that can be dealt with after everything else is finished [3].

What approach to use depends, as always, on estimated system cost and production volume. For a low-volume system, the best way out may be to use expensive components and system solutions to reduce design time. For a high-volume, low-cost application, it may be better to spend more time and resources on the design to reduce the overall cost of the final product [3].

1.5 Design Help

If it can not been had the necessary EMC know-how when starting a project, it can be a good idea to get some help from experts. This will keep your design from making mistakes that may cost a fortune to correct later on. There are a lot of consultants, agencies and companies specializing in EMC design and EMC training. Adding more people in the design phase will also reduce design time and time to market [3].

Good EMC design requires a lot of knowledge, but not have to acquire this knowledge the hard way; by trial and error. Others have done this already [3].

1.6 Noise Sources

Electrostatic discharges, mains, switching of high currents and voltages or radio frequency (RF) generators are just some of the causes of electromagnetic interference, or noise, in microcontroller environments [1].

Within the microcontroller itself, the main contributors to noise are:

- oscillator: continuous RF source,
- system clock circuits: RF divider followed by large amplifiers which drive long lines inside the component,
- output transitions: the relative weight depends on the frequency of the transitions and their duration; i.e. the shorter the transitions, the richer the frequency spectrum,
- data/address buses: for some microcontrollers, a part of the memory space is external, which implies continuous transitions on several lines [1].

1.7 Noise Carriers

EMI can be transferred by electromagnetic waves, conduction, and inductive / capacitive coupling. Obviously, EMI must reach the conductors in order to disturb the components. This means that the loops, long length and large surface of the conductors are vulnerable to EMI, making the PCB the principal subject of EMC improvements [1].

1.8 Affected Areas

In a microcontroller-based system, the core process is intrinsically sequential and must rely on valid data. Once a non-EMC-protected program is disturbed, it cannot resume normal operation [1].

From the electrical point of view, the following areas are vulnerable:

- system-clock integrity
- memory cells: memory blocks, in addition to registers and memory cells supporting the state machine of the processor,
- important signals, i.e. RESET, INTERRUPT, HANDSHAKING STROBE.

1.9 Conclusion

In a microcontroller-based medical device, the EMC effects are very important issues so that for reducing EMC failures from a medical equipment it can be considered firstly that what EMC is and what are the EMC sources. Then secondly it must be known that what are the EMC standarts for Electromagnetic Emissions and Electromagnetic Susceptibility in the regulations for producing a medical device.

2. EMC HARDWARE DESIGN TECHNIQUES

In this chapter, first important design techniques which are hardware-based design rules for reducing EMC effects are explained exactly and some precautions are also given.

2.1 Identify the Noise Sources

A very important general rule is that all types of noise should be handled as close to the source as possible, and as far away from the sensitive parts of a circuit as possible. This, of course, means that the task of identifying these sources is very important [3].

Once the areas involved are identified, EMC performances are improved by decreasing noise source emissions, increasing EMI immunity in susceptible areas and weakening the capacity of noise carriers.

2.1.1 Transmitted Noise

In many microcontroller systems, the microcontroller is the only fast digital circuit. In such systems, the most important internal noise source is the microcontroller itself, and the resources used for preventing conducted and emitted RF are best used close to the microcontroller. This will reduce the amount of RF energy that reaches I/O cables and other parts of the system that may act as transmitting antennas [3].

2.1.2 Received Noise

The sources of received noise are usually outside the system, and therefore out of reach for the system designer. The environment is what it is, and the first possibility for the system designer to do something about the noise is on the system inputs and on the power cables. For a system delivered with dedicated cables, it is even possible to start on the cable itself. A good example here is a computer monitor, where it quite often seen a filter put next to the VGA plug connecting to a computer. On other systems, the first chance comes with the I/O connectors. For a hand-held, battery-powered application without any cables, this is not applicable, but then this problem is similarly smaller. If external noise can be prevented from entering the system at all, there will be no immunity problems [3].

2.2 The Path to Ground

The best way to avoid noise problems is to generate no noise in the first place, but this is usually not applicable. Most kinds of noise are side effects of intended behavior of other parts of the system, and therefore cannot be avoided. All kinds of currents, AC or DC, high-power or low-power, signals or noise, are always trying to find the easiest path to ground. The basic idea behind many EMC design techniques is to control the path to ground for all signals, and make sure that this path is away from signals and circuits that may be disturbed. For transmitted noise, this means making sure that the noise will find a path to ground before it leaves the system. For received noise, it means making sure that the noise will find a path to ground before it reaches sensitive parts of the system [3].

2.3 System Zones

Handling every EMC problem at once is a very complex task. It is therefore a good idea to split the system into smaller subsystems or zones, and handle these individually. The zones may, in some cases, only be different areas of the same PCB. The important part is to have control of what happens inside one zone, and how the zones interact. For each zone, the designer should have some idea about what kind of noise the zone may emit, and what kind of noise it may have to endure. All lines going in and out of a zone may require some kind of filter. It is also very important to be aware about how noise may be radiated from one zone to another. Local shielding of very noisy and/or very sensitive circuits may be necessary [3].

The split may be done in two ways or a combination of these:

- The zones may be put apart from each other to separate noisy circuits from sensitive ones. The typical example here is a line-powered system containing both analog and digital circuits, where the (switch mode) power supply, the digital circuits and the analog circuits are put on different areas of the Printed Circuit Board (PCB).
- The zones may be put inside each other. The noise going into and out of the inner most zone will then have to pass several layers of filters and/or shielding. The total noise reduction will then be much more efficient than what can be received by one layer. An example here is a particularly sensitive analog circuit, perhaps with its own shield, on the analog part of a PCB inside a shielded enclosure with filtered I/O connectors. Another example is a fast microcontroller with fast communication to a nearby memory, and slower communication to other parts of the system. Then the MCU and the memory can be defined as the

inner zone - the noisiest part. All lines leaving this zone should then be filtered, making sure that none of them carry the highest-frequency noise further out. The next level of filters may then be on the edge of the "digital zone", and perhaps also a third layer of filtering on the system I/O ports is used to reduce emitted noise even further. Three layers of filters may sound expensive, but three simple filters may cost much less than an advanced "one-filter-handles-all" solution [3].

2.4 RF Immunity

Long I/O and power cables usually act as good antennas, picking up noise from the outside world and conducting this into the system. For unshielded systems, long PCB tracks may also act as antennas. Once inside the system, the noise may be coupled into other, more sensitive signal lines. It is therefore vital that the amount of RF energy allowed into the system be kept as low as possible, even if the input lines themselves are not connected to any sensitive circuit [3].

This can be done by adding one or more of the following:

- Series inductors or ferrite beads will reduce the amount of High Frequency (HF) noise that reaches the microcontroller pin. They will have high impedance for HF, while having low impedance for low-frequency signals.
- Decoupling capacitors on the input lines will short the HF noise to ground. The capacitors should have low ESR (equivalent series resistance). This is more important than high capacitance values. In combination with resistors or inductors, the capacitors will form low-pass filters. If the system is shielded, the capacitors should be connected directly to the shield. This will prevent the noise from entering the system at all. Special feed-through capacitors are designed for this purpose, but these may be expensive.
- Special EMC filters combining inductors and capacitors in the same package are now delivered from many manufacturers in many different shapes and component values [3].

2.5 ESD and Transients

Handling ESD is usually quite simple: make sure that the user cannot touch the sensitive parts of the system. This is, in most cases, taken care of by the equipment enclosure and only I/O pins leaving the system need special attention. However, ESD discharges may induce currents in nearby paths, causing incorrect values of the signals on these [3].

Keep in mind that both ESD pulses and other types of transients are very high frequency phenomena, and that stray capacitance and inductance have a very important influence of their behavior. A transient on one line may also affect the behavior of other signals nearby [3].

The important thing is to make sure that the most efficient path to ground is one that does not affect the system. If, for instance, the most efficient path to ground for an ESD pulse is along the I/O line, to the microcontroller pin, through the ESD protection diode and then to ground, a logic high input may be read as low. If the system software cannot be made to handle this (and that is usually the case), the system requires some kind of hardware that will create a more controlled path to ground [3].

The RF filters will, of course, also work on ESD and transients, and may, in some cases, be sufficient. But reducing a 4 kV spike to a 4V spike requires a very strong filter. It can by done by large series resistors, but that is not always an option. Large series resistors on input lines will increase the impedance of the ground path described above. This will reduce the amount of noise that reaches the microcontroller pin. The disadvantage of this is that the system also gets high impedance for low frequency and DC signals, and this is therefore not useful for I/O pins that are also used as outputs [3].

Then over-voltage protectors are a better solution. There are many types of these, most of them acting as very fast zener diodes. They will have very high impedance to ground as long as the I/O line voltage is within the specified limits, but will switch to a very low impedance value when the voltage is too high. A transient is then very effectively shorted to ground [3].

2.6 Power Supply, Power Routing and Decoupling Capacitors

One of the most common reasons for EMC problems with microcontroller products is that the power supply is not good enough. Correct and sufficient decoupling of power lines is crucial for stable microcontroller behavior, and for minimizing the emitted noise from the device [3].

Looking at the datasheet for a microcontroller, one can be fooled to believe that power supply is not critical. The device has a very wide voltage range, and draws only a few mA supply current. But as with all digital circuits, the supply current is an average value. The current is drawn in very short spikes on the clock edges, and if I/O lines are switching, the spikes will be even higher [3].

The current pulses on the power supply lines can be several hundred mA if all eight I/O lines of an I/O port changes value at the same time. If the I/O lines are not loaded, the pulse will only be a few ns. This kind of current spike cannot be delivered over long power supply lines; the main source is (or should be) the decoupling capacitor [3].

The standard decoupler for microcontrollers is a 100µF pool capacitor, and in parallel, a 0.1µF high frequency capacitor (typical values). Aluminium electrolytic capacitors should be avoided due to their poor performance at high frequencies. These capacitors must physically be as close as possible to the Vss/Vdd pins of the component in order to reduce the surface of the actual loop. As a general rule, decoupling all sensitive or noisy signals improves EMC performances [1].

There are 2 types of decouplers:

- Capacitors close to components. Inductive characteristics, which apply to all capacitors beyond a certain frequency, must be taken into account. If possible, parallel capacitors with decreasing values (0.1, 0.01,... µF) should be used [1].
- Inductors. Although often ignored, ferrite beads, for example, are excellent inductors due to their good dissipation of EMI energy and there is no loss of DC voltage (which not the case when simple resistors are used) [1].

Figure 2.1 shows an example of insufficient decoupling. The capacitor is placed too far away from the microcontroller, creating a large high current loop. The power and ground planes here are parts of the high current loop. As a result of this, noise is spread more easily to other devices on the board, and radiated emission from the board is increased even further. The whole ground plane will act as an antenna for the noise, instead of only the high current loop [3].

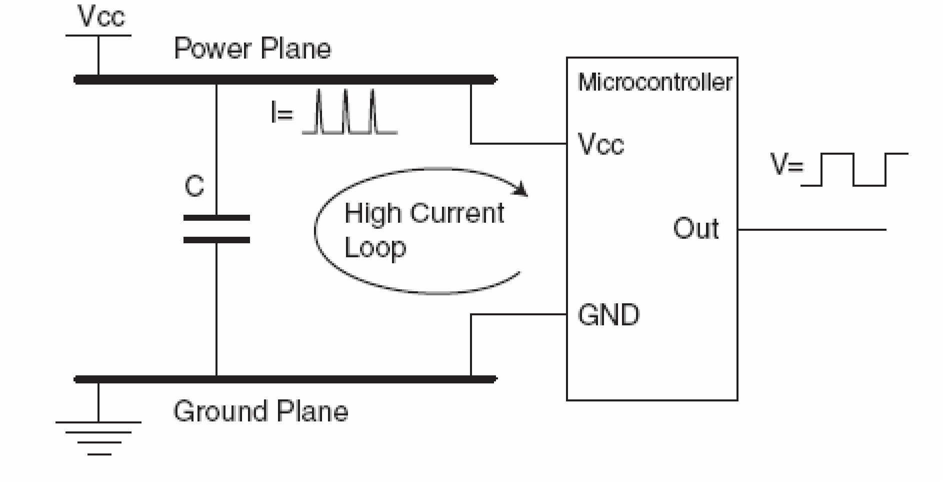


Figure 2.1: Incorrect Decoupling [3].

This will be the case if the power and ground pins are connected directly to the planes (typical for hole-mounted components) and the decoupling capacitor is connected the same way. The same is often seen for boards with surface-mount components if the integrated circuits are placed on one side of the board and the decoupling capacitors are placed on the other [3].

Figure 2.2 shows a better placement of the capacitor. The lines that are part of the high current loop are not part of the power or ground planes. This is important, as the power and ground planes otherwise will spread a lot of noise [3].

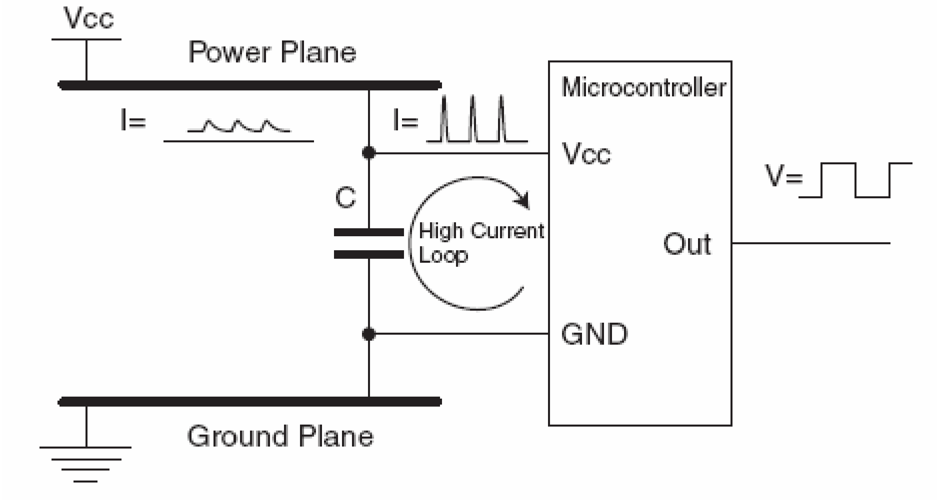


Figure 2.2: Correct Placement of Decoupling Capacitor [3].

Figure 2.3 shows another improvement of the decoupling. A series inductor is inserted to reduce the switching noise on the power plane. The series resistance of the inductor must, of course, be low enough to ensure that there will be no significant DC voltage drop [3].

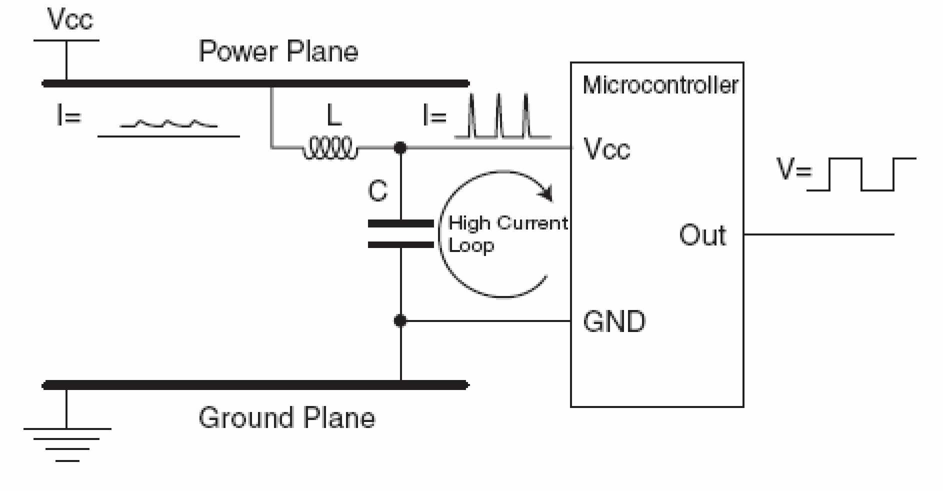


Figure 2.3: Decoupling with Series Inductor [3].

Generally, some microcontrollers where power and ground lines are placed close together (like the Atmel AT90S8535) will get better decoupling than devices with industry standard pinout (like the AT90S8515), where the power and ground pins are placed in opposite corners of the DIP package. This disadvantage can be overcome by using the TQFP package, which allows decoupling capacitors to be placed very close to the die. For devices with multiple pairs of power and ground pins, it is essential that every pair of pins get its own decoupling capacitor [3].

2.7 PCB Location

The PCB must be kept as far away as possible from the main supply wiring as well as extra high voltage lines or very high current lines. Also, they should not be repeatedly switched on/off [1].

In certain cases, “natural” shielding may exist in the application. In this case, it should be used wisely [1].

2.8 Component Mounting

Surface-mounted components (SMCs) or devices (SMDs) have a higher density than standard through-hole mounted components, and therefore require shorter traces on the PCB. For microcontrollers, SMD packages such as small outline (SO) and quad flat packages (QFP) reduce the length of signal lines and require a smaller power supply loop [1].

2.9 Choice of Microcontroller and watchdog

The use of a microcontroller with a high clock rate may cause dangerous EMI levels. This feature should not be used unless it is specifically needed for real-time application requirements. If a high system-clock frequency is requested, certain microcontrollers use an internal PLL to build a system clock frequency higher than the oscillator frequency with an external resonator (EMI reduction). A hardware watchdog must implemented in the microcontroller in order to meet EMC requirements [1].

Certain component suppliers, such as STMicroelectronics, Atmel, Freescale Semiconductors have taken EMC requirements into account when designing their products. It is best to use components designed with specific EMC technical characteristics, rather than those with unknown EMC performance levels.

2.10 Unused Features

All microcontrollers are designed for a variety of applications and often a particular application does not use 100% of the MCU resources [1].

To increase EMC performances, unused clocks or counters, as well as I/Os, should not be left free, e.g. I/Os should be set to “0” or “1” and unused functions should be “frozen” or disabled [1].

2.11 PCB Layout Techniques

When designing an application, the following areas should be closely studied to improve EMC performances:

- noisy signals (clock...),
- sensitive signals (high impedance...).

In addition to:

- signals for which a temporary disturbance affects the running process permanently (the case of interrupts and handshaking strobe signals)

A surrounding ground trace for these signal increases EMC performances, as well as a shorter length and the absence nearby of noisy and sensitive traces (crosstalk effect).

For digital signals, the best possible electrical margin must be reached for the 2 logical states and slow Schmitt triggers are recommended for eliminating parasitic states.

2.11.1 Component Position

A preliminary layout of the PCB must separate the different circuits according to their EMI contribution in order to reduce cross-coupling on the PCB, i.e. noisy, high-current circuits, low voltage circuits, and digital components [1].

2.11.2 Ground and Power Supply (Vss, Vdd)

The GROUND should be distributed individually to every block (noisy, low level sensitive, digital,...) with a single point for gathering all ground returns. Loops must be avoided or have a minimum surface. The power supply should be implemented close to the ground line to minimize the surface of the supply loop. This is due to the fact that the supply loop acts as an antenna, and is therefore the main emitter and receiver of EMI [1].

All component-free surfaces of the PCB must be filled with additional grounding to create a kind of shielding (especially when using single-layer PCBs) [1].

2.11.3 Current Loops and Signal Grounding

Current can only flow in loops. This is true for signals as well as for power supply current. Unfortunately, a current loop will emit noise, and the larger the loop, the larger the noise. Noise also increases with current and with frequency. A large loop is also more likely to receive noise. Loops should therefore be kept as small as possible. This means that every line that may emit or receive noise should have a return path to ground as close to the line as possible [3].

The best way to make sure that every noisy track has such a return path is to add a complete ground plane to the board. Then the area of the loop will only be the length of the track times the distance between the track and the ground plane. This area is usually much smaller than what can be achieved by routing ground paths, so the noise from a board with a ground plane is therefore much less than the noise from a board without a ground plane [3].

2.11.4 Ground Planes

In many designs, it looks like the ground plane is defined to be “all the copper not used for something else, connected to ground somewhere.” This will not be an effective ground plane [3].

Note that for a high frequency signal, the return path in a ground plane will be exactly under the track, even if this path is longer than the direct route. This is because the return path will always be the path of least impedance, and for a high-frequency signal, this is the path with the smallest loop, not the path that has lowest DC resistance [3].

For circuits that include both digital and analog circuits, the ground plane may be divided into an analog ground plane and a digital ground plane. This will reduce the interference between the analog and digital parts of the system [3].

2.11.5 Board Zoning

System zoning, as described on System Zones can also be applied to a single PCB. Noisy parts of a system, like a digital circuit or a switch mode power supply, should be made as small as possible, reducing the size of current loops that will act as emitting antennas. Similarly, sensitive parts of a system, like an analog measurement circuit, should be made as small as possible, reducing the size of current loops that will act as receiving antennas. And of course, the noisy part of a system should be kept as far away from the sensitive ones as possible [3].

Remember that in both cases the important part is reducing the size of the current loops, not the physical board area. Routing in ground planes to save space should therefore be avoided, unless thorough analysis shows that the ground return paths of other signals will not be affected [3].

2.11.6 Single-layer Boards

Single-layer boards are used in many commercial applications due to their low cost. However, from an EMC point of view they are the most demanding boards to work with, as it is not possible to incorporate a ground layer on the board. This may increase the need for external components or shielding to achieve EMC compatibility, especially at high clock speeds. The layout of a single-layer board will require very good EMC design skills from the designer, as the layout very easily ends up having large loops that will act as antennas. It is always a good idea to use wires and straps to overcome some of the worst routing problems, but the task is still demanding [3].

2.11.7 Two-layer Boards

If possible, one of the layers should be used as a dedicated ground plane and only that. If signals are routed in the ground plane, this may interfere with the return paths of the track on the other side. This kind of routing will therefore require detailed analysis of every track on the board, otherwise the whole ground plane may be wasted [3].

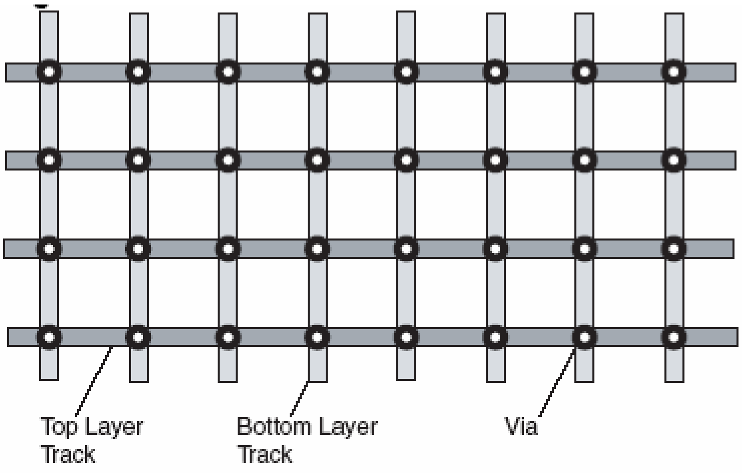


Figure 2.4: Ground Grid [3].

One way of designing a ground plane on a two-layer board and still allow routing on both layers, is to design a ground grid as shown in Figure 2.4. Here every path will have a ground return nearby, creating a relatively small loop. How large the cells and how wide the tracks should be will depend on the application. Higher currents and higher frequencies will require wider tracks and smaller cells [3].

It is very important to first put the ground grid in place, as it will be very difficult to make room for it after all other tracks have been placed. If required, a segment of the ground grid can be moved to the opposite side of the board to make routing easier or to make room for components. But it is “illegal” to delete segments. If a via or a track has to be moved, put an extra one in the grid to make sure that no cells are larger than the others [3].

A ground grid is not as good as a complete, unbroken ground plane, but it is better than routing ground just like any other signal [3].

Another way of designing a similar ground plane is to fill all unused space on both sides of the board and connect the ground planes together with vias wherever needed. It is very important to make sure that the ground plane at every part of the board covers at least one layer and that enough vias are used so the total ground area becomes as complete as possible. This way of creating a ground plane can also be combined with the ground grid described above. Start with a ground grid, then route the rest of the board and fill all unused areas with ground planes. Some of the vias in the ground grid may, in this case, be removed afterwards [3].

For a mixed signal board with both analog and digital circuits, it is recommended to use an unbroken ground plane for the analog part of the board, as this will provide better noise immunity for sensitive analog circuits [3].

2.11.8 Multi-layer Boards

When three or more layers are used, it is essential that one plane is used as a ground plane. It is also recommended to use one layer as a power plane if four or more layers are used. These two planes should then be placed next to each other in the middle of the board, to reduce power supply impedance and loop area. It is not a good idea to place the power and ground planes as the outer layers to act as shields. It does not work as intended, as high currents are running in the ground plane. A shield layer would have to be a second pair of ground layers [3].

For technical reasons, it is best to use a multi-layer printed circuit board (PCB) with a separate layer dedicated to the ground and another one to the Vdd supply, which results in a good decoupling, as well as a good shielding effect. For many applications, economical requirements prohibit the use of this type of board. In this case, the most important feature is to ensure a good structure for the ground and power supply.

2.12 Shielding

In some cases it is not possible to get the noise levels of a system low enough without adding a shield. In other applications a shield may be used because it is easier to use a shield than to achieve low noise levels by other means [3].

Depending on the application, the shield may cover the whole system or only the parts of the system that need it most. If the zone system is used in the design, it is easy to determine which zone(s) that need to be shielded [3].

In either case, the shield must be completely closed. A shield is like a pressurized container: almost good enough is as bad as nothing at all. As described earlier, all lines entering or leaving a zone need to be filtered. A single line that is not filtered will act like a single hole in a bucket of water. It will cause a leak [3].

A semi-closed shield, connected to ground, may still reduce noise. It will act as a ground plane, reducing the size of the loop antennas [3].

A common rule of thumb says that the maximum dimension of any mechanical slit or hole in the shield should be less than 1/10th of the minimum wavelength of the noise. In a system where the maximum significant noise frequency is 200 MHz, this wavelength is 150 cm, and the slits should be less than 15 cm. But such a hole will still cause some reduction of the effectiveness of the shield. A hole that does not affect the effectiveness of the shield has to be less than 1% of the minimum wavelength, in this case 1.5 cm [3].

It may turn out that a 100%-effective shield is not required, though. The filters on the I/O and power lines are usually more important. In many applications, where high frequency noise (>30 MHz) is dominant, it may not even be necessary to use a metal shield. A conductive layer on the inside of a plastic housing will, in some cases, be sufficient [3].

2.13 Cables and Connectors

The three main concerns regarding the EMI role of cables are conceptualized in Figure 2.5. They act as radiated emission antennas, radiated susceptibility antennas, and cable-to-cable or crosstalk couplers. Usually, whatever is done to harden a cable against radiated emission will also work in reverse for controlling EMI radiated susceptibility. The reason for the word usually, is that when differential-mode radiated emission or susceptibility is the failure mode, twisting leads and shielding cables reduces EMI. If the failure mechanism is due to common-mode currents circulating in the cable, twisting leads has essentially no effect on the relationship between each conductor and the common-mode reference. Also cable shields may help or aggravate EMI depending upon the value of the transfer impedance of the cable shield. Transfer impedance is a Figure of merit of the quality of cable shield performance defined as the ratio of coupled voltage to surface current in ohms/meter. A good cable shield will have a low transfer impedance. The effectiveness of the shield also depends on whether or not the shield is terminated and, if so, how it is terminated [6].

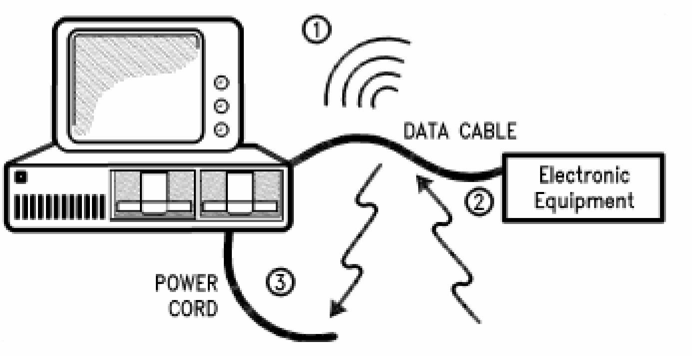
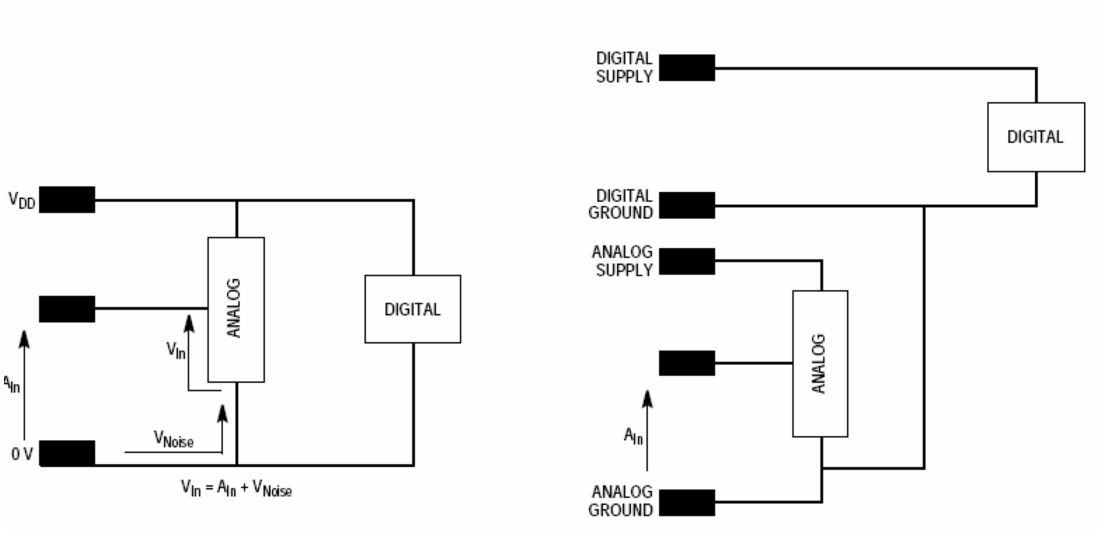


Figure 2.5: EMI effects on cables and connectors [6].

2.14 Analog-Digital Mix

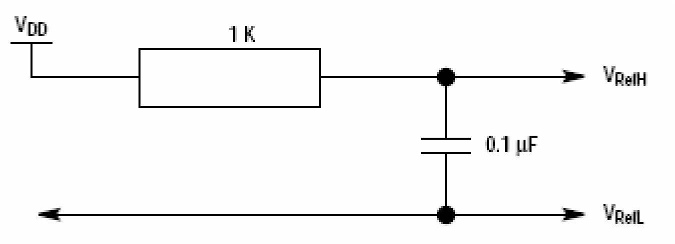
Combining analog and digital circuitry onto a single board requires special attention to PCB layout. Figure 2.6 (a) demonstrates how common-mode impedance ground coupling can superimpose noise on an analog input signal. For example, if the analog section were a 12-bit analog-to-digital (A/D) converter, the added digital noise would significantly reduce the achievable accuracy of the measurements, possibly by several bits. In Figure 2.6 (a), the analog circuit shares its ground and supply with the noisy digital section and is therefore within the digital supply loop. The PCB tracks are also very thin, increasing the parasitic inductance and voltage drop. A better layout of the board is shown in Figure 2.6 (b) in which the digital supply and ground tracks are substantially wider and the analog circuitry is provided with its own supply and ground reference. Any voltage drop occurring on the digital ground track no longer affects the analog input signal because the digital current no longer passes through the analog input loop [5].

Adequate supply decoupling is also a prerequisite to minimizing noise in an analog subsystem. With regard to the MC68HC11 (from Motorola semiconductors) on-chip A/D converter, the recommended decoupling network for the analog reference inputs is shown in Figure 2.7 [5].



(a) Poor Scheme (b) Improved Scheme

Figure 2.6: Analog Circuit Grounding [5].

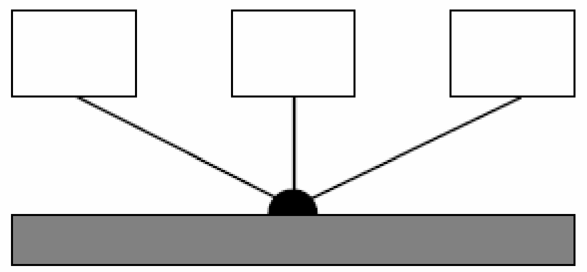


Note: V_{RefL} should not go below V_{SS} –0.6 V

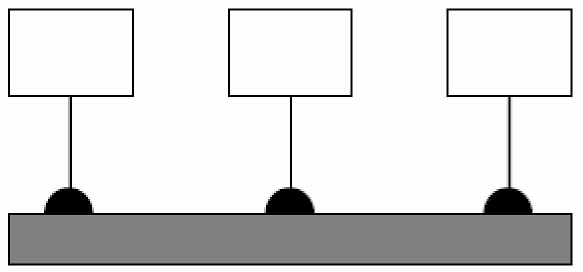
Figure 2.7: Recommended A/D Reference Voltage Decoupling [5].

2.15 Grounding Techniques

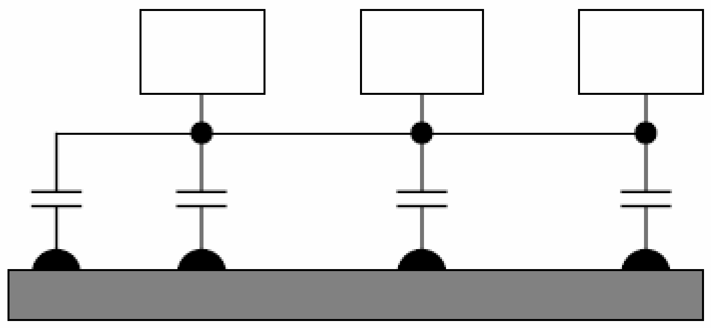
A ground is supposed to be an equipotential point or plane used as a reference potential within a system. In reality, this is untrue due to inevitable parasitic inductance and high ground currents causing significant voltage drops, which can result in common-mode radiation problems. To design a successful grounding scheme, the designer must be aware of the paths that ground currents will take to identify possible common-mode impedance problems, reduce loop areas, and prevent noisy return currents from interfering with low-level circuits. Signal grounds can be classified as single-point, multipoint, or hybrid grounds (see Figure 2.8). Single-point is acceptable for low frequencies but may have too much impedance at higher frequencies to operate correctly [5].



(a) Single Point



(b) Multipoint



(c) Hybrid

Figure 2.8: Grounding Techniques [5].

The ground wire length should be kept as short as possible to reduce inductance and radiating ability. A hybrid ground looks like a single-point ground at low frequencies and a multipoint ground at high frequencies. A typical system is often a mixture of grounding techniques [5].

Figure 2.9 shows a typical MCU application grounding scheme, categorized into low-level analog, digital, input/output (I/O) buffer, high current switching, and hardware grounds. A single-point ground is located at the source of primary power, which is typically the power supply. The on-board digital logic has a multipoint ground, though it is grounded off-board through a single-point ground. To prevent radiation, no high-frequency components of digital return current should be allowed off-board; thus, the board power supply lines should only carry dc current, which is suitable for single-point grounding. A block diagram, such as the one shown in Figure 2.9, is a useful starting point for the design of a good grounding scheme [5].

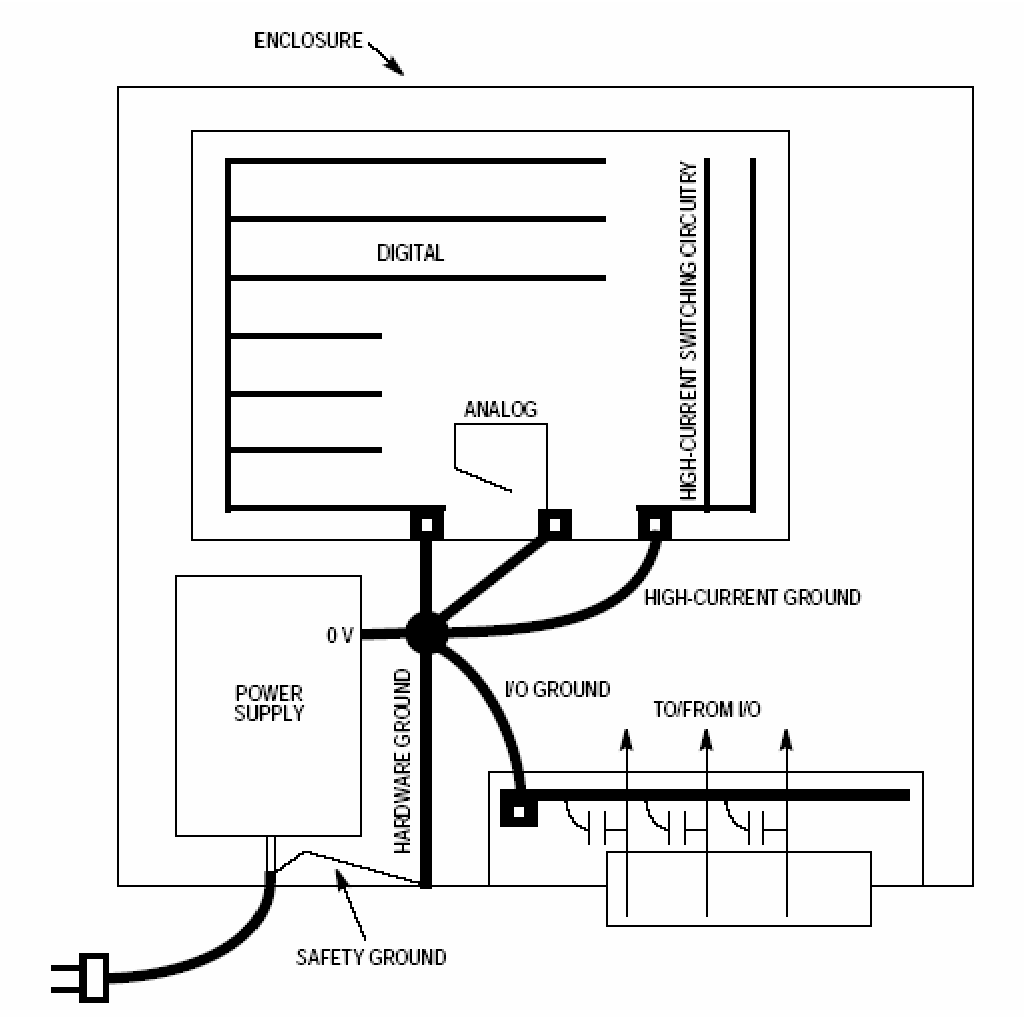


Figure 2.9: Typical MCU Application Grounding Example [5].

2.16 Ferrit Beads

Ferrite beads have excellent high-frequency characteristics and are especially effective in damping high-frequency switching transients or parasitic ringing due to line reflections. Their low impedance (usually below 100 Ω) makes them particularly suitable to filter out supply noise above approximately 1 MHz, preventing the noise from going off-board or into another circuit. However, care must be taken to ensure that the dc current does not saturate the ferrite if it is to be an effective filter. Ferrites having a variety of characteristics are available in many different packages, including surface mount [5].

2.17 Specific Solutions

Most of the items described above are general. There are, however, a few important specific subjects a designer should keep in mind.

Note that the measures described in this thesis are not required in all cases. In most cases, only a minimum of external components (decoupling capacitor, etc) is required. In fact, the embedded low-cost solutions such as the Brown-Out Detection (BOD) and internal pull-ups will do the trick in many designs [3].

2.17.1 General I/O Pin Protection

All general I/O-pins have internal ESD protection diodes to GND and Vcc, as shown in Figure 2.10. If exceeding pin voltage 'Absolute Maximum Ratings' in the datasheet, resulting currents can harm the device if they are not limited accordingly. For parts with LCD-driver, the same situation on segment pins used for general I/O can also influence the LCD voltage level [3].

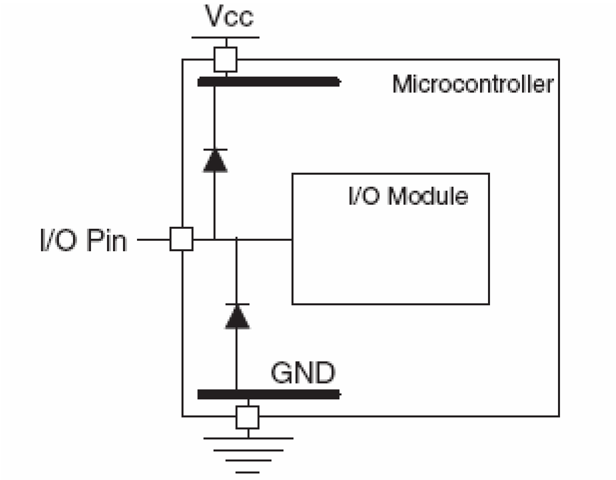


Figure 2.10: I/O Pin Protection [3].

2.17.2 Reset Pin Protection

During parallel programming, a 12V signal is connected to the Reset pin. There is therefore no internal protection diode from Reset to Vcc; there is only one from GND to Reset seen in Figure 2.11 [3].

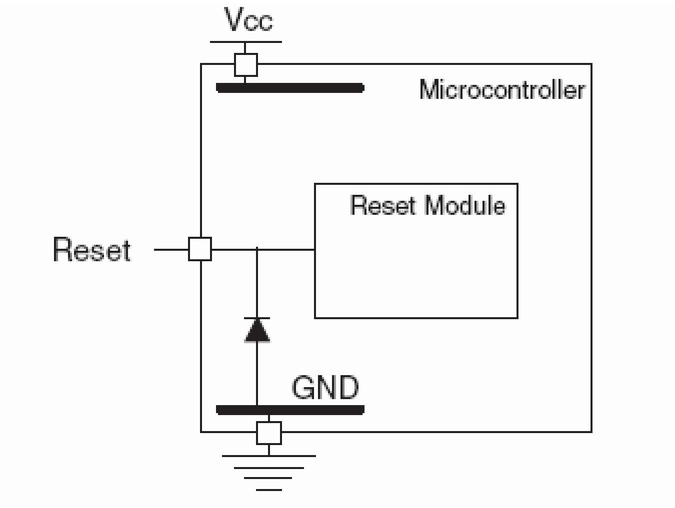


Figure 2.11: Reset Pin Input Protection [3].

To achieve the same protection on Reset as on other I/O pins, an external diode should be connected from Reset to Vcc. A normal small-signal diode will do. In addition, a pull-up resistor (10K typical) and a small filter capacitor (4.7 nF) should be connected as shown in Figure 2.12 [3].

All this, of course, is not needed if Reset is connected directly to Vcc, but then external reset and In-System Programming (ISP) is disabled, too [3].

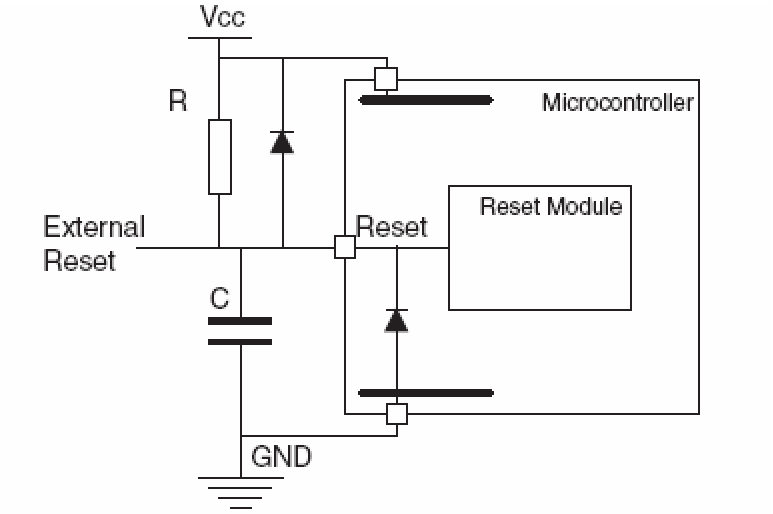


Figure 2.12: Recommended Reset Pin Connection [3].

If high ESD protection of Reset is not required, or is achieved by other components, the diode may be omitted. The resistor and capacitor are still recommended for optimum Reset behavior [3].

The diode must also be omitted if In-System Programming of devices like ATtiny11 microcontroller, which can only be programmed using 12V, is required. Then one of the ESD protection methods described earlier may be used instead [3].

2.17.3 Oscillators

Almost all microcontrollers have an oscillator coupled to an external crystal or ceramic resonator. On the PCB, the copper traces to pins EXTAL/XTAL/Vss (for external capacitors) must be kept as short as possible. These capacitors are included in certain resonators which further shorten traces. Since the RC option is potentially sensitive to spikes which can shorten clock periods, the resonator option is preferable.

The typical oscillator circuit (seen Figure 2.13) consists of an inverter inside the MCU that is connected to a quartz-crystal or ceramic resonator. Also attached are a feedback resistor and some small decoupling capacitors to reduce the harmonics produced by the piezo-electric device.

The inverter within the MCU has a high-input (OSC1) impedance as well as high-ouput (OSC2) impedance. The output has a low drive capability so as not to overdrive and damage the crystal. The oscillator output also goes to another buffer then to a prescaler. The prescaler divides the oscillator clock by two, which ensures a stable 50% duty clock for the internal CPU clock.

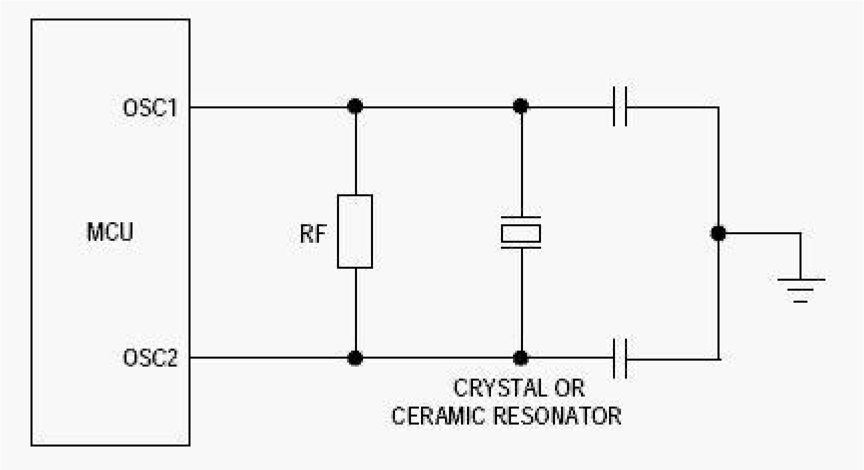


Figure 2.13: Typical Oscillator Circuit

As some microcontroller family is running directly on the clock Oscillator, the Oscillator frequency for a specific throughput is relatively low compared to devices that divide the clock by 4, 8, or 12. This reduces the emitted noise from the Oscillator, but the Oscillator still will be among the noisiest parts of the chip [3].

High-frequency Oscillators are quite delicate devices and are, therefore, sensitive to external noise. In addition, the Oscillator pins are generally more sensitive to ESD than other I/O pins. Fortunately, it is easy to avoid these problems. Keep the Oscillator loop as tight as possible. Place the crystal/resonator as close to the pins as possible. Connect the decoupling capacitors (or the ground terminal of the resonator) directly to the ground plane. Even boards without ground plane should have a local plane under the oscillator. This plane must be connected directly to the ground pin of the microcontroller [3].

Care should also be taken when using an external clock to drive the MCU. If the clock source is far away from the MCU, the clock line will be a strong noise emitter and may also act as a receiving antenna for transients (and other types of noise) that may cause incorrect clocking of the MCU [3].

A buffer should therefore be placed on the clock line. A filter in front of the buffer will help remove incoming noise [3].

2.17.4 PCB track angle

Another source of RFI is an abrupt change of direction of a PCB track which effectively look like impedance discontinuities and will radiate accordingly. For HCMOS designs, it is important to ensure that 90-degree track-direction changes do not occur (see Figure 2.14) [5].

(a) Incorrect (b) Correct

Figure 2.14: Incorrect (a) and Correct (b) PCB Track Layout [5].

2.17.5 Unused input pins

All unused inputs to CMOS devices should be terminated to prevent unintentional random switching and noise generation. Also, unterminated CMOS inputs tend to self-bias into the linear region of operation, which can significantly increase dc current drawn. They are also more susceptible to electrostatic discharge damage [5].

2.18 Conclusion

EMI control has left the specialized realms of electronic design (for example, military) and is rapidly becoming an industry-wide phenomenon. Although the application of good system design will always be a prerequisite to achieving EMC, it is reasonable to suppose that similar design concepts could also be applied to the source of most of the radiation, the very large scale integration (VLSI) HCMOS device. To respond to these and other customer demands for higher performance machines, some semiconductor firms, such as Freescale –new name of Motorola, ATMEL and STMicroelectronics is investigating new system and circuit design, layout, and alternative packaging techniques. This thesis may help to reduce the likelihood of problematic RFI when using MCU devices; however, the user's awareness and understanding of the problem will remain the most vital step toward product EMC [5].

The design and construction of an electromagnetically compatible printed circuit board does not necessarily require a big change in current practices. On the contrary, the implementation of EMC principles during the design process can fit in with the ongoing design. When EMC is designed into the board, the requirements to shield circuitry, cables, and enclosures, as well as other costly eleventh hour surprises, will be drastically reduced or even eliminated. Without EMC in the design stage, production can be held up and the cost of the project increases [6].

3. EMC SOFTWARE TECHNIQUES

In this chapter, it can be explained that the major contributor to improved EMC performance in microcontroller-based medical electronics systems is the design of hardened software. To achieve this goal, it must be included EMC considerations as early as possible in the design phase of your project.

3.1 Introduction

EMC-oriented software increases the security and the reliability of your application. EMC-hardened software is inexpensive to implement, it improves the MCU's immunity performance and saves hardware costs. You should consider EMC disturbances to analog or digital data as parameters that must be managed by the MCU software just like any other application parameter [7].

Examples of software disturbances:

- Microcontroller not responding
- Program Counter runaway
- Execution of unexpected instructions
- Bad address pointing
- Bad execution of subroutines
- Parasitic reset
- Parasitic interrupts
- I/O deprogramming

Examples of the consequences of failing software:

- Unexpected commands
- Loss of context
- Unexpected branch in process
- Loss of interrupts
- Loss of data integrity
- Wrong input measurement values

This thesis describes software techniques divided into two categories:

- Preventive techniques
- Auto-recovery techniques

It can be easily implemented preventive techniques in existing programs. Their purpose is to avoid visible disturbances at user level [7].

The software must include auto-recovery routines. When a runaway condition is detected, a recovery subroutine is used to take the decision to stop program execution, optionally give a warning and then return automatically to normal operations. This operation may be absolutely transparent to the user of the application [7].

There are several other methods for improving EMC performances. Some of these methods are:

- periodic self-checks of data integrity (checksum...),
- when critical tasks are executed, verify data redundancy and check for runaway conditions,
- create a kind of milestone (i.e. trace point) throughout the program that is verified using a “status register” that makes sure that step n follows step n-1,
- periodic updating of the control/data registers, which is particularly useful for the I/O registers which are in the first in line to face EMI.

Each time a runaway condition is detected, the initialization routine must be performed [1].

3.2 Parallel Processes

With a programmable system, an obvious possible EMS weakness arises from an unique process that relies on valid memorized data. At first, the unique process must be split into as many parallel and independent processes as possible. This is particularly important for security functions such as the watchdog, refresh routine and the initialization routine. Additionally, such a split is useful for locating weaknesses during EMC debugging [1].

3.3 Preventive Techniques

It can be easily implemented these techniques in an existing program as they do not require any change to the structure of the software.

3.3.1 Using the Watchdog Correctly

The watchdog is a circuit which must be updated within a maximum time slot. The best systems maintain the watchdog independent of the CPU (not built with a soft routine). For example a microcontrollers have a watchdog integrated in the component, and is able to run independently of the CPU [1].

The watchdog update routine must be treated as a critical process to reduce chances that the watchdog is updated when the process is no longer in normal operation [1].

The watchdog is the most efficient tool you have available for ensuring that the MCU can recover from software runaway failures. Its principle is very simple: it is a timer which generates an MCU reset at the end of count. The only way of preventing the Watchdog resetting the microcontroller is to refresh the counter periodically in the program [7].

But to make the watchdog work at its full potential, you have to insert the enable and refresh instructions in your software in the right way. Figure 3.1 shows the classic examples of bad watchdog implementation: [7]

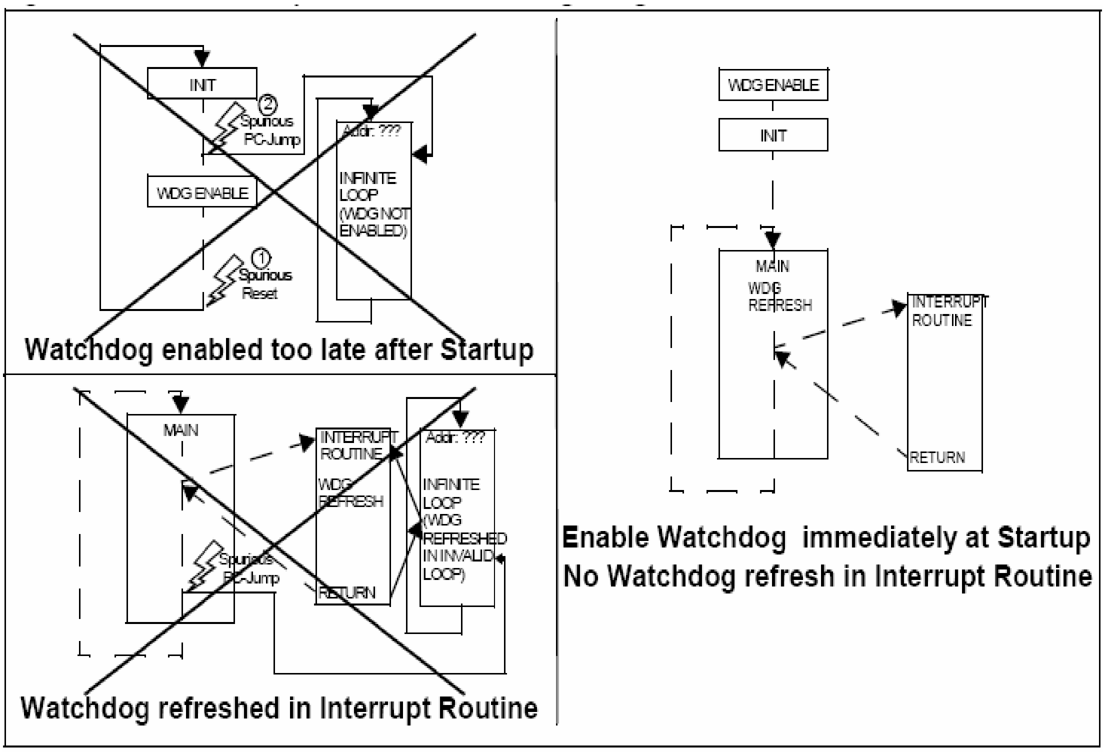


Figure 3.1: Classic Examples of Bad Watchdog Usage [7].

To do it the right way, the golden rules are:

- Enable the watchdog as soon as possible after reset, or use the Hardware Watchdog option if its available.

- Never refresh the watchdog in an interrupt routine.

It is very important to optimize the period between the two refresh instructions according to the duration of the various routines, including the interrupt rountines [7].

The minimum use of the watchdog resets the MCU, this means that the program execution context is lost as well as the application data’s integrity [7].

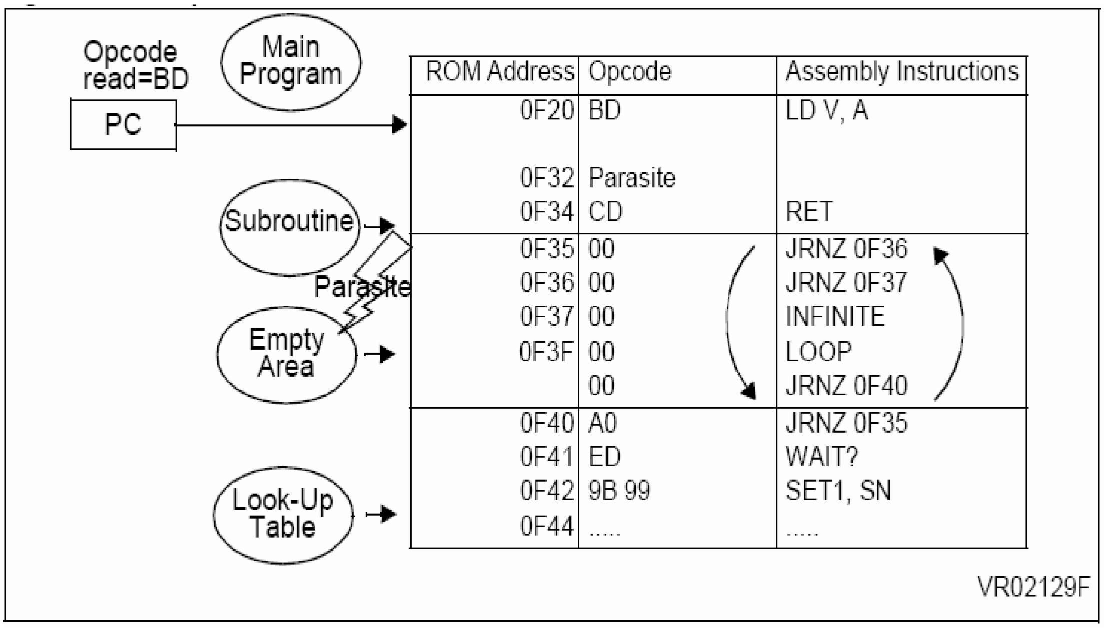
After reset, in addition to enabling the watchdog, on some MCUs it can be used the reset flags to distinguish between a Power On (POR) or Low Voltage (LVR) Reset and a Watchdog reset [7].

3.3.2 Securing the Unused Program Memory Area

In many cases, the internal program space is not used 100%. This creates a free memory area where normally, the application program must never take instructions. This area must be used as a trap which leads to a Reset routine. This is done by filling this area with No-Operation instructions (NOPs) followed by a “JUMP to Reset Routine” command [1].

For extra security, fill the unused memory locations with code that forces a watchdog reset or jumps to a known program location if you do not want to generate a reset [7].

This will ensure that even if the program counter is corrupted and jumps to an unused memory location, the MCU will recover and return to normal operations [7].



ROM Address	Opcode	Assembly Instructions
0F20	BD	LD V, A
0F32	Parasite	
0F34	CD	RET
0F35	00	JRNZ 0F36
0F36	00	JRNZ 0F37
0F37	00	INFINITE
0F3F	00	LOOP
	00	JRNZ 0F40
0F40	A0	JRNZ 0F35
0F41	ED	WAIT?
0F42	9B 99	SET1, SN
0F44	.....	.....

Figure 3.2: Example of a Microcontroller lock condition [7].

In the example (seen Figure 3.2 in which the ST6 from ST Microcontroller family is used), at address 0F3F if you put *LDI WDT,01h*, this instruction causes the MCU to be reset by the internal watchdog and thus avoids microcontroller lock condition [7].

In this unused area it can also be jumped to a Parasite Detection subroutine, which allows to return to normal operations [7].

For ST7 (from ST Microcontroller family) users, the ST7 "TRAP" instruction is also very convenient (only one instruction byte:83) for generating a software interrupt in order to recover from a jump to an unexpected location in memory [7].

3.3.3 Input Filtering

The routine given below (for ST6) checks several times that PB4=1 before continuing the program execution [7].

This is a simple means of filtering a critical input at no extra cost!

```
MAIN1       LDI   LOOP,08h          ;repeat measurement 8 times
MAIN2       JRR   4,PB,MAIN1        ;Check bit 4 of port B
            DEC   LOOP              ;Decrement loop
            JNRZ MAIN2              ;until Loop=0
```

3.3.4 Management of Unused Interrupt Vectors

To avoid problems caused by unexpected interrupt occurrences (whatever the source) it is recommended to manage all the possible interrupt sources by putting a valid interrupt routine address in the corresponding vector [7].

In the example below the unused interrupt vectors point to a "dummy" label filled with a simple "return from interrupt" instruction [7].

Example of unused interrupt management (ST7):

```
.dummy
iret
segment ’vectit’
.pwm_it         DC.W dummy          ;location FFE0-FFE1h
                DC.W dummy          ;location FFE2-FFE3h
.i2c_it         DC.W i2c_rt         ;location FFE4-FFE5h
.sci_it         DC.W dummy          ;location FFE6-FFE7h
.tb_it          DC.W dummy          ;location FFE8-FFE9h
.ta_it          DC.W dummy          ;location FFEA-FFEBh
.spi_it         DC.W dummy          ;location FFEC-FFEDh
.can_it         DC.W can_rt         ;location FFEE-FFEFh
```

```
.ext3_it            DC.W dummy            ;location FFF0-FFF1h
.ext2_it            DC.W dummy            ;location FFF2-FFF3h
.ext1_it            DC.W dummy            ;location FFF4-FFF5h
.ext0_it            DC.W dummy            ;location FFF6-FFF7h
.mcc_it             DC.W dummy            ;location FFF8-FFF9h
.nmi_it             DC.W dummy            ;location FFFA-FFFBh
.softit             DC.W pc_jp            ;location FFFC-FFFDh
.reset              DC.W init             ;location FFFE-FFFFh
```

Another example of unused interrupt management (Motorola HC908 family):

```
; Vectors
org  VectorStart;
     dw  gas_syc_ov_time   ; TBM Vector
     dw  dummy_ret         ; IRSCI Transmit Vector
     dw  dummy_ret         ; IRSCI Receive Vector
     dw  dummy_ret         ; IRSCI Error Vector
     dw  dummy_ret         ; SPI Transmit Vector
     dw  dummy_ret         ; SPI Receive Vector
     dw  dummy_ret         ; ADC Conversion Complete
     dw  dummy_ret         ; Keyboard vector
     dw  dummy_ret         ; SCI Transmit Vector
     dw  sci_r_isr         ; SCI Receive Vector
     dw  dummy_ret         ; SCI Error Vector
     dw  dummy_ret         ; MMIIC Interrupt vector
     dw  TIM2_pwm_int      ; TIM2 Overflow Vector
     dw  TIM2_pwm_chan     ; TIM2 Channel 0 Vector
     dw  time_base_int     ; TIM1 Overflow Vector
     dw  gas_syc_icsr      ; TIM1 Channel 1 Vector
     dw  gas_cntc_icsr     ; TIM1 Channel 0 Vector
     dw  dummy_ret         ; PLL Vector
     dw  dummy_ret         ; ~IRQ2 Vector
     dw  dummy_ret         ; ~IRQ1 Vector
     dw  dummy_ret         ; SWI Vector
     dw  main_init         ; Reset Vector
; DUMMY_Interrupts - returns from a error interrupts
dummy_ret:
     rti
```

3.3.5 Removing Illegal and Critical Bytes from your Code

3.3.5.1 Critical Bytes

A critical byte is an instruction like WAIT or STOP which is decoded by the microcontroller and forces it to stop executing any further instructions [7].

When the PC is corrupted it often becomes desynchronized (as most of the instructions have several bytes), and as a result it may read and decode critical bytes [7].

To check and minimize the occurrence of these critical bytes you can edit the program ".list" file [7].

Very often critical bytes are generated by the compiler as label address bytes. In this case, if you simply insert one or several NOP instructions, all the label addresses will shift and this will change the critical byte value to another value [7].

Example:

In the ST7 instruction sequence shown below, the "main" label address bytes contain the HALT op-code (8E) and the "loop1" label address bytes contain the WFI op-code (8F) [7].

If you add two "NOP" instructions before "loop1", the addresses are shifted from C18E to C190 for "main" and from C08F to C091 for "loop1" and the critical bytes disappear! [7]

```
.loop1
C08F        .....
C09A        81              ret
.main                     ;Led PB3 freezed on
C18E  1415                  bset  PBDR,#2
C190  1715                  bres  PBDR,#3
C192  CDC08F                call  loop1
C195  CDC08F                call  loop1
C198  1515                  bres  PBDR,#2
C19A  CDC08F                call  loop1
C19D  CDC08F                call  loop1
C1A0  CCC18E                jp    main
```

3.3.5.2 Illegal Bytes

Illegal bytes are defined as any byte value which is not part of the instruction set. They will either be executed as a NOP instruction or (on some MCUs) a reset is generated if an illegal byte is encountered. In some ST6 devices however "E5h" is executed as a WAIT and "65h" as a STOP. In this case, use the techniques described above (for criticall bytes) to remove illegal bytes from your code [7].

3.3.6 Averaging the A/D Converter Results

If you are performing A/D conversion, you can repeat conversions several times, store the results in the RAM and then average them (or select the most frequently-occuring value) to obtain accurate results in spite of any potential noise errors [7].

In the below, there is a hardened software example written with Motorola MC68HC908JL3 Microcontroller in an application of ADC.

```
DHW_pot_cal:
    lda     AD_pot_dom_2
    sta     total_adc_high
    lda     AD_pot_dom_2+1
    sta     total_adc_low
    jsr    ADC_divide

    lda     #$FF
    sub      total_adc_low              ; for correct direction of pot
    sta     total_adc_low

    ldx     #!100                       ; total_adc_low*100
    mul
    pshx
    pulh
    ldx     #!255                       ; total_adc_low*100/255
    div
    sta     param_pot_dom

    lda     param_cont_reg              ; shows 0-100 values in parameters sel mode
    cbeqa   #$00,DHW_Norm_opr
    cbeqa   #$A1,DHW_Norm_opr
    cbeqa   #$A9,DHW_Norm_opr
    bra     CH_pot_cal
```

In this software, ADC values are added on different times and then devided in order to find correct ADC vaue.

3.3.7 Register Reprogramming

It rarely happens that EMC disturbances alter the content of the registers. Generally the registers concerned are clock control registers or I/O configuration and data registers because they are close to the chip output pads [7].

In such cases a good security measure is to refresh these registers frequently [7].

In the Table 3.1, it can be seen that there are some advantages and disadvantages of using preventive methods.

There is an example of writing registers to their own values at the determined time periods to protect EMC disturbances.

```
write_regs_per_5sec:
    jsr    write_IO_regs
    jsr    write_Timer_regs
    jsr    write_Sci_regs
    jsr    write_Values_regs
    jsr    write_adc_val_regs
    jsr    write_Flash_regs
    jsr    write_type_sel_regs
    jsr    write_param_slow_ign
    rts
```

3.4 Auto – Recovery Techniques

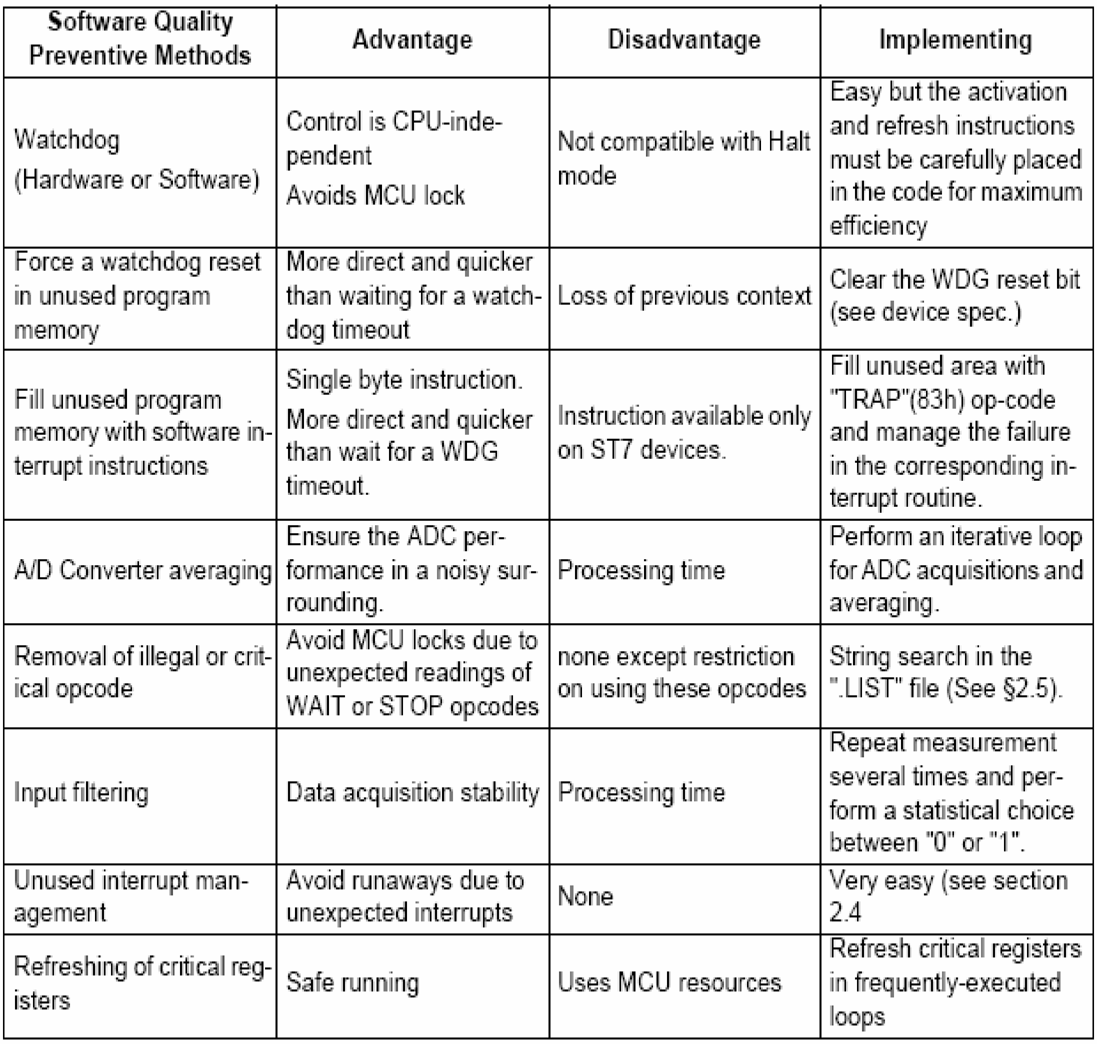
This section gives some techniques for quickly recovering your application context after an EMC failure [7].

Unexpected resets, Program Counter jumps and parasitic interrupts are the most common EMC failures observed in the MCU whatever the source of the disturbance.

In both any of cases the RAM (or EEPROM data memory when available) remains unchanged and can be used as very efficient way to save the application context and parameters [7].

Note that the RAM will lose its contents if the device is powered-off. The EEPROM data keeps its content at power-off but the writing time is much longer [7].

Table 3.1: Summary of Preventive Techniques [7].



Software Quality Preventive Methods	Advantage	Disadvantage	Implementing
Watchdog (Hardware or Software)	Control is CPU-independent Avoids MCU lock	Not compatible with Halt mode	Easy but the activation and refresh instructions must be carefully placed in the code for maximum efficiency
Force a watchdog reset in unused program memory	More direct and quicker than waiting for a watchdog timeout	Loss of previous context	Clear the WDG reset bit (see device spec.)
Fill unused program memory with software interrupt instructions	Single byte instruction. More direct and quicker than wait for a WDG timeout.	Instruction available only on ST7 devices.	Fill unused area with "TRAP"(83h) op-code and manage the failure in the corresponding interrupt routine.
A/D Converter averaging	Ensure the ADC performance in a noisy surrounding.	Processing time	Perform an iterative loop for ADC acquisitions and averaging.
Removal of illegal or critical opcode	Avoid MCU locks due to unexpected readings of WAIT or STOP opcodes	none except restriction on using these opcodes	String search in the ".LIST" file (See §2.5).
Input filtering	Data acquisition stability	Processing time	Repeat measurement several times and perform a statistical choice between "0" or "1".
Unused interrupt management	Avoid runaways due to unexpected interrupts	None	Very easy (see section 2.4
Refreshing of critical registers	Safe running	Uses MCU resources	Refresh critical registers in frequently-executed loops

3.4.1 Saving your Context in RAM

In Figure 3.3 it can be seen that the critical software sequences (door OPEN or CLOSE commands, high speed motor controls) are memorized in a RAM byte ("RAM(SEQ)") [7].

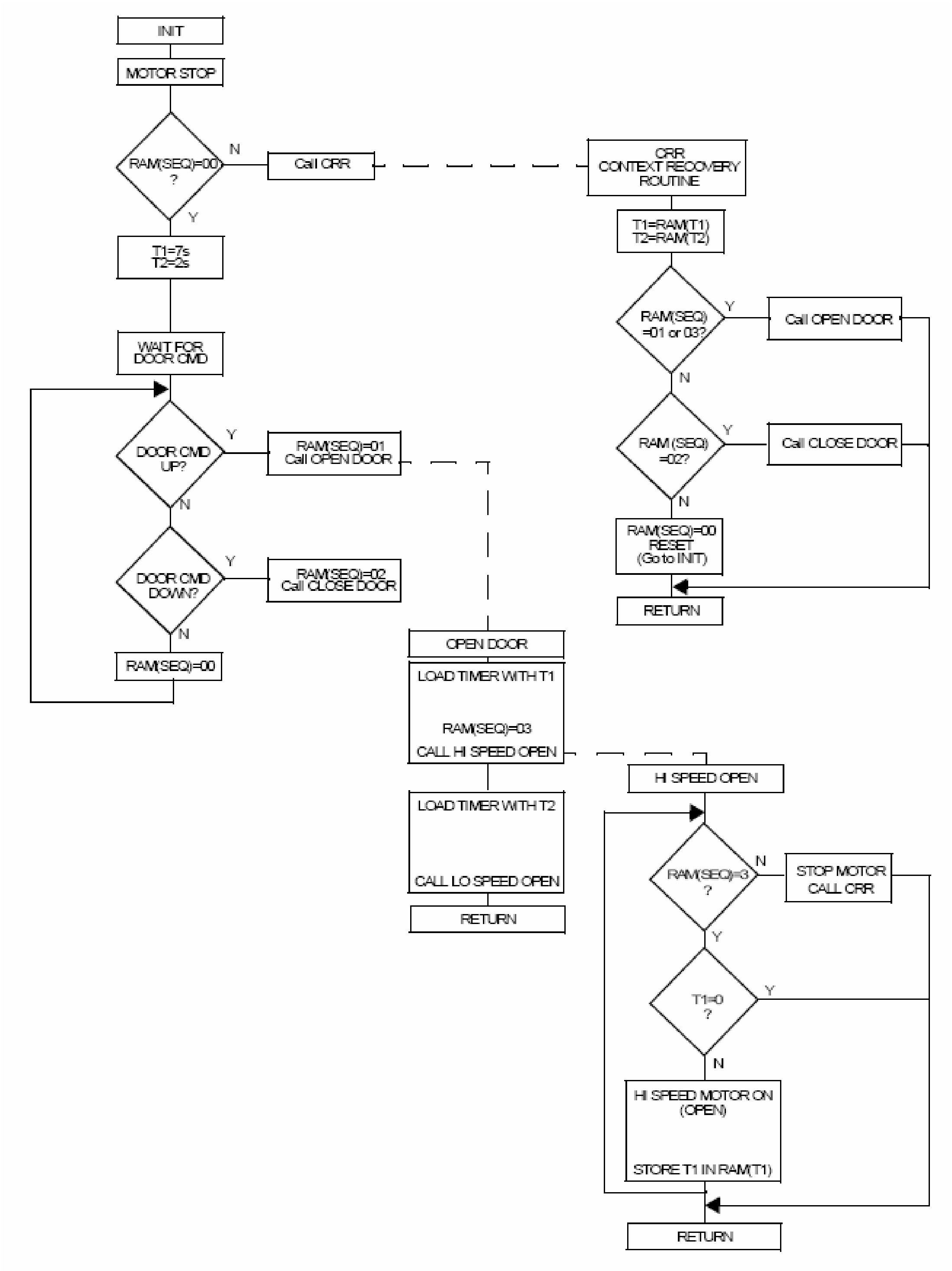


Figure 3.3: An example of a software auto-recovery implementation [7].

This allows us on the one hand to recover the context if an EMC event leads to an MCU reset, and on the other hand it can be checked the source before an executing critical subroutine. In this case the high speed motor activation is allowed only if RAM(SEQ)=03) [7].

The application parameters (T1&T2 timing values) are also stored in RAM when they are changed. This means if a software runaway event occurred or the MCU is reset (by the LVD or the watchdog), the recovery routine (CRR) will restore the last door command, reload the timing parameters and resume the program execution without any external intervention [7].

3.4.2 Using the Watchdog for Local Control

Very often programmers consider the Watchdog Timer more or less just as a time bomb and only refresh it to its maximum value to have the widest possible margin without any direct relation to the expected program execution time [7].

This is a poor approach, a far better method seen in the Figure 3.4 is to use the watchdog timer register to check the execution times of individual software routines and in case of an abnormality to react promptly before the Watchdog end of count and either perform an immediate reset or go into a software recovery routine [7].

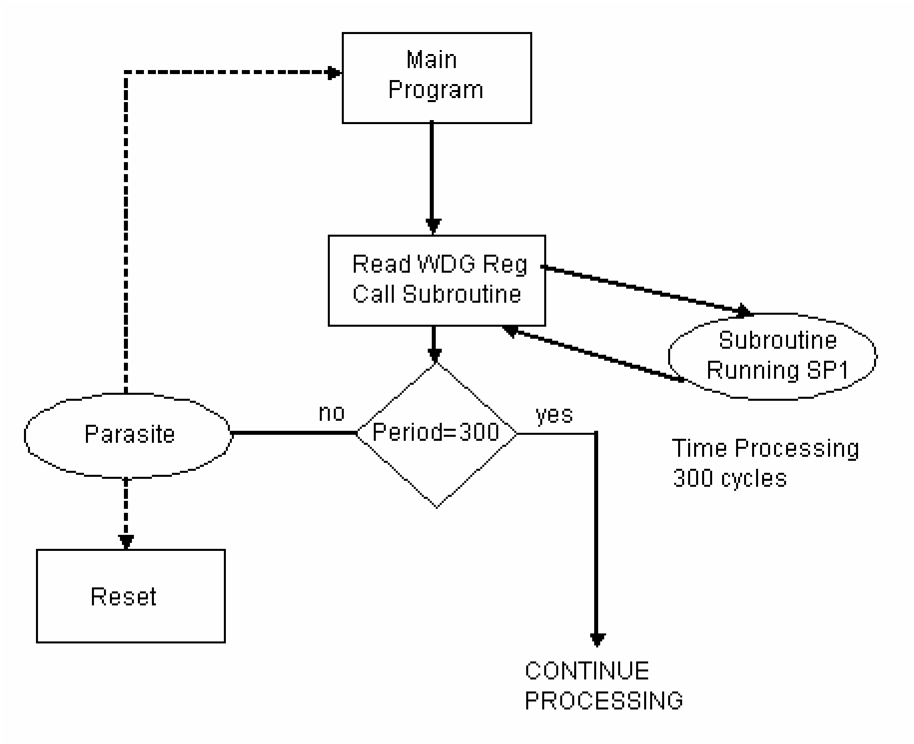


Figure 3.4: Local Control by the Watchdog [7].

An example of a local control by the watchdog below in an application;

```
main_loop_return:
    jsr   tim_increase        ; increases all time regs
    jsr   disp_ref            ; refresh the display data's
    jsr   AD_check            ; adc is read per 5msec, 16*5=80msec
    jsr   Adc_mod_read         ; modulation adc reading per 2 msec
    jsr   check_inp_ports     ; check all switches
    jsr   circ_mon_cont       ; No water circulation monitoring func control
    jsr   anti_block_func     ; antiblocking function control
```

```
    jsr    pump_anti_blck          ; antiblocking pump timer control
    jsr    PI_Out_Loading          ; PI values are loading with slow steps
    jsr    Over_105C_Sub_Rout      ; over 105 cel. temperature control
    jsr    Freeze_Sub_Rout         ; freeze control subroutine
    jsr    error_module            ; branch to error module
    jsr    Flsh_Err_Ctrl           ; non volatile error control after freeze control
    jsr    NVol_Err_Clr            ; Non-Volatile error clearing control
    jsr    NVol_pwr_clr            ; Non-Volatile after power off error clearing cont
    jsr    NVol_One_Hour           ; Non-Volatile waiting about 1Hour
    jsr    Pump_OFF                ; turns pump off after X minutes completed
    jsr    fan_OFF                 ; turns fan off after X minutes completed
    jsr    ion_flame_cnt           ; flame on control after closing of gas valve
    jsr    Exh_time_ctrl           ; exhaust thermostat timing control
    jsr    Exh_1Hour_reset         ; exhaust thermostat 1 Hour reset timing control
    jsr    Pump_work_cont          ; Pump working control
    jsr    flow_req_cnt            ; flow switch control
    jsr    Swch_Err_Control        ; all switches or sensor error control
    jsr    Wait_inh_ppurge         ; waiting for inhibition time or post purge time
    jsr    Air_pres_cntrol         ; air pressure contact control
    jsr    fan_15sec_er            ; waiting for air pressure error control
    jsr    Param_menu              ; go to parameter entering control routine
    jsr    Out_Cap_4538            ; 4538 reset control for security
    jsr    flash_time_cnt          ; Non-Volatile programming is done

    lda    reset_24_Hour           ; Hardware reset control
    cbeqa  #$D8,Go_Main_Loop
    lda    #0
    sta    COPCTL                  ; resets COP regs

    lda    Freeze_OK_Reg
    beq    Go_Main_Loop
    jmp    Start_Heat_Cont

Go_Main_Loop:
    jmp    main_loop
```

3.4.3 Using the Reset Flags to Identify the Reset Source

There are several possible internal reset sources: LVD (Low Voltage detector) or Watchdog reset, POR (Power On Reset), hot reset (parasitic or external reset following a low state of the Reset pin) [7].

On most of the MCUs the reset source is flagged in a "reset register" and this information is kept as long as the MCU's power supply is on [7].

Figure 3.5 shows how it can be tested the reset register at the beginning of your program and then branch to a context recovery routine (depending to the detected reset source) instead of restarting the "Power On Reset" initialization routine which is often complex and time consuming [7].

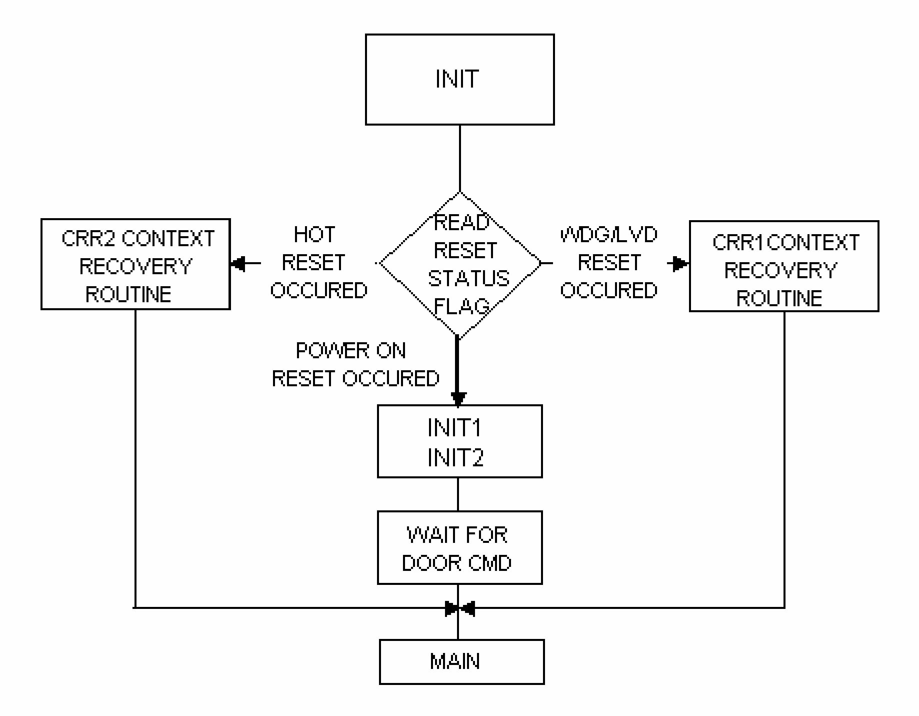


Figure 3.5: Identify Reset Sources [7].

There is an example of identifying reset sources in a Motorola MCU.

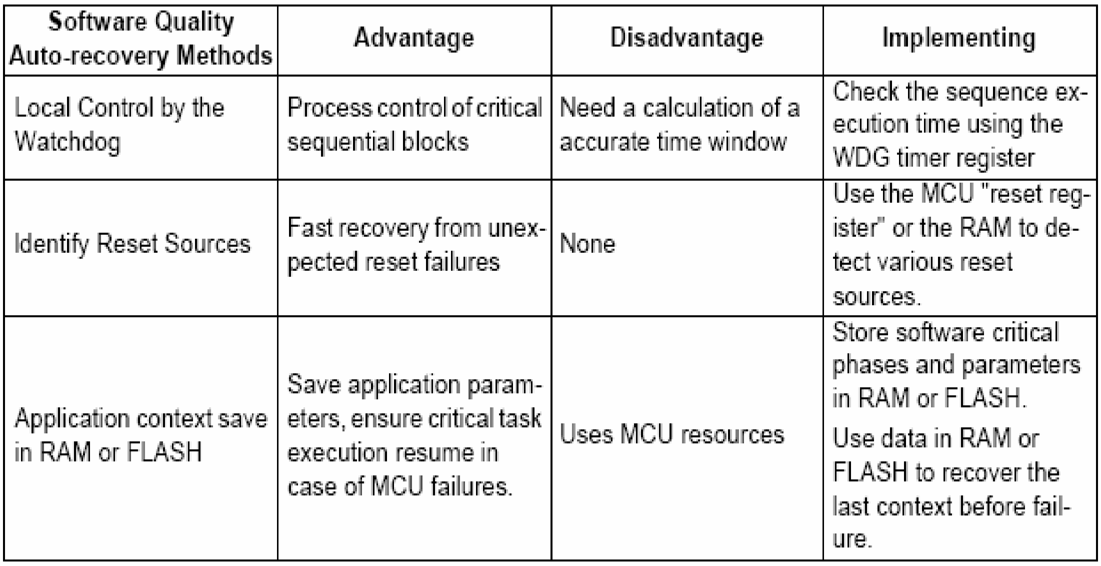
The MCU has these reset sources:

- Power-on reset module (POR)
- External reset pin (RST)
- Computer operating properly module (COP)
- Low-voltage inhibit module (LVI)
- Illegal opcode
- Illegal address

All of these resets produce the vector $FFFE–FFFF ($FEFE–FEFF in Monitor mode) and assert the internal reset signal (IRST). IRST causes all registers to be returned to their default values and all modules to be returned to their reset states. An internal reset clears the system integration module (SIM) counter, but an external reset does not. Each of the resets sets a corresponding bit in the reset status register (RSR).

It is very important to detect and manage parasitic resets as they are the most usual cause of microcontroller EMC failures [7].

Table 3.2: Summary of Auto-Recovery Techniques [7].



Software Quality Auto-recovery Methods	Advantage	Disadvantage	Implementing
Local Control by the Watchdog	Process control of critical sequential blocks	Need a calculation of a accurate time window	Check the sequence execution time using the WDG timer register
Identify Reset Sources	Fast recovery from unexpected reset failures	None	Use the MCU "reset register" or the RAM to detect various reset sources.
Application context save in RAM or FLASH	Save application parameters, ensure critical task execution resume in case of MCU failures.	Uses MCU resources	Store software critical phases and parameters in RAM or FLASH. Use data in RAM or FLASH to recover the last context before failure.

In the Table 3.2, it can be seen that there are some advantages and disadvantages of using auto-recovery methods.

3.5 What results can be achieved?

Many microcontrollers are designed tested and optimized to remain fully functional with +/-1Kv ESD voltages (according EN1000-4-2 standard) directly applied on any pin. Although this performance is acceptable in most cases, it does not guarantee that the MCU will be fully robust at application level which is sometimes above 4kV. Such voltages cannot be withstood by any microcontroller using standard programming techniques [7].

It can be understood that the EMC hardening techniques described in this chapter are absolutely necessary to improve medical application robustness in many cases.

3.6 Conclusion

In many cases of making a medical application, hardened software programming techniques are very important phase of EMC hardening so that it can be carefull when writing a software to cancel the disturbing EMC effects because of the quality of our medical devices depend on our hardened software programming.

Figure 3.6 quantifies the typical EMC robustness limits expected from hardware or software EMC-hardening measures.

It can be seen that good EMC-hardened software can bring the application immunity to a very high level, limited only by the physical silicon resistance.

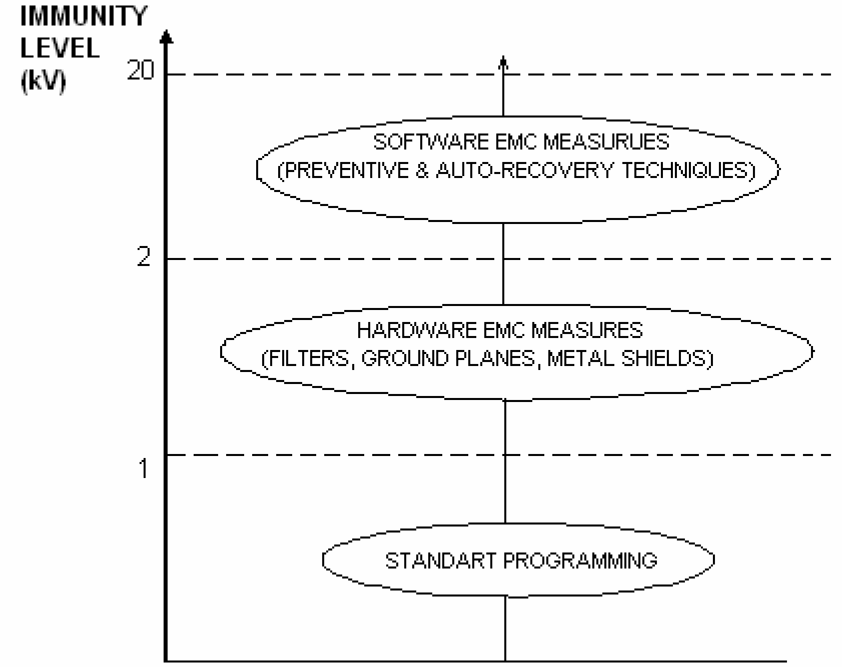


Figure 3.6: Impact of Hardware and Software EMC Hardening [7].

4. EMC TESTING

In this chapter, it can be explained the EMC testing issues when the microcontroller based medical equipment is completed. This chapter will also give a short introduction to the most common EMC phenomena encountered in MCU system designs. To make it easier to understand the different phenomena and the tests used to emulate them are described together.

4.1 Introduction

Unlike many other design issues (for instance, power calculations), there are no exact rules for EMC design saying, “Do it like this and it will work.” Instead, there are a lot of design suggestions saying, “Do it like this and it may work,” or “This is more likely to work, but at a higher cost.” [3]

For most medical applications, it is not possible to prove EMC compliance without actual lab testing. Several new CAD packages include EMC simulations. These may be good design help, saving some extra trips to the test lab, but they can not replace the final compliance test.

EMC performances are measured according to two different aspects:

- Electromagnetic Emissions (EME),
- Electromagnetic Susceptibility / Immunity (EMS).

The two aspects differ according to the method of measurement, the problems identified and their solutions [1].

If an MCU based medical application passes a susceptibility test, it does not mean that it will pass emissions tests, regardless of the types of test performed. Therefore, both EMS and EME testing must be carried out [1].

4.1.1 ESD Immunity Test

ESD (electrostatic discharge) is a phenomenon most people have experienced. This is what happens if you feel a small electric shock when you touch your kitchen sink or another grounded object. What happens is that your body has been charged with a small electrostatic charge (easily achieved by walking on synthetic fiber carpets). This charge is released when you touch an object with a different charge or an object connected to ground. For a human being to actually feel the discharge, the voltage must be about 4 kV or more, and it is not difficult to achieve tens of kV [3].

A simple way of modeling this phenomenon is to use a capacitor that will hold the same charge as the body and a series resistor that will release this charge the same way the body does [3].

Figure 4.1 shows a principle schematic of this setup. Cs is the storage capacitor that equals the capacitance of the human body, Rd is the discharge resistance that equals the resistance of the human body. Vs is a high-voltage power supply, and Rc the series resistance of this power supply. When the switch S is connected to Rc, the capacitor is charged. When the switch S is connected to Rd, the capacitor is discharged through Rd and the device under test, which is connected to or placed near the discharge tip. The value of Rc is of no practical value for what amount of energy is stored in the capacitor or for how this is transferred to the device under test [3].

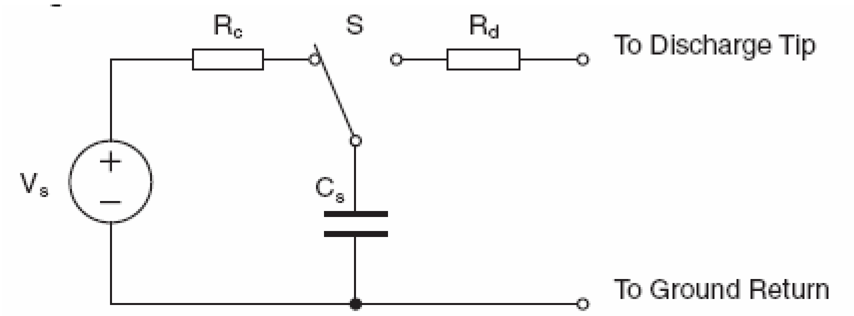


Figure 4.1: ESD Test Generator [3].

Integrated circuits are usually tested according to MILSTD-883. Here Rc is 1 - 10 MΩ, Rd is 1.5 kΩ and Cs is 100 pF. This is the so-called Human Body Model, which tries to emulate the ESD an integrated circuit may experience as a result of manual handling during board production. The traditional test voltage Vs a CMOS device is expected to handle is ±2 kV. Newer devices like AVR microcontrollers are often rated to ± 4 kV or more [3].

Another model, the Machine Model, tries to emulate the ESD an integrated circuit will experience from automatic handlers. Here Cs is twice as big, 200 pF. The current limiting resistor Rd is zero (!), but an inductor up to 500 nH may be inserted instead. Rc is 100 MΩ. In this model, the rise time of the current is much higher, and most devices fail at voltages higher than ±500V [3].

ESD compliance according to the EMC directive is based on IEC 1000-4-2. This standard specifies a Human Body model that tries to emulate the ESD a product will experience as a result of normal use. The component values are therefore slightly tougher here than in MIL-STD-883: Rc is 100 MΩ, Rd is 330Ω and Cs is 150 pF.

This means that a product built by circuits rated at 4 kV may not necessarily pass IEC 1000-4-2 at 4 kV without adding some kind of external protection [3].

Another important difference here: MIL-STD-883 only requires that the device is not damaged by the test. The demand of the EMC directive is stronger: the product shall continue to operate as intended, without being disturbed by the ESD pulse. This requirement is tough, as a high-voltage ESD transient on an input pin may easily change the logic value of the pin. This means that the designer of a microcontroller based medical system must either design hardware to make sure that ESD transient never reaches the I/O pins, or write software that detects and handles such incorrect readings [3]. These harware and software techniques are explained in the chapter-2 and chapter-3.

Electrostatic discharge (ESD) tests, in compliance with standard IEC 1000-4-2, are very important to ensure that the application is not disturbed by the high amount of static voltage produced by the human body [1].

There are two types of tests; air-discharge tests that use a spherical tip and contact discharge tests that use a conical tip. For contact discharge tests, the tips are placed on the pins and the ESD voltage is in the 0-8 kV range. For air-discharge tests, the product is placed on a ground plane separated with 10 cm of insulation. Discharges are made on the ground plane. A statistical method gives more reproducible results [1].

4.2 Fast Transient Burst Immunity Test

This test consists of coupling these disturbances to the power supply or to the I/O of the MCU of the medical device. Fast transients described in standard IEC 1000-4-4 are generated by switches or relays [1].

Fast transients or bursts are generally a power line phenomenon, but it can also be a problem on signal lines due to inductive or capacitive coupling. It can occur when a power switch or a relay with an inductive load is operated: When the current is disconnected, a series of small sparks will put high-voltage spikes on the power line [3].

Figure 4.2 shows the fast transient burst pulse train used for EMC testing and Figure 4.3 shows a close-up of a burst. Note that the pulse is only about 50 ns wide, this is much smaller than the Figure indicates. It can be seen in IEC 1000-4-4 for details of the pulses and the test setup [3].

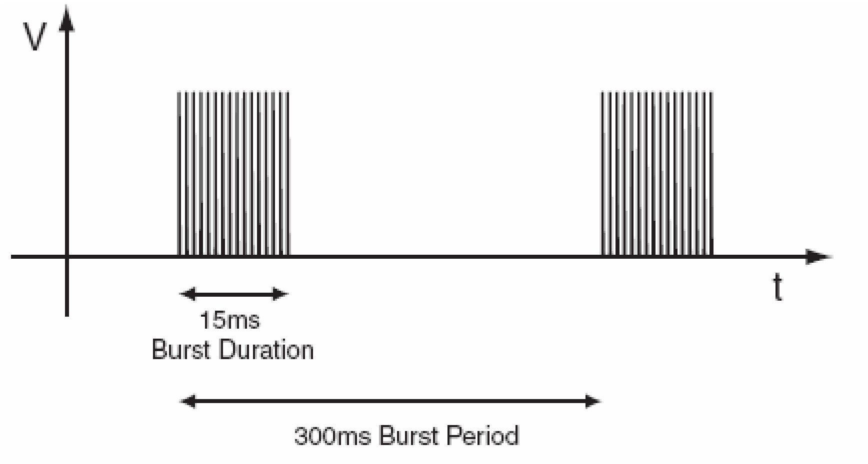


Figure 4.2: Fast Transient Burst [3].

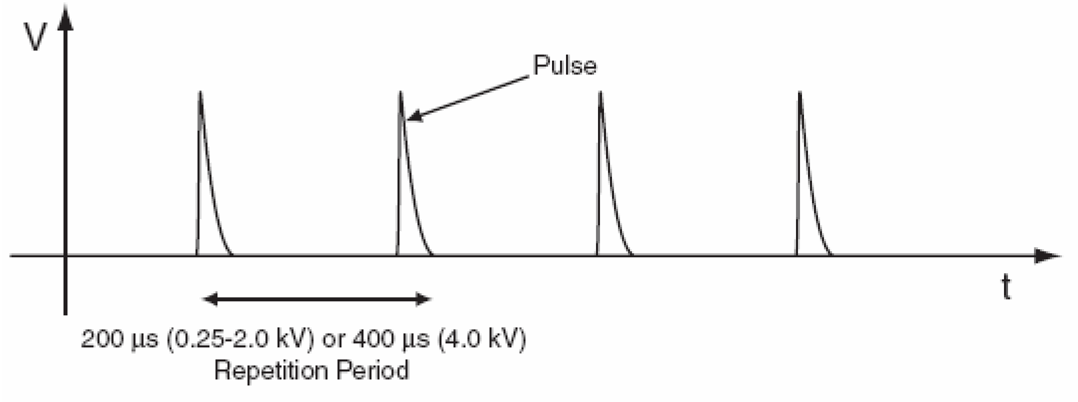


Figure 4.3: Close-Up of Burst [3].

Test voltages on power supply lines are typically 1 kV for protected environment, 2 kV for industrial environment. Severe industrial environments may require up to 4 kV transient testing [3].

Test voltages on I/O lines are half the values used for power supply lines. On an I/O line, the pulse may seem similar to an ESD pulse, but there are some very important differences:

- The energy of a single transient pulse may be higher than an ESD pulse at the same voltage, depending on the coupling path into the system.
- ESD testing is performed once or only a few times, with several seconds cool-down time between each pulse. The fast transient pulse is repeated at 5 kHz (2.5 kHz @ 4 kV) for 15 ms: this is one burst. The burst is repeated every 300 ms [3].

Figure 4.4 shows disturbance diagram and Figure 4.4 shows also coupling network.

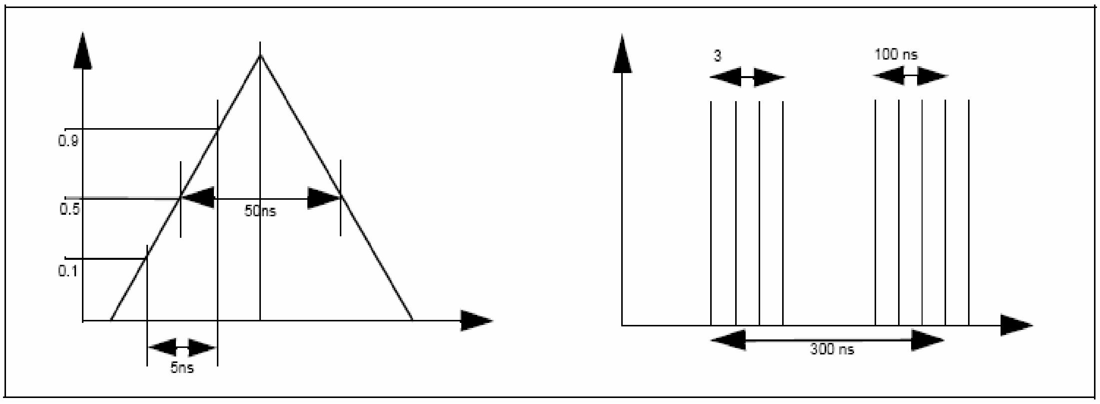


Figure 4.4: Disturbance Diagram

The spike frequency is 5 kHz. The generator produces bursts of spikes that last 15 ms every 300 ms. The fast transients are coupled to the device under test (DUT) with capacitors Cc. An attenuator must be used because the burst generators are too powerful to be directly applied to the components [1].

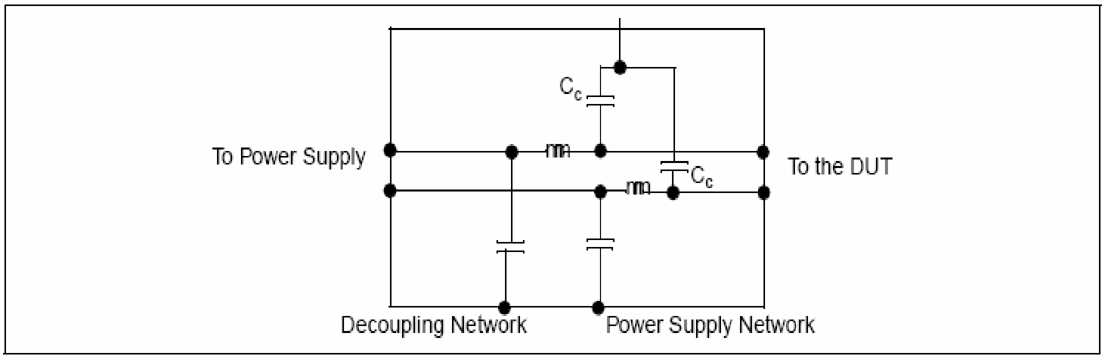


Figure 4.5: Coupling Network

The fast transients are coupled to the I/O with a small capacitor. The test is performed in compliance with standard IEC 1000-4-4. Measurements are performed on a ground plane. The generator is connected to ground plane by a short wire. The HT wire is 10 cm from the ground plane. The DUT is on the insulator 10 cm from the ground plane [1].

The first method consists of increasing the generator voltage until the MCU fails. If this method demonstrates reproducibility problems (the voltage is lower than when the spike occurs), a statistical method must be used [1].

4.2.1 Surge Immunity Test

This is the mother of all transient tests. It tries to emulate what happens when lightning hits (near) the power network, and the energies involved are high. The capacitance of the energy storage capacitor is up to 20 µF, 200,000 times bigger than the 100 pF used in an ESD test. The test setup is not identical to the one shown in Figure 4.1, a few pulse-shaping components are added, but the basic principle is the same. It can be seen in IEC 1000-4-5 for details of this test setup [3].

The surge test is performed only on power supply lines, so this is typically a power supply design issue. However, note that if the design is made to operate on DC power, powered from any approved DC power supply, the designer may still have to incorporate surge protectors on the DC input. The protection of a commercial power supply may be limited to only protecting the power supply itself, resulting in heavy surges on its DC output [3].

Don’t get confused by the similarities between 4 kV ESD testing, 4 kV fast transient burst testing and 4 kV surge. The voltages are the same, but the energy behind them is totally different. Dropping a small rock on your foot may hurt, but you will still be able to walk. Dropping a large rock from the same height will most likely cause severe damage to your foot. Doing this 250 times per second will reduce your shoe size permanently. When the surge boulder falls, you'd rather be somewhere else [3].

The Surge test does not affect the microcontroller as long as the supply voltage remains correct since the rise time is much greater when compared to the clock period.

4.2.2 RF Emission Test

Radio frequency emissions or noise are among the most difficult problems to handle when designing with fast digital circuits. Problems do not occur only as noise radiated to the outside world. Handling noise issues internally in the system is equally important [3].

The tests are split into two different types: radiated emission and conducted emission. This split is mainly done to make the tests practical to implement and because conducted emission dominates in the low-frequency range, while radiated emission dominates in the high-frequency range [3].

Radiated emission is radiated directly from the system and its signal/power cables. This is high-frequency radiation, as a normal PCB is too small to be a good antenna for low frequencies. The EMC directive which are explained in Chapter-1 requires measurements in the range 30 MHz to 1 GHz. American FCC rules require measurements at higher frequencies for certain applications. Lower frequencies are measured directly on the cables [3].

To isolate the component’s EMC behaviour, the board is designed according to SAE 1752 specifications. The board is placed on a metallic box in order to mask all other components. Performances are measured in a Faraday cage with the electromagnetic radiator placed at a distance of 3 meters. The results are measured using a spectrum analyser [1].

The high frequencies will typically be generated by harmonics of digital oscillators and I/O pins. Note that the upper frequency generated by a digital circuit is not limited by the clock frequency of the device, but by the rise time of the signals. Lowering the clock speed of the system will therefore not lower the bandwidth of the noise, but will lower the power radiated at high frequencies. (Reducing the number of noisy transitions will reduce the total power of the noise.) [3]

Conducted emission is measured on cables. The EMC directive requires measurements in the range 150 kHz to 30 MHz. Some test standards require measurements down to 9 kHz. Noise in this frequency range is typically from switch mode power supplies and from the base frequencies of digital oscillators and I/O pins [3].

Long cables will, of course, also act as antennas for both low frequency and high frequency signals. But if the LF signals are damped sufficiently to be below the limits of the conducted emission test, the radiation from the cable will be negligible. It is therefore not necessary to measure radiated emission in the range below 30 MHz [3].

Similarly, conducted HF noise on the cables will show in the radiated emission test. If the noise is sufficiently damped to be below the limit for radiated emission, the conducted noise on the cable will be negligible [3].

Test setups and limits for different applications are given in various standards issued by the International Special Committee on Radio Interference (CISPR). CISPR 22, for instance, covers information technology equipment [3].

The noise radiated by the microcontroller of the medical device is caused by the supply current and the output signal. So, the most significant conducted emission measurements consists of analysing these signals with a spectrum analyser [1].

Two probes are used to extract the signal and to adapt the impedance to the spectrum analyser input seen in Figure 4.6 [1].

The 1-ohm resistor is inserted into the main GND wire (Figure 4.7), i.e. between the power supply, decoupling capacitor and pin load on one side and the IC GND and oscillator load on the other [1].

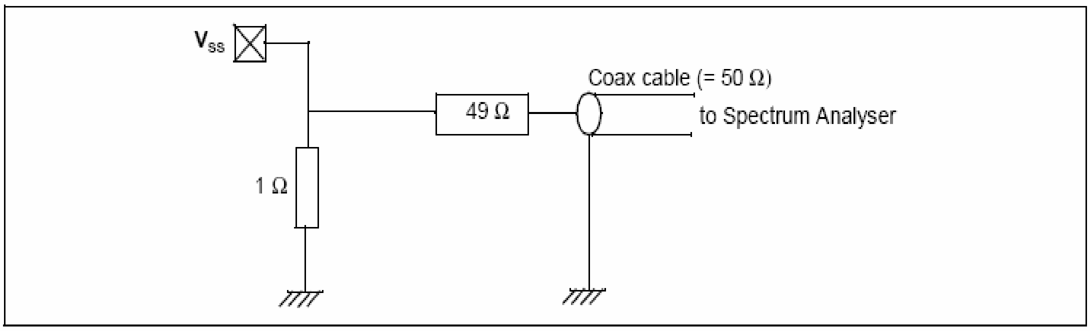


Figure 4.6: Ground Current Probe [1].

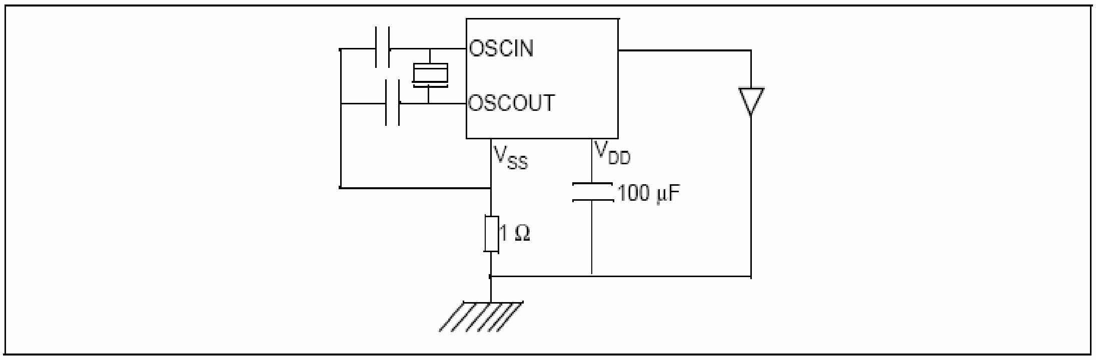


Figure 4.7: Output Signal Probe [1].

A good correlation can be found between radiated EME and ground current measurements. The 1-ohm probe has very good high frequency (HF) characteristics up to 1 GHz. Due to low signal levels, an amplifier is used [1].

The HF resistance of wires on application boards is typically in the range of 100-300 ohms. Therefore, the MCU can be seen as a noise generator connected to a 150-ohm antenna system. These definitions are taken from standard IEC 1000-4-6. To convert the 150-ohm board load to 50 ohms, a voltage divider seen Figure 4.8 is used [1].

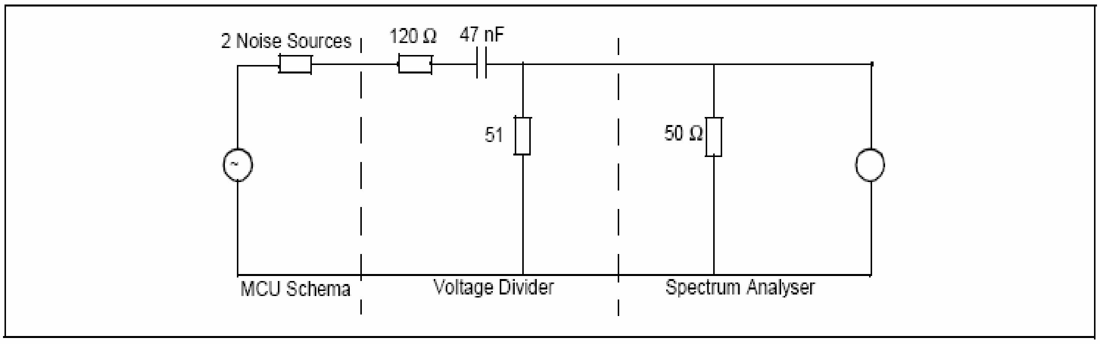


Figure 4.8: Voltage Divider Diagram [1].

4.3 RF Immunity Test

This test is done to verify that a product can operate as intended even if it is exposed to a strong radio transmitter. The test limit for immunity is much higher than the test limit for emission, so the fields involved are strong [3].

Be aware that the RF fields a system may be exposed to can be higher than the test limits required for EMC approval. The test limit for conducted RF fields is 3V/m for household applications. A GSM cell phone transmitting at maximum power will produce this field strength at a distance of 3 meters. If the cell phone is closer, the field strength will be higher. If the intended use of the system may include operation while someone is using a cell phone nearby, it is therefore a good idea to test the system for higher immunity levels than the minimum levels required. Industrial applications usually require 10V/m or higher [3].

Digital systems usually do not experience problems with this test, but analog parts of the system may. As for RF emission, the RF immunity tests are split into two different types: radiated and conducted emission [3].

The test setup for radiated disturbances is given in IEC 1000-4-3; for conducted disturbances the test setup is given in IEC 1000-4-6 [3].

There are an infinite number of disturbances, but the principal types can be classified according to their spectrum in Figure 4.9 [1].

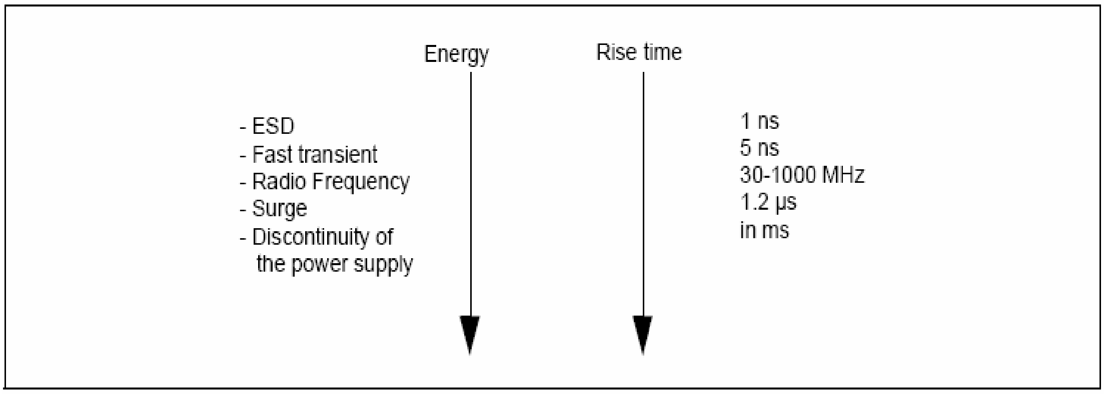


Figure 4.9: Disturbance Spectrum Diagram [1].

The discontinuity of the power supply is irrelevant since electrical energy is not stored in MCUs [1].

4.4 EMC/EMI Test Laboratory Equipment

The EMC/EMI Laboratory has a set of test equipment that can be conFigured to perform specific batch of tests to investigate the limits of compliance in terms of EMI and ensures the basic EMI standards in terms of Electromagnetic emissions and immunity. The equipment described below are used to perform different kinds of EMC testing on all the experimental prototype circuits [8].

The GTEM 250 (Figure 4.10) is used to perform the radiated emissions and immunity tests for small size DUTs (0.2x0.2x0.15m) without the need for an full size anechoic chamber. The frequency range of the cell is 0.01 to 18000 MHz. It meets IEC/EN 61000-4-3, FCC C63.4 and IEC/EN 61000-4-20. It allows simple calculation to be performed and requires only simple single channel power meters. There is no need for measurement of reflected power with excellent voltage standing wave ratio (VSWR) over the entire frequency range - It is equipped with a decoupling power input filter to segregate between the DUT noise and the ambient noise [8].

Figure 4.10: Schaffner GTEM Cell 250 for Emitted Compliance Test [8].

The R3131A Spectrum Analyzer seen Figure 4.11 is used to measure the current and power spectrums generated from the time-domain waveforms for the designed circuit. As power spectrum and current drawn are required to meet different IEC standards, it is necessary to make sure that all the designed circuits built in the lab can provide high efficient and low-noise compatible solutions for future switch mode power supply (SMPS) designs. The synthesized architecture and specifications of this analyzer ensure measurement accuracy and repeatability. The spectrum analyzer forms an integrate part of the conducted and radiated emissions test setup. The analyzer is controlled through interface software from SCHAFFNER (COMPLIANCE3) in which the test setup can be conFigured according to the type of test and the DUT septum height [8].

Figure 4.11: Advantest R3131A Spectrum Analyzer (9kHz-3GHz) [8].

The ZVR62 network analyzer seen Figure 4.12 measures the complex transmission (S1-2) and reflection (S1-1) characteristics of two-port devices in frequency domain. The task is performed by first sampling the incident signal, separating the transmitted and reflected waves. Then the ratios between the reflection and transmission coefficients of the two-port are performed. Frequency sweep can be performed to rapidly obtain amplitude and phase information over the band of frequencies of interest [8].

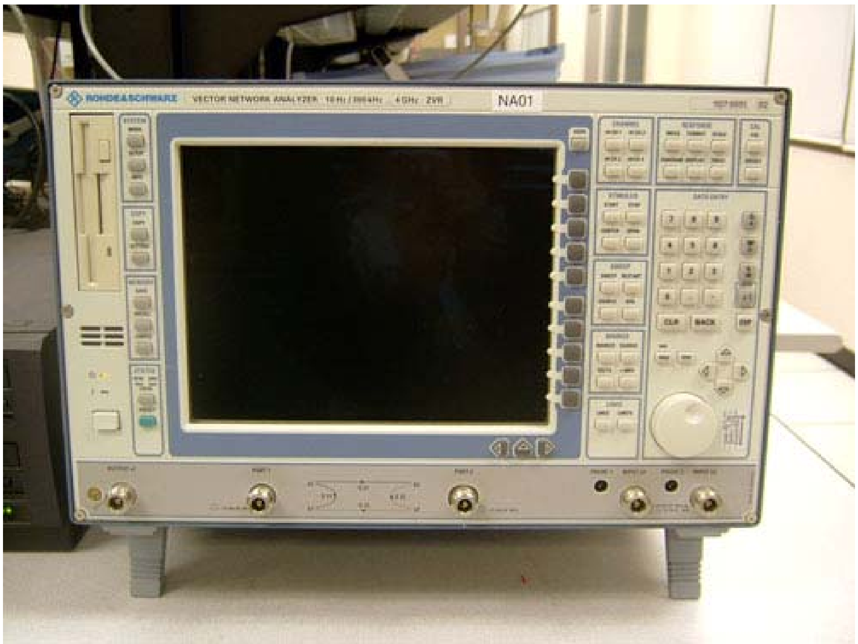


Figure 4.12: Rohde & Schwarz Vector Net. Analyzer ZVR-62 (300kHz-4GHz) [8].

The E7402A EMC analyzer seen Figure 4.13 provides analysis and calculations on both radiated emissions and Conducted emissions testing. When combined with a broadband antenna, the E7402A provides the capabilities to test the radiated emissions coming from the designed circuit [8].

Figure 4.13: EMC Analyzer 9KHz to 3 KGz (E7402A) [8].

The Agilent 4294A precision impedance analyzer seen Figure 4.14 is an integrated solution for efficient impedance measurement for all the designed power circuits. The wide signal-level ranges enable device evaluation under actual operating conditions. Advanced calibration and error compensation functions improve and minimize measurement errors when performing measurements on in-fixture devices [8].

Figure 4.14: Precision Impedance analyzer (4294A) [8].

The 2023A RF signal generator seen Figure 4.15 covers a broad frequency range from 9kHz to 1.2GHz. It consists of both linear and logarithmic sweep mode with excellent spectral purity. It allows different kinds of modulation sources to be used, including: amplitude modulation (AM), frequency modulation (FM), pulse or frequency shift keying (FSK) modulation [8].

Figure 4.15: RF Signal Generator (2023A) [8].

4.5 Conclusion

The test phase of a microcontroller based medical device is also very important issue because of the fact that medical equipment are determined as high or low level reliable equipment related the EMC directives when the test phase has done. For that reason many companies have launched for testing any equipment to determine reliabilty of EMC. In Turkey has also some testing laboratories such as TÜBİTAK Ulusal Metroloji Enstitüsü (UME) EMC Labarotary seen Figure 4.16.

Figure 4.16: UME EMC Laboratory

5. MEDICAL APPLICATON

5.1 Introduction

In this chapter, it can be shown that how a microcontroller-based medical device design are made considering with all of the precautions that are software and hardware techniques to reduce the EMC effects. For that reason, an application, temperature controlled incubator (TCI), is made with a microcontroller MC68HC908JL3 from Motorola Corporation (now called Freescale Semiconductor).

TCI has two step motor and drive capability for controlling of heat & cool of the inner and the outer air which are circulated. For controlling of amount of the air, the direction of the step motors which control the valves of the heat and the cool air are clockwise or counter clockwise.

TCI are also controlled with a computer for remote controlling and the temperature of the TCI can be seen via the graphical user interface (GUI) or 4 up, 4 down 7 segment display. For temperature sensing, TCI has two temperature sensors which are for outer and inner temperature values.

5.2 Microcontroller

The MC68H(R)C908JL3 is a member of the low-cost, high-performance M68HC08 Family of 8-bit microcontroller units (MCUs). The M68HC08 Family is based on the customer-specified integrated circuit (CSIC) design strategy. All MCUs in the family use the enhanced M68HC08 central processor unit (CPU08) and are available with a variety of modules, memory sizes and types, and package types [9].

5.2.1 Features of the MCU

Features of the MC68H(R)C908JL3 include the following:

- High-performance M68HC08 architecture
- Fully upward-compatible object code with M6805, M146805, and M68HC05 Families
- Low-power design; fully static with stop and wait modes
- 5V and 3V operating voltages

- 8MHz internal bus operation
- RC-oscillator circuit or crystal-oscillator options
- In-system FLASH programming
- FLASH security
- User FLASH memory 4096 bytes
- 128 bytes of on-chip random-access memory (RAM)
- 2-channel, 16-bit timer interface module (TIM)
- 12-channel, 8-bit analog-to-digital converter (ADC)
- 23 general purpose I/O ports for MC68H(R)C908JL3:

– 7 keyboard interrupt with internal pull-up

– 2 × 25mA open-drain I/O with pull-up

- System protection features:

– Optional computer operating properly (COP) reset

– Optional low-voltage detection with reset and selectable trip

- points for 3V and 5V operation.

– Illegal opcode detection with reset

– Illegal address detection with reset

- Master reset pin with internal pull-up and power-on reset
- IRQ1 with programmable pull-up and schmitt-trigger input
- 28-pin PDIP and 28-pin SOIC packages for MC68H(R)C908JL3

Features of the CPU08 include the following:

- Extensive loop control functions
- 16 addressing modes (eight more than the HC05)
- 16-bit index register and stack pointer
- Memory-to-memory data transfers
- Fast 8 × 8 multiply instruction
- Fast 16/8 divide instruction
- Optimization for controller applications
- Efficient C language support [9].

5.2.2 MCU Block Diagram

Figure 5.1 shows the structure of the MC68H(R)C908JL3 which is general purpose MCU and can be also used in medical devices. But MCU has only 8-bit analog to digital converter (ADC).

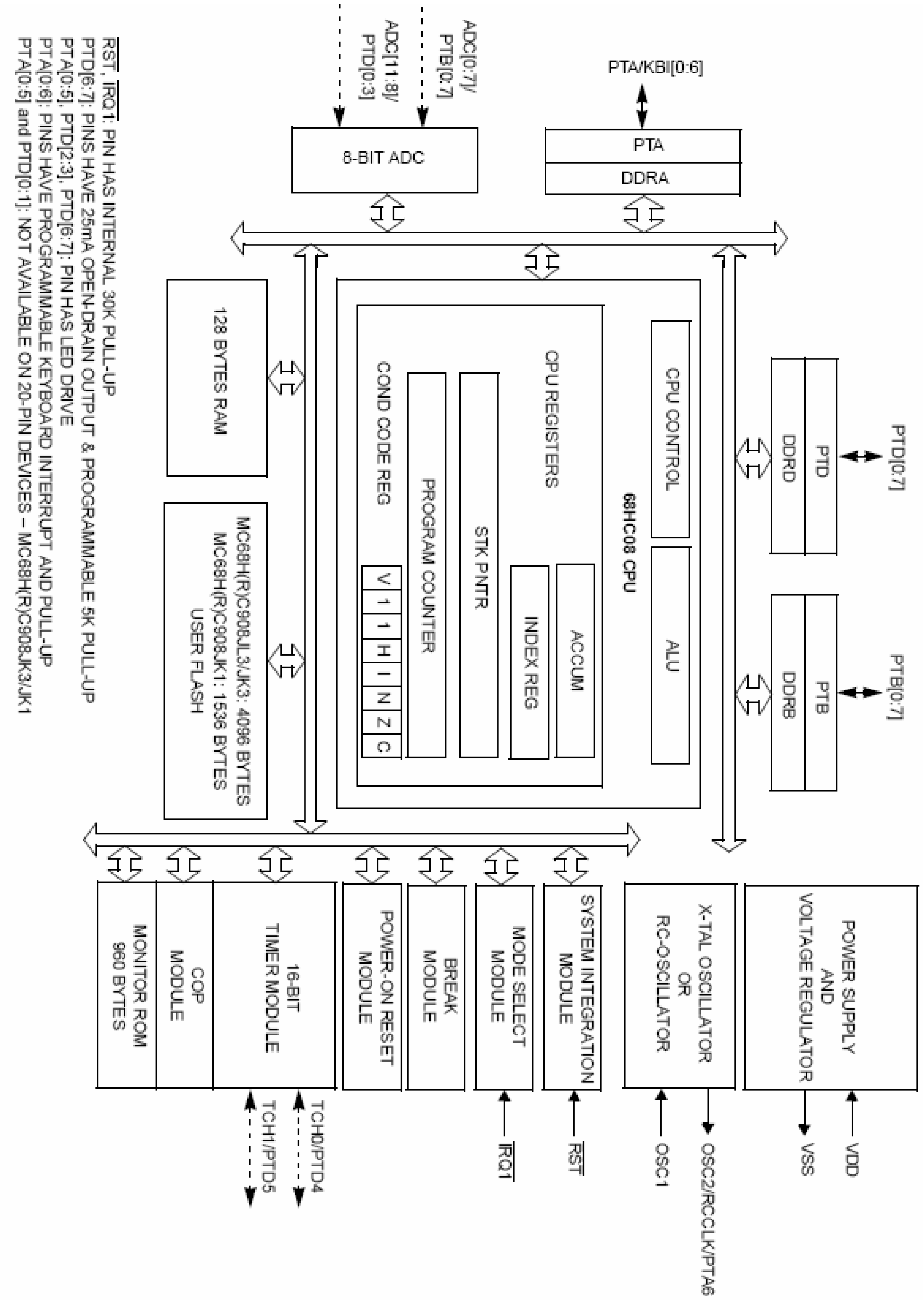


Figure 5.1: MCU Block Diagram [9].

5.2.3 Pin Assignments

The MC68H(R)C908JL3 is available in 28-pin packages and the MC68H(R)C 908JK3/JK1 in 20-pin packages. Figure 1-2 shows the pin assignment for the package.

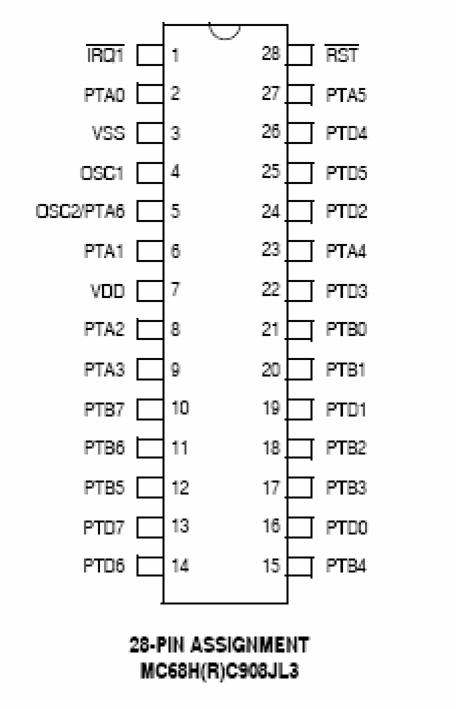


Figure 5.2: MCU Pin Assignments [9].

5.2.4 Pin Functions

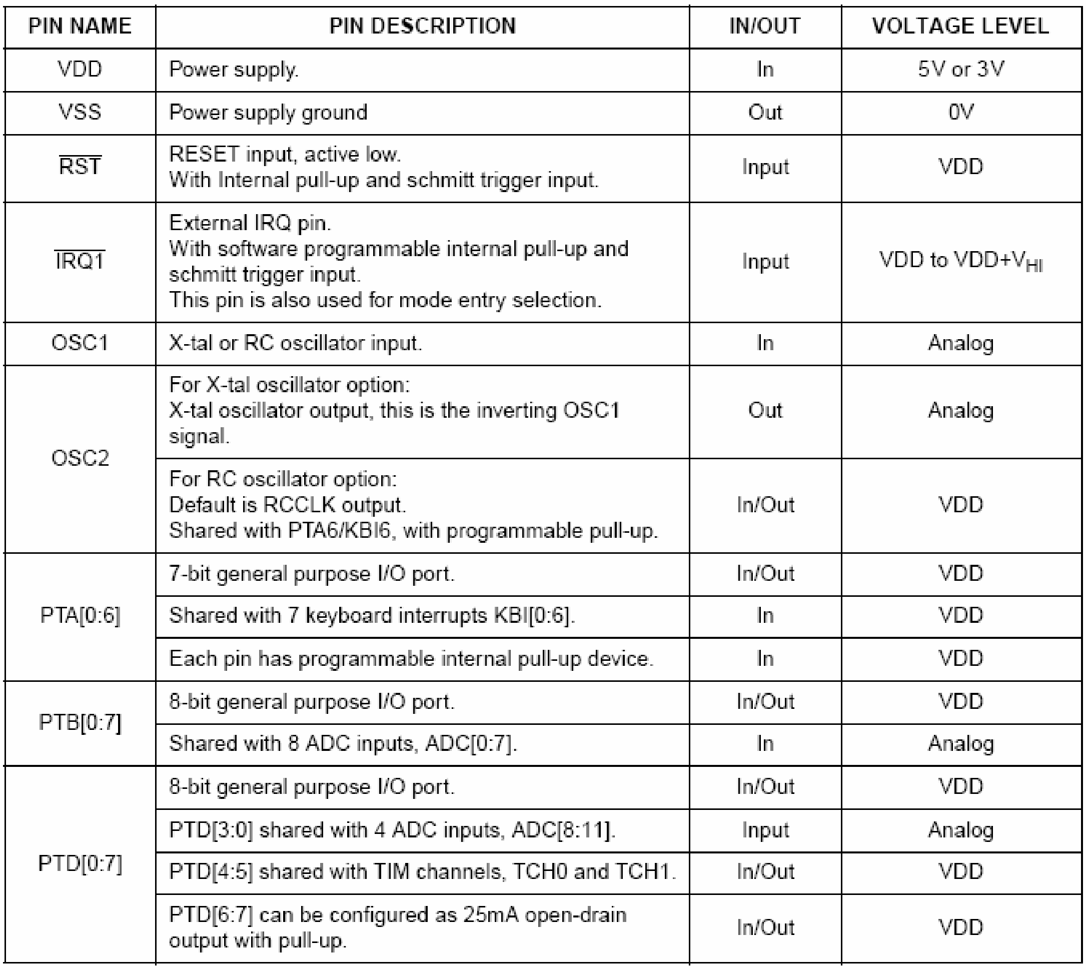
Description of the pin functions are provided in Table 1-2.

Port A is an 7-bit special function port that shares all seven of its pins with the Keyboard Interrupt (KBI) Module. Each port A pin also has software configurable pull-up device if the corresponding port pin is conFigured as input port. PTA0 to PTA5 has direct LED drive capability [9].

Port B is an 8-bit special function port that shares all eight of its port pins with the Analog-to-Digital converter (ADC) module [9].

Port D is an 8-bit special function port that shares two of its pins with Timer Interface (TIM) Module and shares four of its pins with Analog to Digital Conversion Module. PTD6 and PTD7 each has high current drive (25mA sink) and programmable pullup. PTD2, PTD3, PTD6 and PTD7 each has LED driving capability [9].

Table 5.1: Pin Functions [9].

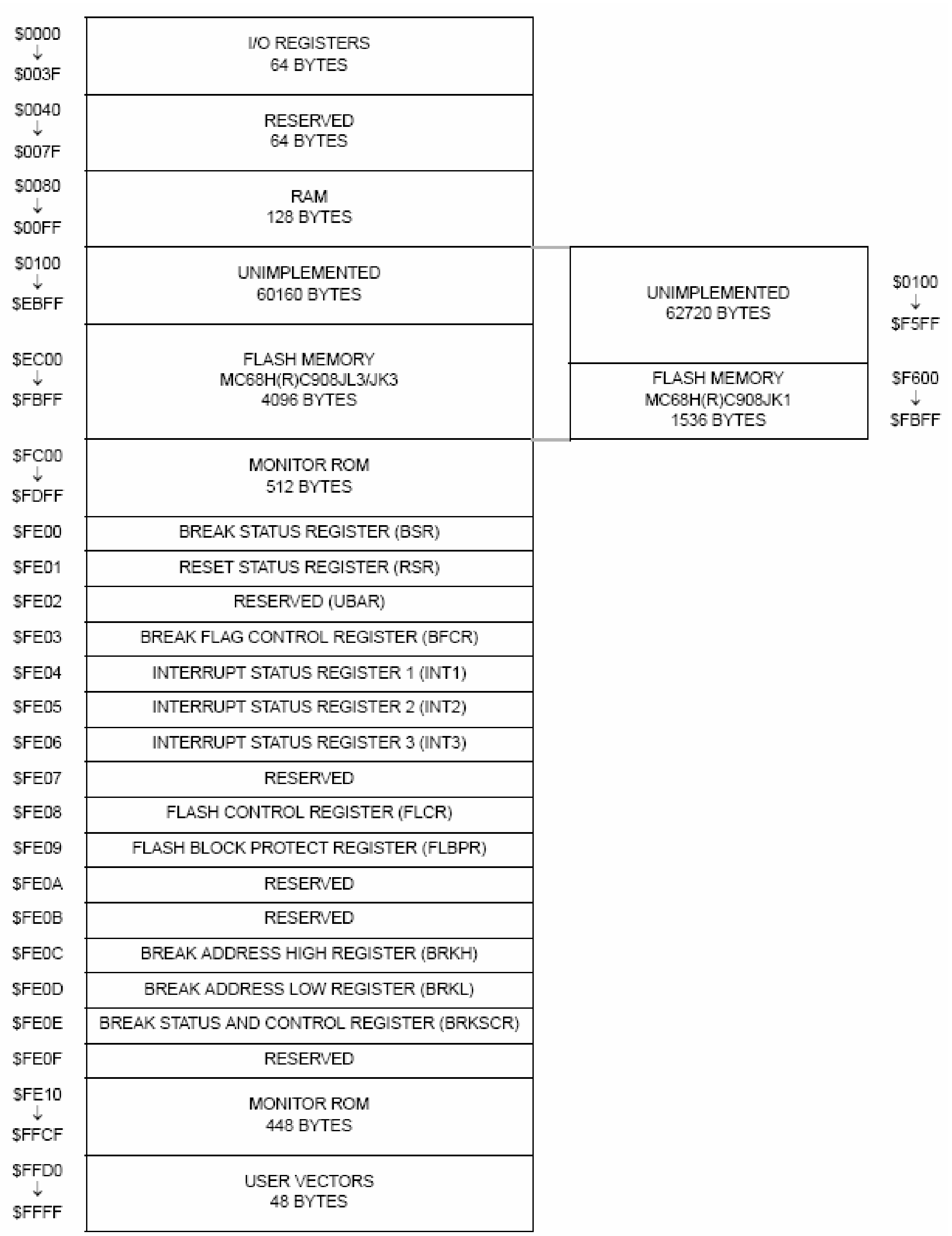


PIN NAME	PIN DESCRIPTION	IN/OUT	VOLTAGE LEVEL
VDD	Power supply.	In	5V or 3V
VSS	Power supply ground	Out	0V
$\overline{\text{RST}}$	RESET input, active low. With Internal pull-up and schmitt trigger input.	Input	VDD
$\overline{\text{IRQ1}}$	External IRQ pin. With software programmable internal pull-up and schmitt trigger input. This pin is also used for mode entry selection.	Input	VDD to VDD+V_{HI}
OSC1	X-tal or RC oscillator input.	In	Analog
OSC2	For X-tal oscillator option: X-tal oscillator output, this is the inverting OSC1 signal.	Out	Analog
	For RC oscillator option: Default is RCCLK output. Shared with PTA6/KBI6, with programmable pull-up.	In/Out	VDD
PTA[0:6]	7-bit general purpose I/O port.	In/Out	VDD
	Shared with 7 keyboard interrupts KBI[0:6].	In	VDD
	Each pin has programmable internal pull-up device.	In	VDD
PTB[0:7]	8-bit general purpose I/O port.	In/Out	VDD
	Shared with 8 ADC inputs, ADC[0:7].	In	Analog
PTD[0:7]	8-bit general purpose I/O port.	In/Out	VDD
	PTD[3:0] shared with 4 ADC inputs, ADC[8:11].	Input	Analog
	PTD[4:5] shared with TIM channels, TCH0 and TCH1.	In/Out	VDD
	PTD[6:7] can be configured as 25mA open-drain output with pull-up.	In/Out	VDD

5.2.5 Memory map

The CPU08 can address 64 Kbytes of memory space. The memory map, shown in Figure 5.3, includes:

- 4096 bytes of user FLASH for MC68H(R)C908JL3/JK3
- 128 bytes of RAM
- 48 bytes of user-defined vectors
- 960 bytes of Monitor ROM



Address	Contents
\$0000 ↓ \$003F	I/O REGISTERS 64 BYTES
\$0040 ↓ \$007F	RESERVED 64 BYTES
\$0080 ↓ \$00FF	RAM 128 BYTES
\$0100 ↓ \$EBFF	UNIMPLEMENTED 60160 BYTES
\$EC00 ↓ \$FBFF	FLASH MEMORY MC68H(R)C908JL3/JK3 4096 BYTES
\$FC00 ↓ \$FDFF	MONITOR ROM 512 BYTES
\$FE00	BREAK STATUS REGISTER (BSR)
\$FE01	RESET STATUS REGISTER (RSR)
\$FE02	RESERVED (UBAR)
\$FE03	BREAK FLAG CONTROL REGISTER (BFCR)
\$FE04	INTERRUPT STATUS REGISTER 1 (INT1)
\$FE05	INTERRUPT STATUS REGISTER 2 (INT2)
\$FE06	INTERRUPT STATUS REGISTER 3 (INT3)
\$FE07	RESERVED
\$FE08	FLASH CONTROL REGISTER (FLCR)
\$FE09	FLASH BLOCK PROTECT REGISTER (FLBPR)
\$FE0A	RESERVED
\$FE0B	RESERVED
\$FE0C	BREAK ADDRESS HIGH REGISTER (BRKH)
\$FE0D	BREAK ADDRESS LOW REGISTER (BRKL)
\$FE0E	BREAK STATUS AND CONTROL REGISTER (BRKSCR)
\$FE0F	RESERVED
\$FE10 ↓ \$FFCF	MONITOR ROM 448 BYTES
\$FFD0 ↓ \$FFFF	USER VECTORS 48 BYTES

Contents	Address
UNIMPLEMENTED 62720 BYTES	\$0100 ↓ \$F5FF
FLASH MEMORY MC68H(R)C908JK1 1536 BYTES	\$F600 ↓ \$FBFF

Figure 5.3: Memory Map [9].

5.3 Medical Application schematics

In this medical application, there are three options to be shown by the operator. These are via serial communication to a computer using RS232, 7-segment displays and graphic LCD. For that reason, MCU timer module are used as a communication port.

5.3.1 Seven segment displays schematic

In Figure 5.4, seven segment displays are used for showing the situation of the temperature values and motor speeds. 4-upper displays and 4-lower displays are used with driver 3 CD4094 (shift register and latch logic).

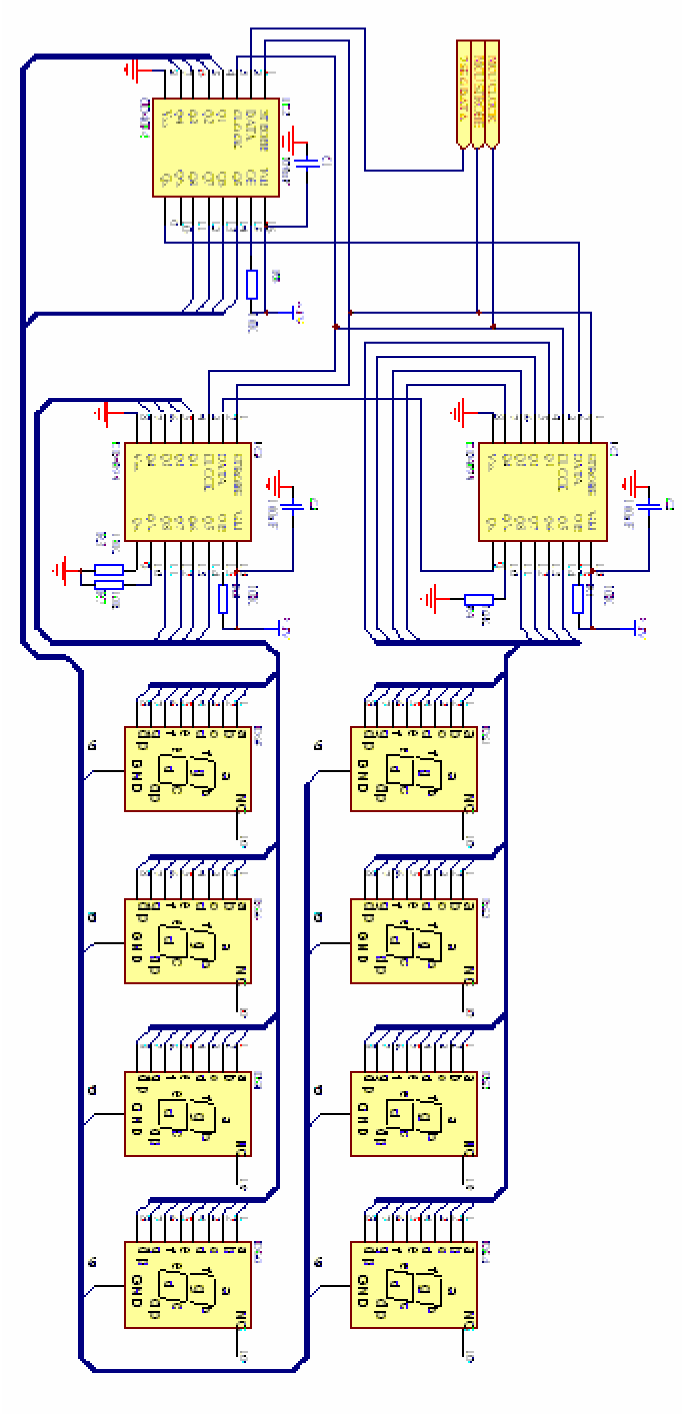


Figure 5.4: Seven segment shematic

5.3.2 Power source schematic

As a power source, the LM2575 series of regulators are used. These series are monolithic integrated circuits that provide all the active functions for a step-down (buck) switching regulator, capable of driving a 1A load with excellent line and load regulation. These devices are available in fixed output voltages of 3.3V, 5V, 12V, 15V, and an adjustable output version.

Requiring a minimum number of external components shown in the Figure 5.5, these regulators are simple to use and include internal frequency compensation and a fixed-frequency oscillator [10].

The LM2575 series offers a high-efficiency replacement for popular three-terminal linear regulators. It substantially reduces the size of the heat sink, and in many cases no heat sink is required [10].

A standard series of inductors optimized for use with the LM2575 are available from several different manufacturers. This feature greatly simplifies the design of switch-mode power supplies [10].

Other features include a guaranteed ±4% tolerance on output voltage within specified input voltages and output load conditions, and ±10% on the oscillator frequency. External shutdown is included, featuring 50 µA (typical) standby current. The output switch includes cycle-by-cycle current limiting, as well as thermal shutdown for full protection under fault conditions. Features of the LM2575 are; [10]

- 3.3V, 5V, 12V, 15V, and adjustable output versions
- Adjustable version output voltage range, 1.23V to 37V (57V for HV version) ±4% max over line and load conditions
- Guaranteed 1A output current
- Wide input voltage range, 40V up to 60V for HV version
- Requires only 4 external components
- 52 kHz fixed frequency internal oscillator
- TTL shutdown capability, low power standby mode
- High efficiency
- Uses readily available standard inductors
- Thermal shutdown and current limit protection
- P+ Product Enhancement tested

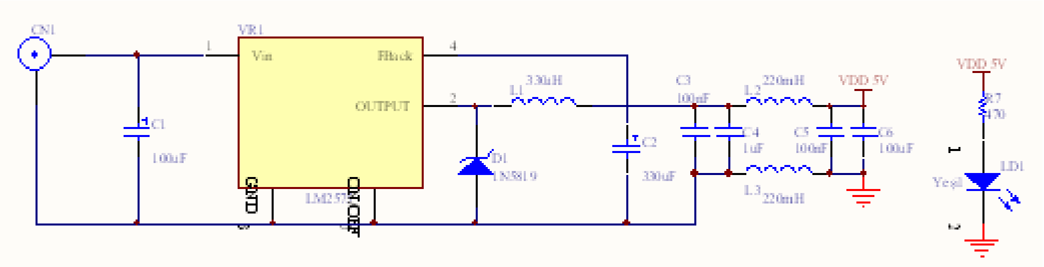


Figure 5.5: Power source shematic

5.3.3 Graphic LCD shematic

Another option for displaying and controlling the status of the TCI is this graphic LCD due to its thin profile, light weight, low power consumption and easy handling, liquid crystal graphic display modules are used in a wide variety of applications such as medical applications. The 128 x 64K LCD display is very popular in a number of different computing environments. It is for this reason that a controller is included on the module.

Possible choices of controllers include an embedded 8-bit microcontroller with an LCDcontroller, such as the Epson/S-MOS SED1335 or the OKI MSM6255/6355. Some embedded microcontrollers, such as the National NS486SXF, have built-in LCD controllers and will interface directly to the display. But in our design Motorola MCU is used and there isn’t any built-in LCD modules.

For PC-based embedded controllers like the Intel 386/486EX, a VGA controller chip, such as the Chips and Technology F65545 or the Vadem VG-660, is the best choice. If the display is to be run directly from a PC, a number of VGA cards are available that will operate with this display. A number of single board computers are available with LCD display outputs.

This thesis will deal with one of the most popular application environments, the 8-bit embedded Motorola microcontroller 8-bit series. The medical application detailed here is based on a MC68HC908 microcontroller driving an Epson/S-MOS SED1335 LCD controller in LCD.

The LCD 128 x 64 series of displays have an industry standard 8-bit parallel interface. This interface requires the controller to continuously refresh the display and to maintain the video display RAM.

Before the display can be used the microcontroller must first send a series of initialization bytes to the LCD controller to set up its operational parameters and to describe the display to the controller. Once initialized the application microcontroller can send text or graphic data to the LCD controller where it will be formatted and stored in the display RAM. Coincident with these RAMupdates the LCD controller is continuously reading data from the display RAM, serializing it and sending it to the display. The application microcontroller doesn't have direct access to the display RAM and must send all data and commands to the LCD controller chip.

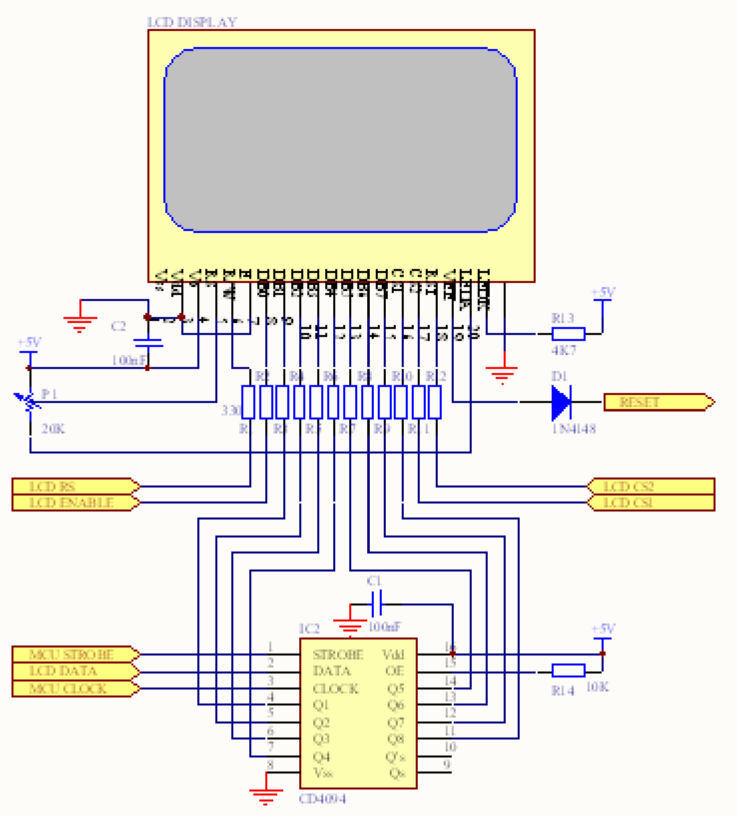


Figure 5.6: Graphic LCD shematic

5.3.4 Motor drive schematic

In this application, two step motors shown in Figure 5.7 are used for controlling the inner and the outer air. A step motor is a constant output power transducer, where power is defined as torque multiplied by speed. This means motor torque is the inverse of motor speed. To help understand why a step motor's power is independent of speed, we need to construct (figuratively) an ideal step motor.

An ideal step motor would have zero mechanical friction, its torque would be proportional to ampere-turns and its only electrical characteristic would be inductance. Ampere-turns simply mean that torque is proportional to the number of turns of wire in the motor's stator multiplied by the current passing through those turns of wire.

Anytime there are turns of wire surrounding a magnetic material such as the iron in the motor's stator, it will have an electrical property called inductance. Inductance describes the energy stored in a magnetic field anytime current passes through this coil of wire. Inductance (L) has a property called inductive reactance, which for the purposes of this discussion may be thought of as a resistance proportional to frequency and therefore motor speed.

According to ohm's law, current is equal to voltage divided by resistance. In this case we substitute inductive reactance for resistance in ohm's law and conclude motor current is the inverse of motor speed. Since torque is proportional to ampere-turns (current times the number of turns of wire in the winding), and current is the inverse of speed, torque also has to be the inverse of speed.

In an ideal step motor, as speed approaches zero, its torque would approach infinity while at infinite speed torque would be zero. Because current is proportional to torque, motor current would be infinite at zero speed as well.

Electrically, a real motor differs from an ideal one primarily by having a non-zero winding resistance. Also the iron in the motor is subject to magnetic saturation, as well as having eddy current and hysteresis losses. Magnetic saturation sets a limit on current to torque proportionality while eddy current and hysteresis (iron losses) along with winding resistance (copper losses) cause motor heating.

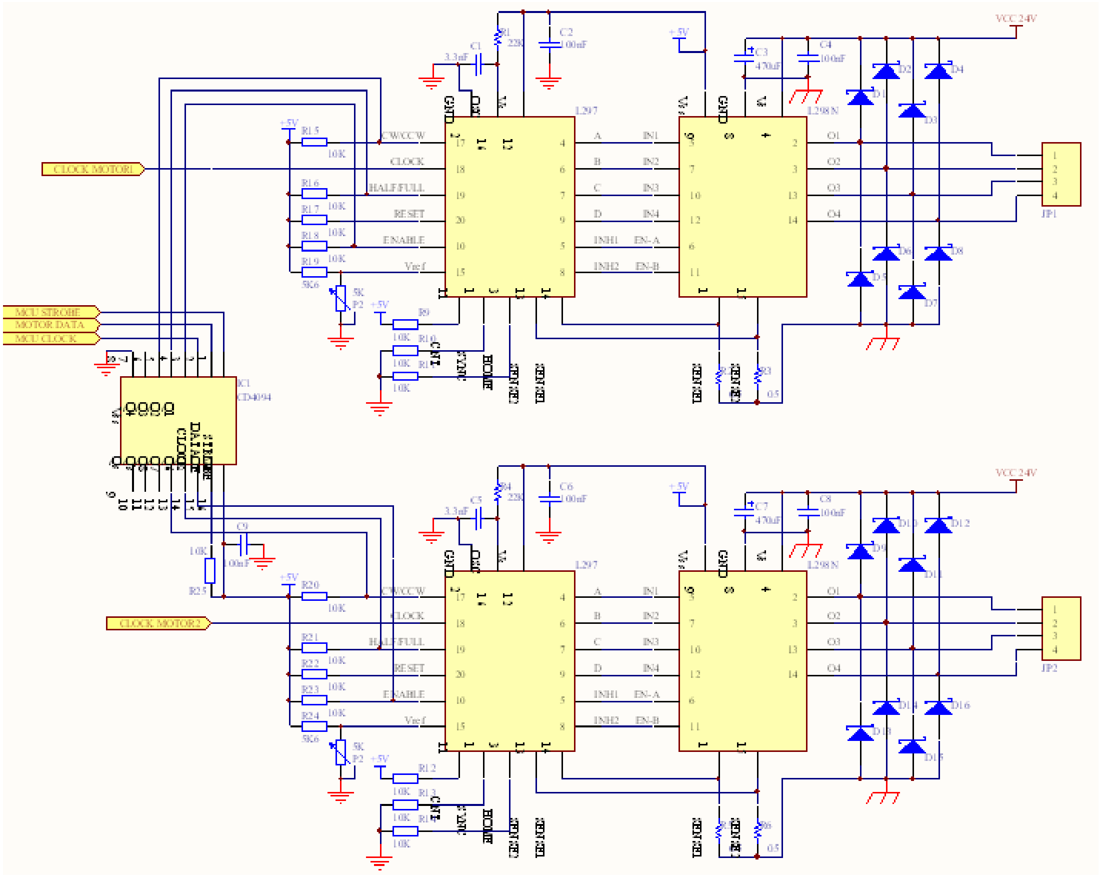


Figure 5.7: Motor drive shematic

To drive two motors, step motor integrated circuits are used L297 and L298. The L297 Stepper Motor Controller IC generates four phase drive signals for two phase bipolar and four phase unipolar step motors in microcontroller-based applications like TCI. The motor can be driven in half step, normal and wave drive modes and on-chip PWM chopper circuits permit switch-mode control of the current in the windings. A feature of this device is that it requires only clock, direction and mode input signals. Since the phase are generated internally the burden on the microprocessor, and the programmer, is greatly reduced. Mounted in DIP20 and S020 packages, the L297 can be used with monolithic bridge drives such as the L298N or L293E, or with discrete transistors and darlingtons.

The L298 is an integrated monolithic circuit in a 15-lead Multiwatt and Power S020 packages. It is a high voltage, high current dual full-bridge driver designed to accept standart TTL logic levels and drive inductive loads such as relays, solenoids, DC and stepping motors. Two enable inputs are provided to enable or disable the device independently of the input signals. The emitters of the lower transistors of each bridge are connected together and the corresponding external terminal can be used for the connection of an external sensing resistor. An additional supply input is provided so that the logic works at a lower voltage.

5.3.5 MCU and hardware watcdog schematic

As a MCU, Motorola MC68HCJL3 explained before is used but as a hardware supervisory circuits, MAX6324 series is also used. Supervisory circuits mean Watchdog and Manual Reset integration. The connection of the MCU and MAX6324 are seen in Figure 5.8.

The MAX6324 microprocessor (µP) supervisory circuits monitor power supplies and µP activity in digital systems. A watchdog timer looks for activity outside an expected window of operation. Six laser trimmed reset thresholds are available with ±2.5% accuracy from +2.32V to +4.63V. Valid RESET output is guaranteed down to Vcc = +1.2V.

The RESET output is open-drain (MAX6324). RESET is asserted low when VCC falls below the reset threshold, or when the manual reset input (MR) is asserted low. RESET remains asserted for at least 100ms after VCC rises above the reset threshold and MR is deasserted.

The watchdog pulse output (WDPO) utilizes an opendrain configuration. It can be triggered either by a fast timeout fault (watchdog input pulses are too close to each other) or a slow timeout fault (no watchdog input pulse is observed within the timeout period). The watchdog timeout is measured from the last falling edge of watchdog input (WDI) with a minimum pulse width of 300ns. WDPO is asserted for 1ms when a fault is observed. Eight laser-trimmed timeout periods are available.

The MAX6324 are offered in a 6-pin SOT23 package and operate over the extended temperature range (-40°C to +125°C).

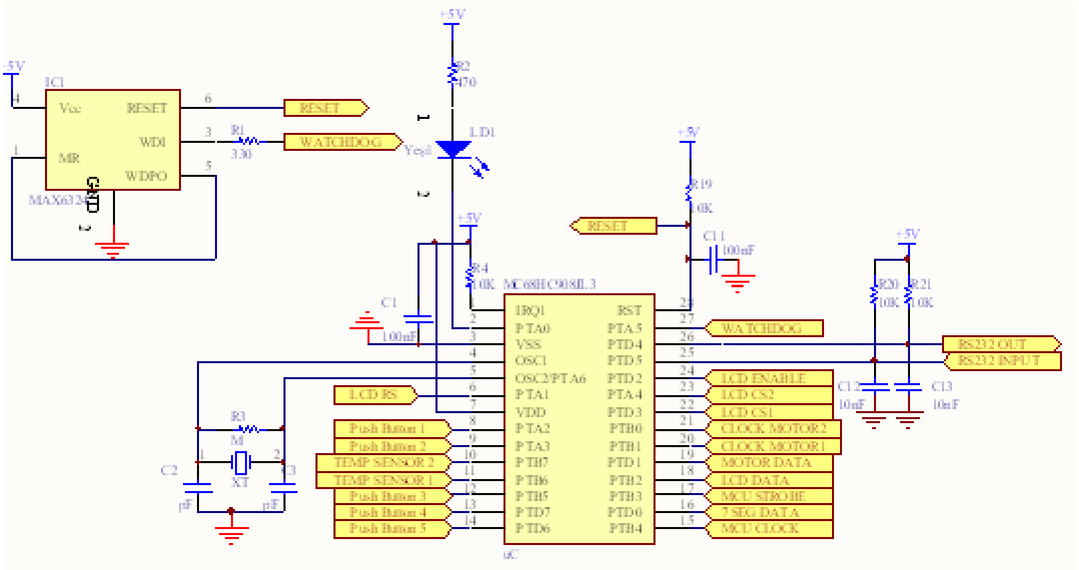


Figure 5.8: MCU and Watchdog shematic

5.3.6 Serial RS-232 communication schematic

As a serial communication circuit, MAX232 IC is used. Connections beetween the RS-232 ports and MCU ports are shown in Figure 5.9.

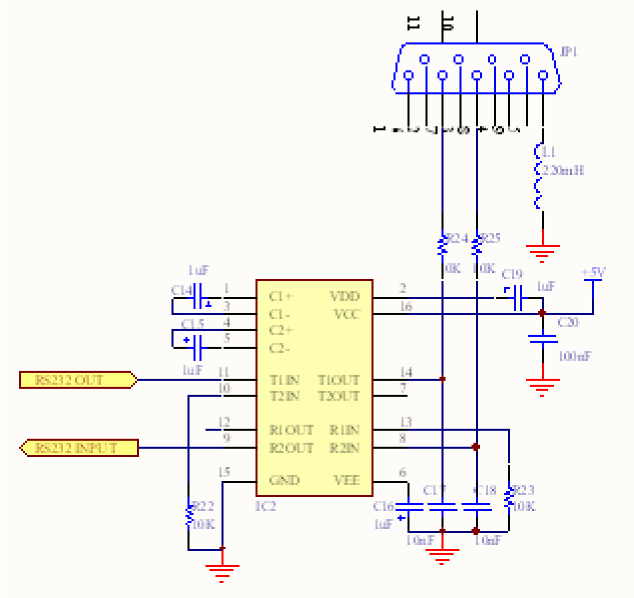


Figure 5.9: Serial communication shematic

The MAX232 is a dual driver/receiver that includes a capacitive voltage generator to supply TIA/EIA-232-F voltage levels from a single 5-V supply. Each receiver converts TIA/EIA-232-F inputs to 5-V TTL/CMOS levels. These receivers have a typical threshold of 1.3 V, a typical hysteresis of 0.5 V, and can accept ±30-V inputs. Each driver converts TTL/CMOS input levels into TIA/EIA-232-F levels. The driver, receiver, and voltage-generator functions are available as cells in the Texas Instruments LinASIC and Maxim ICs.

5.3.7 Temperature sensors and push buttons schematics

In this appication, there are two temperature sensors seen in Figure 5.10 for sensing temperature values of the inner and outer of the incubator. Sensors convert the temperature value to the electrical signal then this signal goes to the analog-digital convertor (ADC) of the MCU. MCU ADC module converts the electrical value to the 8-bit digital value so that this digital value are used for controlling the motor speed.

There are also 5 push-button (UP, DOWN, OK, CLR, MENU) in this application shown also in Figure 5.10 in order to control the graphical display or LCD as a graphical user interface. All inputs of the buttons are protected by decopling capacitors such as 100nF and have pull-up resistors 10K.

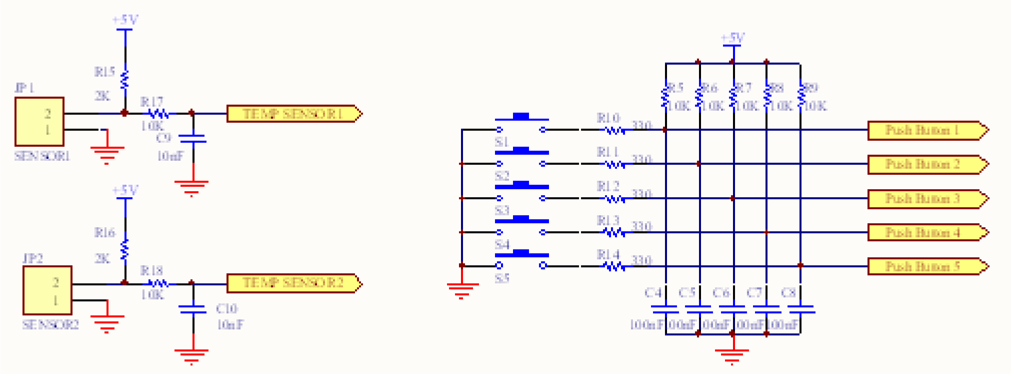


Figure 5.10: Sensors and buttons shematic

5.4 PCB designing of the TCI application

Generally known that there are four layers of double side of a PCB board. These are top layer seen Figure 5.11, bottom layer seen Figure 5.12, top overlay seen Figure 5.13 and bottom overlay seen Figure 5.14 for the TCI medical application. In this sub-chapter, it can be applied all of the EMC hardware techniques. These importants are listed below;

5.4.1 Suppressing the noise source

- Used the lowest frequency clock and the slowest rise time that satisfy TCI medical system specifications,
- Placed the clock circuit near the oscillator pins of the MCU,
- Kept clock signal loop areas as closo to zero as possible,
- Located I/O drivers near where they leave the board,

- Filtered all signals entering the TCI board,
- Filtered all signals leaving a noisy environment,
- Terminated all unused pins of the ICs by grounding the + input and connecting the - input to the output,
- Used 45-degree angle trace turns instead of 90-degree angle trace turns to decrease radiation.

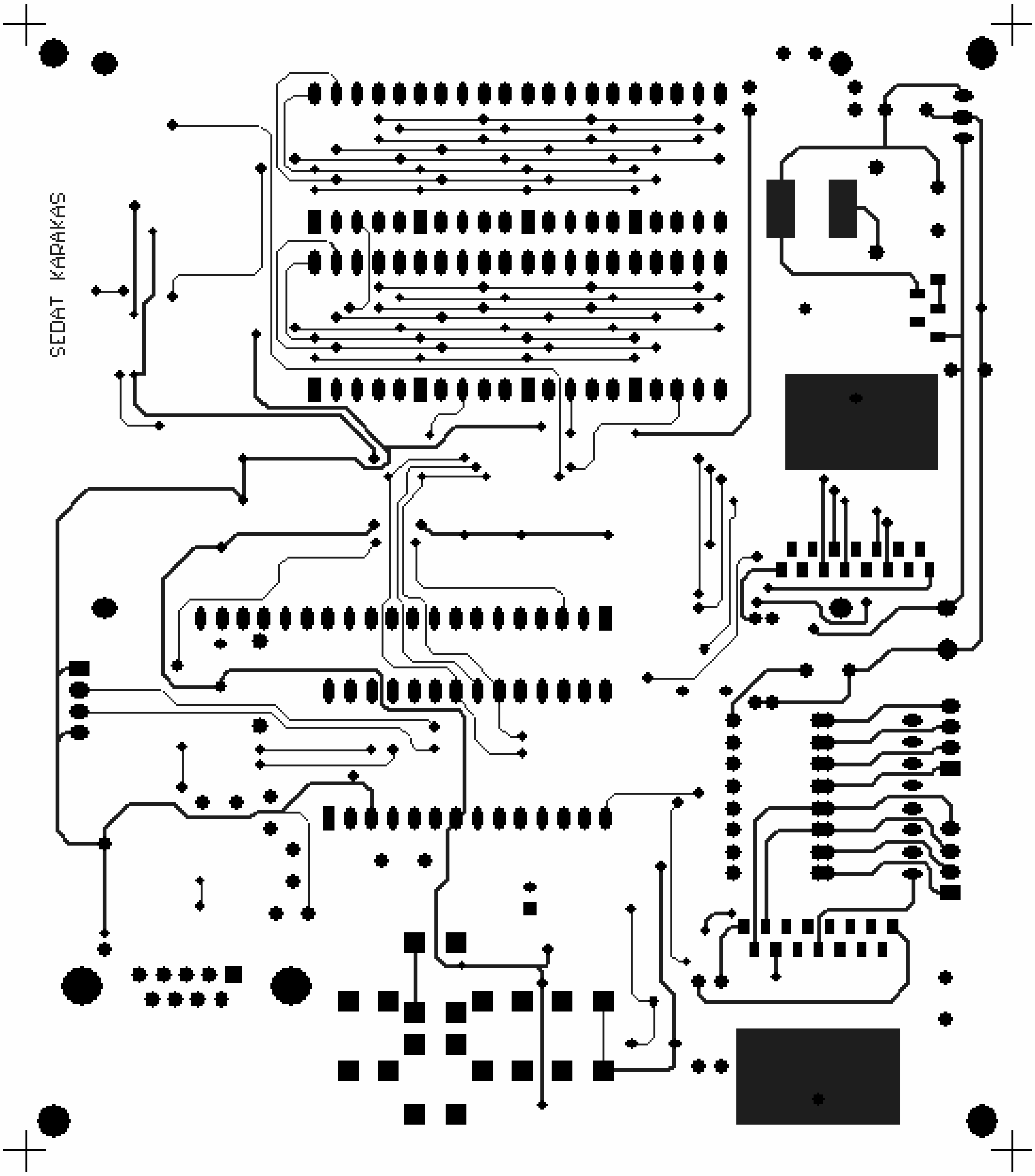


Figure 5.11: Top Layer of the TCI medical application

5.4.2 Reducing noise coupling

- Seperated circuits on a PCB according to their frequency and current switching levels,

- Placed chips for short clock runs,
- Confined high speed logic to specific functions,
- Placed I/O chips next to the board edge and close to the connector,
- For economically don't possible, not used a multi-layer board to minimize power and ground inductance,
- Used single-point power and ground layouts for double-sided boards,

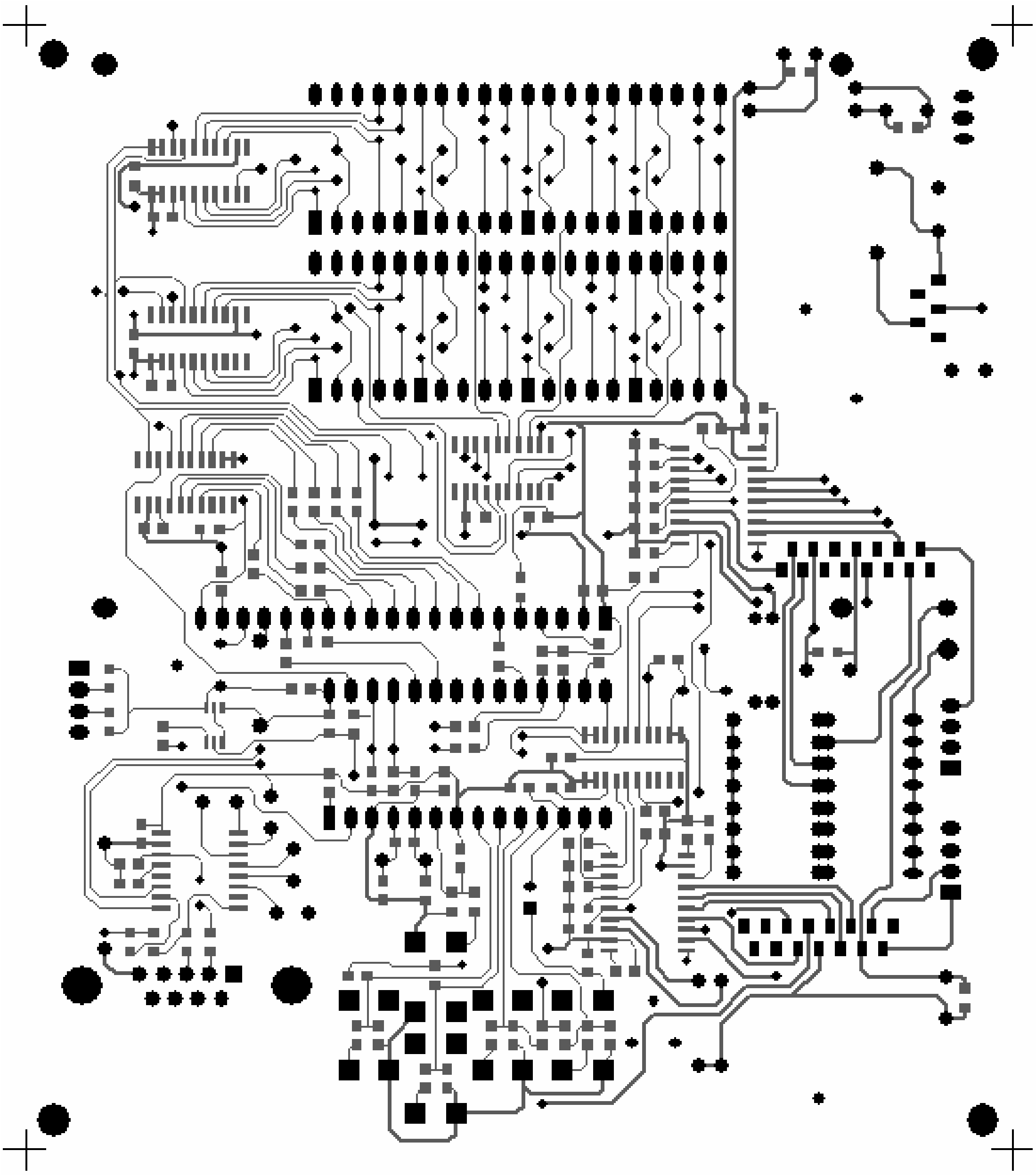


Figure 5.12: Bottom Layer of the TCI medical application

- Used wide traces for power and ground (for 24V 0.5mm, for 5V 0.4mm) whereas the other data traces is 0.3mm,

- Kept clock traces, buses, and chip enables seperate from I/O lines and connectors,
- Kept digital signal lines, especially the clock, as far away from analog input and voltage reference pins as possible,
- Not crossed digital and analog lines and routed the signals away from each other,
- Seperated noisy and quied leads,
- Routed clock signals perpendicular to I/O signals,

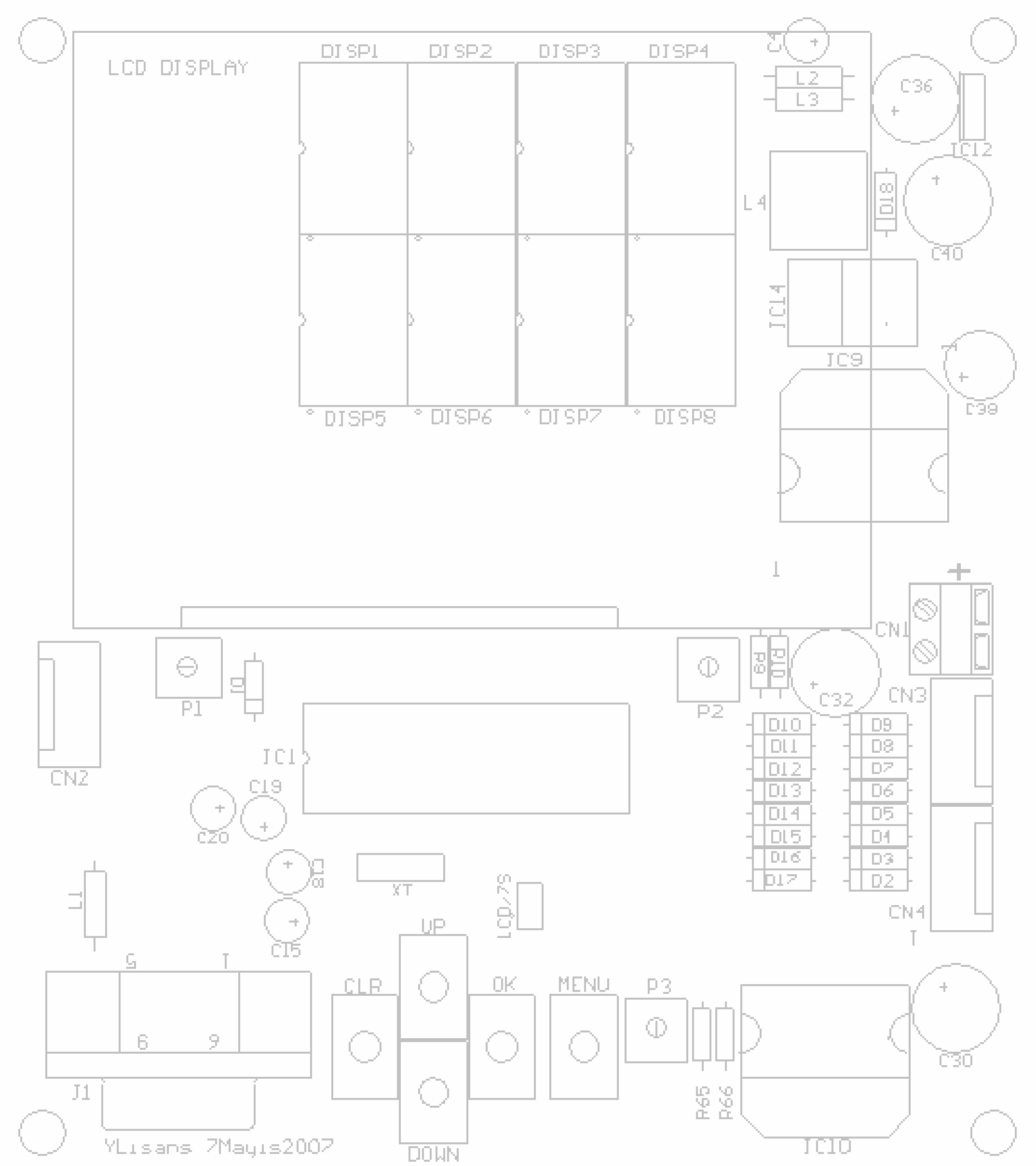


Figure 5.13: Top Overlay of theTCI medical application

- Kept clock circuits and leads away from I/O cables,
- Kept the length of sensitive leads as short as possible,

- Handled critical traces by fat traces and guardbading with a ground on each side of the trace,
- Not runned sensitive traces in paralel with high-current, fast switching signals,
- Minimized lead lengths on decoupling capacitors,
- Kept high-speed lines short and direct,
- Minimized trace length of clocks and other periodic signals,
- Avoided running traces under crystal and other critically noise-sensitive circuits,

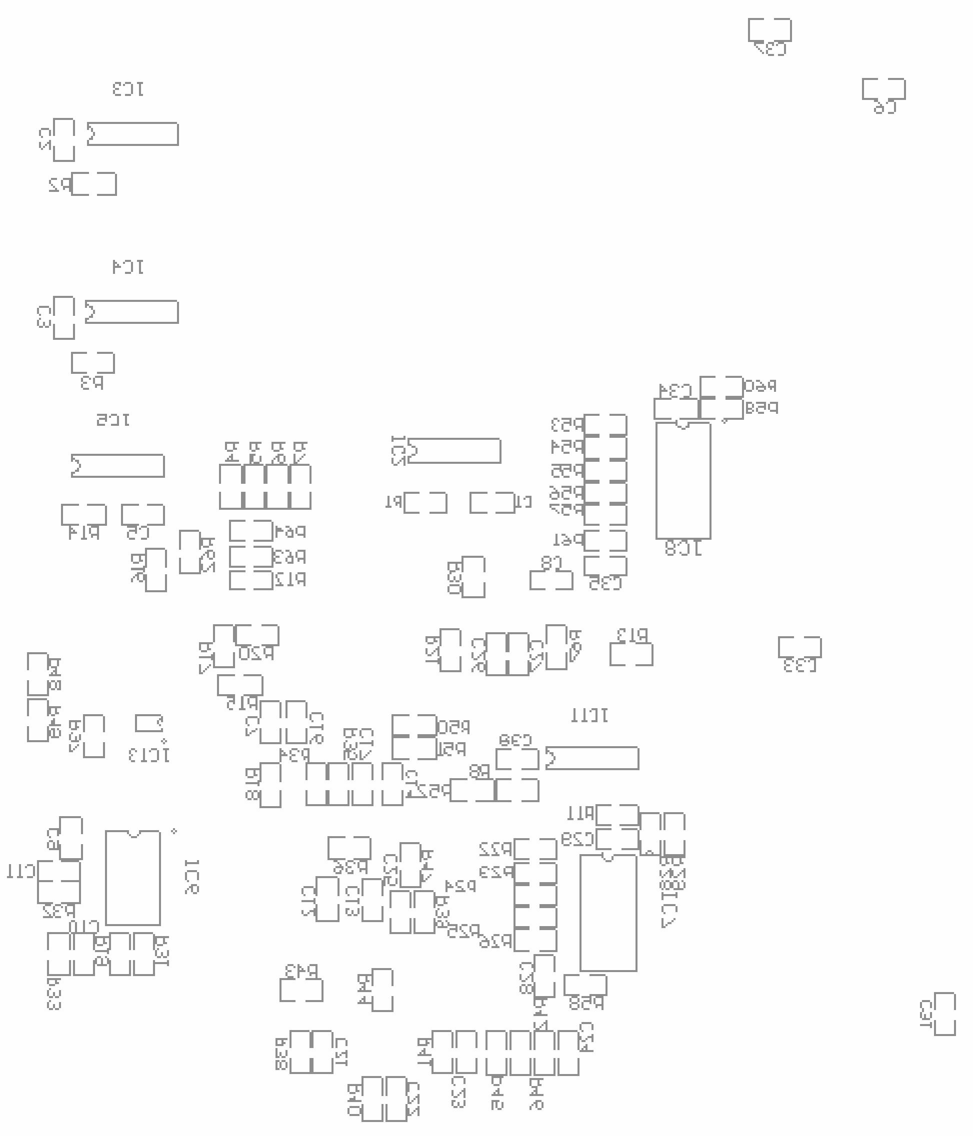


Figure 5.14: Bottom Overlay of theTCI medical application

- Filtered any leads entering enclosures containing sensitive circuits.
- Avoided ground loops in low level, low frequency circuits,

- Used all power and ground pins on an IC.

5.4.3 Reducing noise reception

- Avoided all signal loops wherever possible; if not possible, minimized the loop area,
- Used high-frequency, low-inductance ceramic disk or multilayer ceramic capacitors for IC decoupling such as SMD capacitors,
- Located decoupling caps next to the each IC in the application,
- Used a bulk tantalium electrolytic or metalized polycarbonate decoupling capacitor to recharge the individual IC decoupling caps.
- Bypassed all electrolytic caps with small high-frequency caps,
- Supplemented decoupling with ferrite beads in series,
- Seperated signal, noisy, and hardware power and grounds,
- Used frequency selectable filters when applicable,
- Connected all unused inputs of the ICs to power or ground or conFigure them as outputs,
- Bypassed all analog reference voltages,

5.5 Applying of all hardware EMC reducing techniques

5.5.1 System clock

The system clock is often the primary source of radiation. Avoided ground loops and long tracks (always take the most direct route) seen in Figure 5.15.

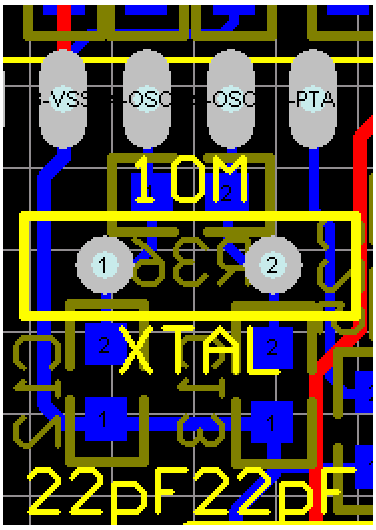


Figure 5.15: MCU clock PCB mounting

Wherever possible, clock tracks had adjacent ground-return tracks. Minimized the number of devices requiring the system clock. Ensured that clock circuitry and associated lines are located well away or shielded from PCB I/O tracks or circuitry. Never mix clock and bus or I/O drivers in the same package—used separate buffer drivers for clock and buses.

5.5.2 Decoupling capacitors

Ensured that decoupling capacitors are as close as possible to the device supply pins to reduce the loop area through the capacitor seen in Figure 5.16.

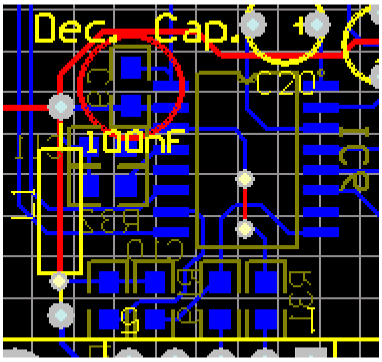


Figure 5.16: Decoupling Capacitors (100nF) mounting

On power supplying always parallel decouple large-value (dc ballast) capacitors (330 & 470 uF) with one or more smaller (100nF) high-frequency capacitors seen in Figure 5.17.

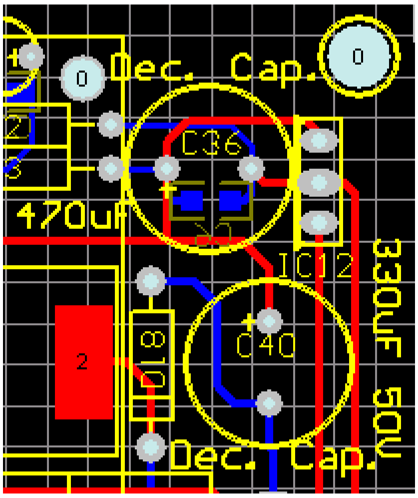


Figure 5.17: Large Decoupling Capacitors (330 & 470 uF) mounting

5.5.3 Ferrite beads

In addition to local device decoupling, decoupled the power supply where it enters the PCB seen in Figure 5.18. A ferrite bead (for instance, Z > 50 Ω at 100 MHz) will also help prevent switching transients from going off-board.

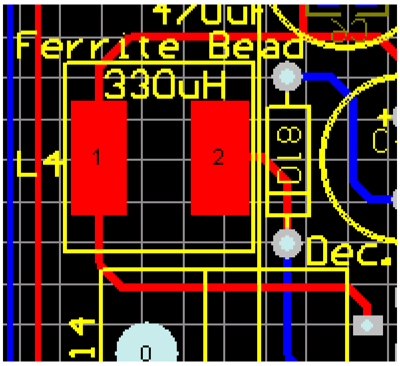


Figure 5.18: Ferrite bead mounting

5.5.4 Minimizing address/data lines

For PCBs without a ground plane, minimized address/data line loop areas by routing a minimum of one ground-return track adjacent to each of the eight lines and by keeping the lines as short as possible seen in Figure 5.19. For the address lines, routed the ground return next to Ao because this line is likely to be the most active. Note also that long address lines will ring, which is another potential source of RFI. These lines be individually terminated. Operating an MCU in single-chip mode will almost eliminate radiation from address/data lines (still exists internally, of course).

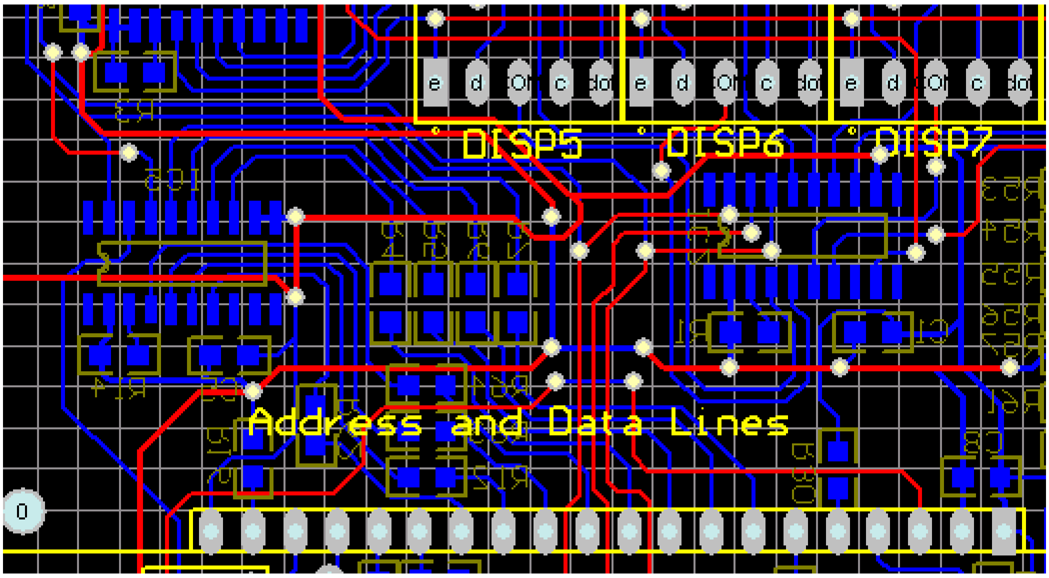


Figure 5.19: A view of address and data lines

5.5.5 Avoiding ground loops

If remembered that breaking a loop with a small gap may be fine at dc but gap capacitance may effectively close the loop at RF frequencies, creating a large loop antenna. Apart from the radiation problems, large ground loops can make a system more susceptible to malfunction when subjected to external EMI sources.

5.5.6 Ground and Supply track

Used a printed copy of the PCB artwork and a marker pen, trace the ground and supply tracks. Long, thin, or looped tracks can then be easily identified and subsequently modified seen in Figure 5.20.

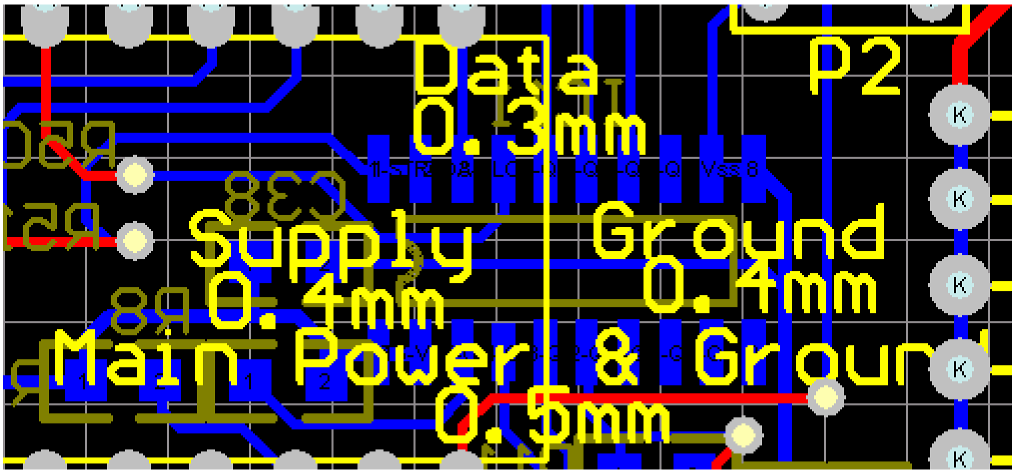


Figure 5.20: Ground and Supply tracks

5.5.7 Unused Inputs

Terminated all unused inputs seen in Figure 5.21 to prevent unintentional random switching and noise generation (in addition, unterminated CMOS inputs tend to self-bias into the linear region of operation, significantly increasing the dc current drawn).

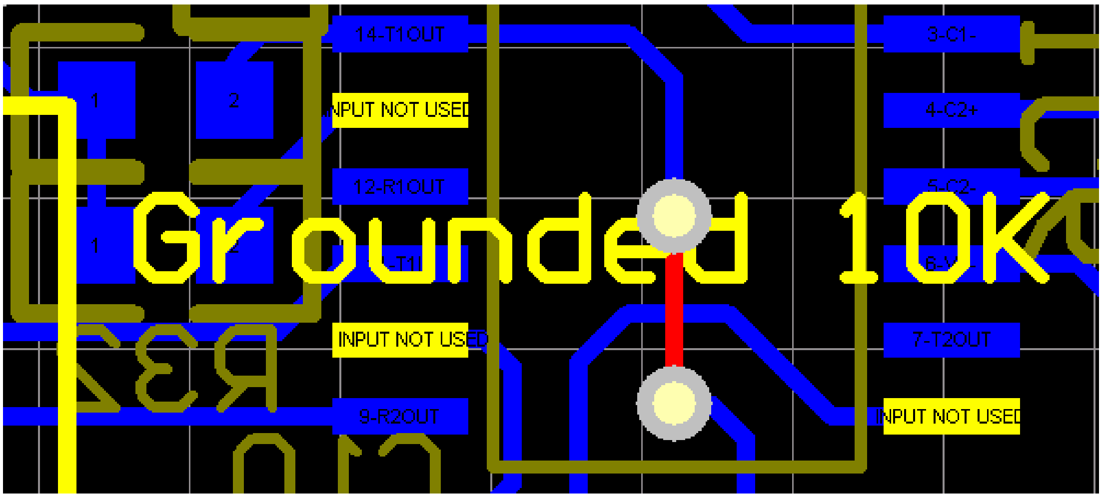


Figure 5.21: An example of grounded unused input pins

5.5.8 SMD components

The smaller footprint of surface-mount components be used advantageously to reduce loop areas as possible seen in Figure 5.22.

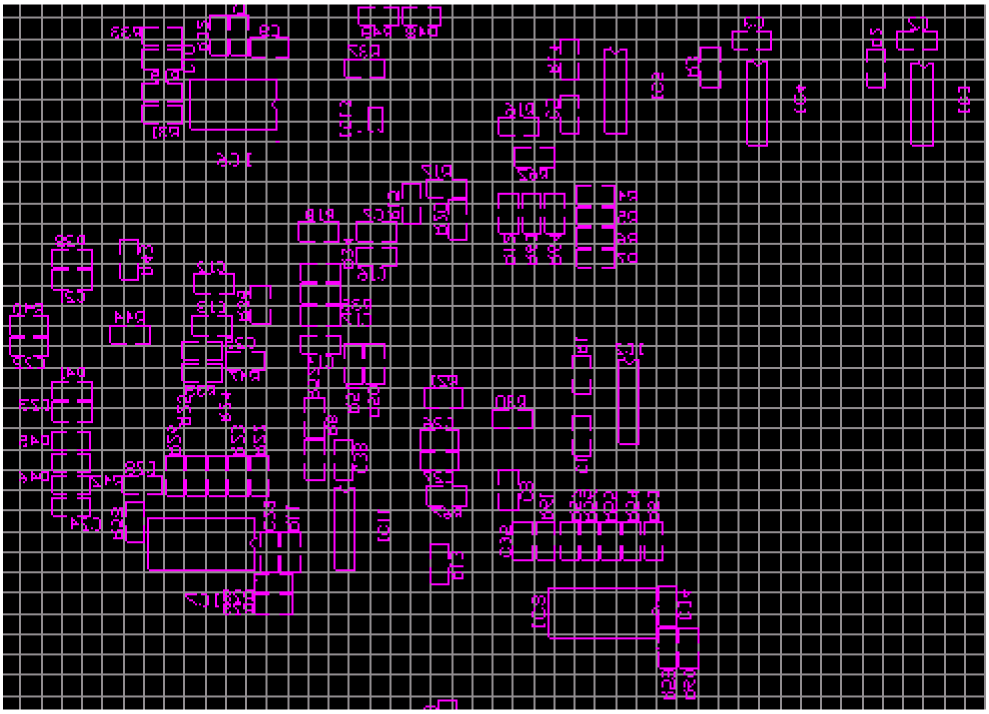


Figure 5.22: A view of SMD components

5.5.9 Ground plane and track widths

Ensured a good ground plane and choose the external ground connection to minimize the overall common-mode voltage drop. Increased both supply and return-supply track widths (as a general rule, cover as much as possible of the unused part of a PCB).

5.5.10 Grounding scheme

A grounding scheme that isolates digital and I/O (including any analog sections) reduces radiation from I/O cables. Shielding these cables is ineffective if the shield termination grounds are noisy. In digital systems, the shield should be connected to noise free grounds at both ends.

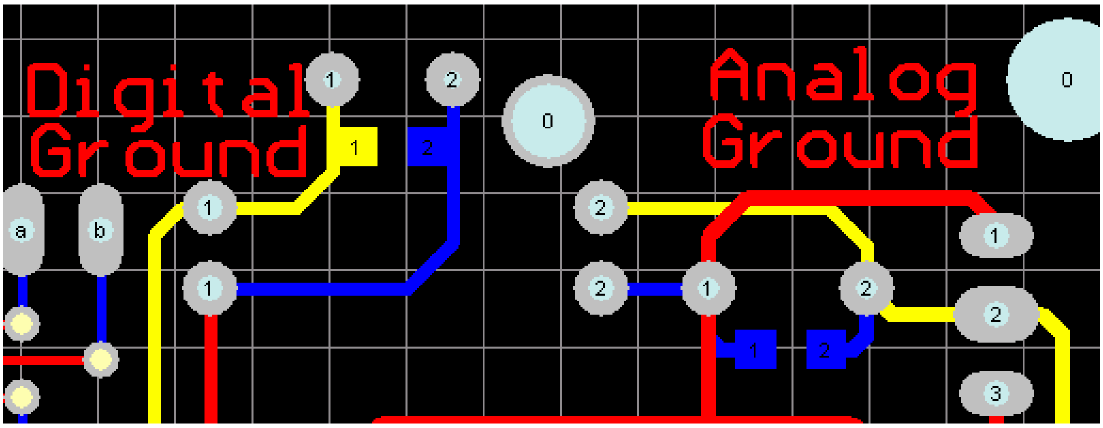


Figure 5.23: Analog and digital ground

If this configuration is not possible, then ground only the source end. For that reasons, ground scheme was separated as a digital ground and an analog ground seen in Figure 5.23.

5.5.11 PCB track angle

All PCB track angles were made a 45-degree track-direction to reduce RFI effects on our medical device, TCI seen in Figure 5.24.

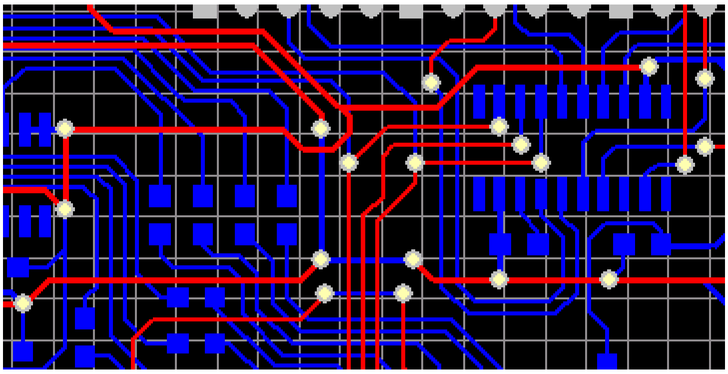


Figure 5.24: A view of track angle

5.5.12 Reset components

All reset components for MCU resetting, a capacitor (generally used 100nF) and pull-up resistor (generally used 10K) were mounted near the MCU seen in Figure 5.25 for reducing EMI effects especially relay contacting and arcs.

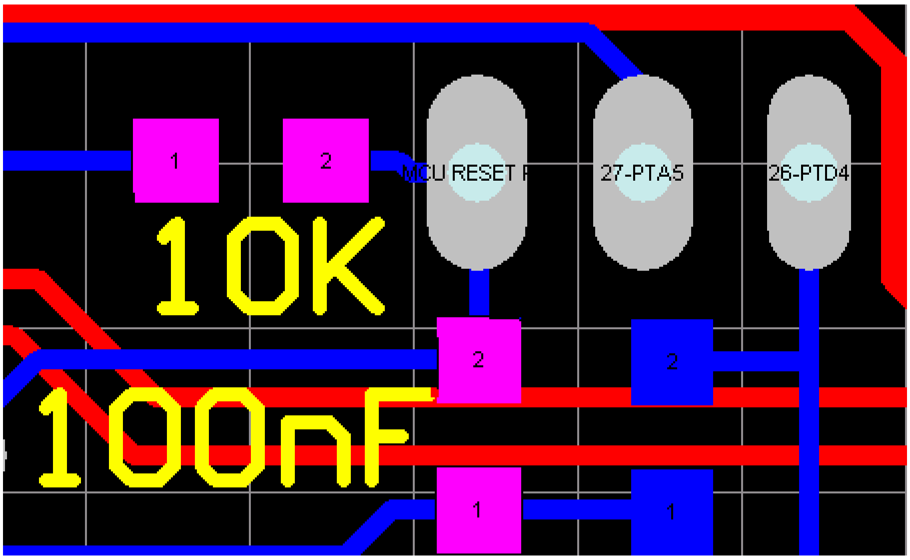


Figure 5.25: Reset components

5.5.13 Hardware Watchdog

In this application, TCI, not only software watchdog but also a supervisory circuit that means Watchdog and Manual Reset integration are used nearly MCU. The connection of the MCU are seen in Figure 5.26.

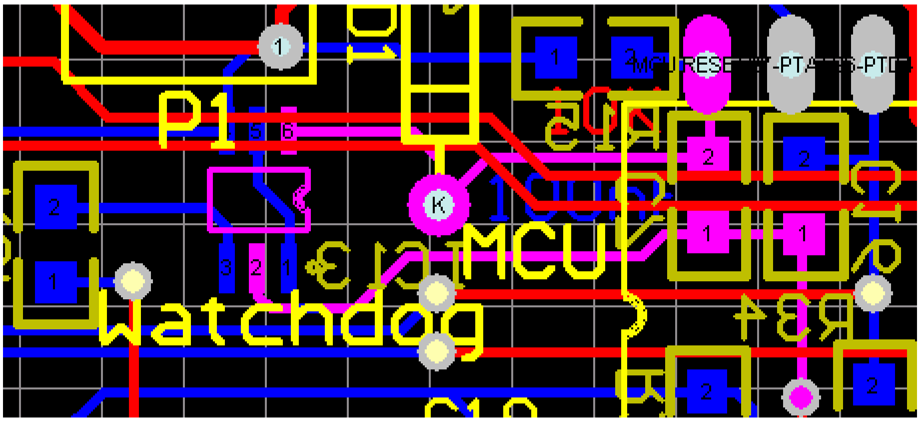


Figure 5.26: Watchdog and MCU connection

5.6 Applying of all software EMC reducing techniques

All of the hardened software techniques are explained in the other chapter so that in this sub-chapter TCI software can be written with regarding to the EMC software techniques.

5.6.1 Using software watchdog

In some microcontrollers such Motorola, the name of the watchdog can be different. In Motorola Microcontrollers, this is named as Computer Operating Properly (COP). COP module contains a free-running counter that generates a reset if allowed to overflow. The COP module helps software recover from runaway code. Prevent a COP reset by clearing the COP counter periodically. The COP module can be disabled through the COPD bit in the CONFIG1 register.

5.6.2 Using software watchdog with hardware watchdog

It is explained that the hardware watchdog IC is used in TCI so that the software is able to support this IC. In software, the subroutine related this IC is written on the main backbone of the software because of the fact that this is especially recommended whenever software problem has occured this IC has produced a master clear reset in a specific time range. Related software subroutine is below:

```
watchdog_out:
        lda     watchdog_count
        cmp      #2
```

```
        blo      exit_watch_out
        clr      watchdog_count
        lda      watchdog_reg
        cbeqa    #$11,set_watchdog
        mov      #$11,watchdog_reg
        bclr     0,pta
        bra      exit_watch_out
set_watchdog:
        mov      #$12,watchdog_reg
        bset     0,pta
exit_watch_out:
        rts
```

5.6.3 Input Filtering

All inputs which are five push button inputs for getting the user interface commands and one LCD/Seven Segment selection input in this application are filtered by means of below software subroutine;

```
check_inp_ports:
        lda      input_count
        cmp      #!13                          ; 12 msec * 10 = 120 msec
        bhs      start_check_inputs
        jmp      Exit_check_port
start_check_inputs:
        clr      input_count
        brclr    1,real_pta,clr_up_button     ; up keyboard input control
        brset    1,pta,up_check_true
        inc      in_up_count
        cmp      #!10
        blo      check_clr_button
        bclr     1,real_pta
clr_up_button:
        brclr    1,pta, up_check_true
        inc      in_up_count
        cmp      #!10
        blo      Exit_check_port
        bset     1,real_pta
up_check_true:
```

```
        clr     in_up_count
Exit_check_port:
        rts
```

5.6.4 Management of Unused Interrupt Vectors

All unused interrupt vectors are addressed to the specific address which are used to return address before the interrupt thanks to rts command.

```
**************************************************************
* DUMMY_ISR - Dummy Interrupt Service Routine.     *
*            Just does a return from interrupt.                  *
**************************************************************
dummy_isr:
      rti          ; return

**************************************************************
* Vectors                                                                    *
**************************************************************
   ORG  VectorStart
      dw  dummy_isr   ; ADC Conversion Complete Vector
      dw  dummy_isr   ; Keyboard Vector
      dw  dummy_isr   ; (No Vector Assigned $FFE2-$FFE3)
      dw  dummy_isr   ; (No Vector Assigned $FFE4-$FFE5)
      dw  dummy_isr   ; (No Vector Assigned $FFE6-$FFE7)
      dw  dummy_isr   ; (No Vector Assigned $FFE8-$FFE9)
      dw  dummy_isr   ; (No Vector Assigned $FFEA-$FFEB)
      dw  dummy_isr   ; (No Vector Assigned $FFEC-$FFED)
      dw  dummy_isr   ; (No Vector Assigned $FFEE-$FFEF)
      dw  dummy_isr   ; (No Vector Assigned $FFF0-$FFF1)
      dw  timer_int    ; TIM1 Overflow Vector
      dw  dummy_isr   ; TIM1 Channel 1 Vector
      dw  dummy_isr   ; TIM1 Channel 0 Vector
      dw  dummy_isr   ; (No Vector Assigned $FFF8-$FFF9)
      dw  dummy_isr   ; ~IRQ1
      dw  dummy_isr   ; SWI Vector
      dw  main_init    ; Reset Vector
```

5.6.5 Averaging the A/D Converter Result

All ADC inputs which are two ADC inputs for getting temperature values of the inner and the outer air in this application are taken the averaging of the A/D convertor results by means of below software subroutine. This method can be applied if not the convertion time is important in any application.

```
adc_read:
        lda      adc_read_cnt
        cmp       #!40                ; 40msec
        blo      exit_adc_read
        clr     adc_read_cnt

        inc      adc_counter
        lda      adc_counter
        cmp       #!16                ; 16 times reading per 40msec
        bhi      calc_adc_val

        mov       #2,ADSCR             ; Modulation ADC input (PORTB2)
        brclr    7,ADSCR,*            ; wait if coco=0
        lda      ADR
        sta      adc_read_sen1         ; copy the high byte to the data register
        lda      adc_read_11+1
        add       adc_read_sen1
        sta      adc_read_11+1
        lda      #0
        adc       adc_read_11
        sta      adc_read_11

        mov       #3,ADSCR              ; Modulation ADC input (PORTB3)
        brclr    7,ADSCR,*             ; wait if coco=0
        lda      ADR
        sta      adc_read_sen2          ; copy the high byte to the data register
        lda      adc_read_22+1
        add       adc_read_sen2
        sta      adc_read_22+1
        lda      #0
        adc       adc_read_22
        sta      adc_read_22
```

```
        bra      exit_adc_read
calc_adc_val:
        clr      adc_counter
        clrh
        ldx      #4
calc_loop:
        clc
        ror      adc_read_11
        ror      adc_read_11+1
        ror      adc_read_22
        ror      adc_read_22+1
        dbnzx    calc_loop

        lda      adc_read_11+1
        ldx      #!99                ; adc_read_11*99
        mul
        pshx
        pulh
        ldx      #!255               ; adc_read_11*100/255
        div
        sta      real_adc_sen1

        lda      adc_read_22+1
        ldx      #!99                ; adc_read_22*99
        mul
        pshx
        pulh
        ldx      #!255               ; adc_read_22*100/255
        div
        sta      real_adc_sen2

        clr      adc_read_11
        clr      adc_read_11+1
        clr      adc_read_22
        clr      adc_read_22+1
```

```
exit_adc_read:
        rts
```

5.6.6 Modular programming

This program technique is very important about EMC issue because of reducing EMC effects depends on modular program technique that is exampled in the below subroutine. It is shown in this program that all of the program is only here not more than so that controlling of this program is easier than the other program techniques.

```
main_loop:
        lda     #0
        sta     COPCTL          ; resets COP regs

        jsr     watchdog_out    ; COP period is (2^18 - 2^4) × 2OSCOUT cycles
        jsr     simul_prog
        jsr     adc_read
        jsr     check_inp_ports
        jsr     motor_exec
        jsr     disp_sel_module

        lda     sim_enter_reg
        cmp     #$FF
        bne     main_loop

        jsr     tci_menu
        jsr     tci_temp_cnt
        jsr     tci_motor_cont
        jsr     graphic_lcd
        jsr     serial_com
        bra     main_loop
```

5.6.7 Not used nested interrupts

It can be careful when using nested subroutines. The CPU may overwrite data in the RAM during a subroutine or during the interrupt stacking operation. Generally not allowed nested interrupt because of the fact that it is possible to collide with each interrupt to another one.

5.6.8 Cyclic Redundancy Check (CRC) control

When program starts, it can be firstly made a CRC check because it is possible to cause a damage in program software map. To find this damage it is generally used this program technique. It is a kind of mathematical equation which produce a code. This code is memorized in a non-volatile memory of the MCU.

5.6.9 Using of short interrupt routine

It is also important program technique to write a short interrupt routine because the time is very limited for a MCU which have the other interrupt sources such as ADC convertion interrupt, IRQ and the others. There is a subroutine below related interrupt routine of the TCI application.

```
timer_int:                              ; 500us interrupt routine
        pshh
        bclr    7,TSC                   ; clear TOF
        inc     adc_read_cnt            ; adc read time  10 msec
        inc     disp_count              ; display on time = 5 msec
        inc     menu_count              ; menu load time = 200 msec
        inc     input_count             ; input pins total read time 100 msec
        inc     motor1_exe_cnt
        inc     motor2_exe_cnt
        inc     sim_seg_count
        inc     watchdog_count

        inc     time_base_count
        lda     time_base_count
        cmp      #!200                  ; 100 msec time base
        blo     end_tim_int
        clr     time_base_count

        inc     sel_temp_count
        inc     flash_count
        inc     tci_count
        inc     simul_count

end_tim_int:
        pulh
        rti
```

5.6.10 Not change port status and output in interrupt

Because it is possible to occur a runaway condition so that interrupt routine may run each cycle therefor these ports have activated continuously which might be dangerous situation for mcu based application.

5.6.11 Register Reprogramming

Register reprogramming is a very important technique in a MCU based application. This must be made a specific time interval because of the fact that initial condition for an application is also vital to keep for example port status. In this application, all registers are reprogrammed per 24 hour time interval.

```
main_loop:
    lda      reset_24H_OK          ; when 24Hour is OK, SWI will occur
    cbeqa    #$13,main_loop

     lda     #0                    ; COP (2^18 - 2^4) × 2OSCOUT cycles
     sta     COPCTL                ; resets COP regs

     jsr     hardw_watchdog        ; hardware watchdog output control
     jsr     simul_prog
     jsr     adc_read
     jsr     check_inp_ports
     jsr     motor_exec
     jsr     disp_sel_module
```

5.7 Conclusion

In this chapter, some hardware and software techniques explained in before chapters are applied. As a result of this, our application, TCI, has improved towards to EMC bad effects by means of these techniques. This is only a design in order to show some hardened techniques which are used in any application especially in medical field. Because of the fact that hospital environment has a lot of bad EMI sources such as wireless devices, communication devices and the others. In conclusion, these techniques have been strongly recommended to electronic designers to reduce the EMI effects on their designs.

RESULTS AND DISCUSSION

A- General aspect

The aim of this study was to evaluate the possible interference EMI or RFI effects on biomedical equipment which are generally used to diagnosis patients by means of sensors. Medical Devices which are equipped in hospitals can be subject to interference from various external electromagnetic sources. Although modern (MCU-based) equipment are effectively shielded from electromagnetic interference (EMI), the magnitude of electromagnetic radiation in hospitals is higher and of a different nature than experienced in daily life.

An increasing number of MCU-based medical equipment are being used anywhere such as cardiac pacemakers in any induvidual or an ECG. However, the possible EMI with modern types of medical devices has been investigated until now. Methods explained in this thesis:

In order to evaluate the effect of EMI on modern types of medical equipment in the hospital environment or any person individually equipped, it was explained in this thesis that the best way to evaluate the EMC effects are hardened hardware and software, to a series of observations. TCI medical application was equipped with data logging capabilities which were used for detection of possible EMI effects.

After each test, the medical application were examined by means of the dedicated test equipment.. This enabled an exact analysis of TCI medical application function and of possible EMI. Results: No effect of EMI could be detected in the TCI by interrogating their internal counters after the test. In addition, no signs of EMI could be detected on the test recordings of the TCI medical equipment. Conclusion: We conclude that any medical device that have hardened hardware and software are unaffected by EMI in any environment in which EMI effects are within determined limits.

B- EMC/EMI TEST PLAN

THE COMPLIANCE MANAGEMENT GROUP

CLIENT INFORMATION			
Customer	THY TECHNIC	***Contact Person***	SEDAT KARAKAŞ
Telephone #	+90 212 463 63 63 – 9516	***Fax #***	
Email address	***skarakas@thy.com***		

PRODUCT INFORMATION	
Product Name	Temperature Control Incubator (TCI)
Model Number	TCI4031TA130103
Serial Number	2007-0705-0001
Dimensions	20,15,1
Weight	250gr
Test Purpose (such as qualify new or modified product)	To get some results which supply thesis subject

TEST SERVICES REQUESTED		
Top Level Standard	***Description***	***Check (if yes)***
Emissions		
Radiated Pre-Scan	Engineering evaluation.	
FCC Part 15	Radio Frequency Devices	
FCC Part 18	Industrial, Scientific & Medical Equipment	**X**
ICES-001	Industrial, Scientific & Medical Equipment	**X**
ICES-003	Digital Apparatus	
EN55011	Industrial, Scientific & Medical Equipment	**X**
EN55014	Household Appliances	
EN55022	Information Technology Equipment	
EN61000-3-2	Harmonics	
EN61000-3-3	Flicker	
Other		
Immunity		
EN55014	Household Appliances	
EN55024	Information Technology Equipment	
EN60601-1-2	Medical Equipment	**X**
EN61000-6-1	Residential, Commer & Light Ind. Environment	
EN61000-6-2	Industrial Environment	
EN61326-1	Laboratory/Measurement Equipment	
Other		

TEST SETUP INFORMATION

Voltage: 24V **Current:** 2A **Frequency:** 50Hz [x] Single-Phase [ ] 3-Phase

Please note any special conditions that would affect product configuration and testing.

MAGNETIC DEVICES

Are there any magnetic devices in the EUT that may be susceptible to magnetic fields (i.e., magnetic switches or Hall effect sensors)?

PRODUCT DESCRIPTION

(Provide a detailed description of the product under test. What is its function? Describe in adequate detail that an administrator at a government agency can understand)

MCU-Based Temperature Controlled Medical Equipment with two different display options which are
7-segment and graphic LCD.

TEST JUSTIFICATION

(If the DUT represents a product family, please explain why this configuration represents the operating mode that should produce the highest emissions while remaining consistent with normal operating conditions.)

Because of the fact that this device can be used in any environment such as hospitals be exposed to some
harsh equipment that emits EMI effects.

PRODUCT [internal] CONFIGURATION INFORMATION				
***Type of Device** (such as disk drive, I/O, etc.)*	***Rev***	***Part Number***	***Serial Number***	***Manufacturer & Capacity of Device***
Medical Equipment	R0	TCI4031TA130103	2007-0705-0001	

OSCILLATORS & Other Internally Generated Frequencies (such as CPUs, etc.)	
Frequency	***Description***
32Mhz	MCU has an external 32Mhz crystal oscillator

NOTE: The highest frequency generated determines the test level.

EXTERNAL CABLING INFORMATION					
Cable From	***Cable To***	***Cable Length***	***Part Number***	***# of cable if multiples***	***Description***
Sensor 1	Board	20cm	FN21	2	Sensing Cable
Sensor 2	Board	20cm	FN21	2	Sensing Cable

UNPOPULATED PORTS	
Port/Device	***Description/Reason***

SUPPORT EQUIPMENT LIST			
Type of Device *(workstation, keyboard, etc)*	***Part Number***	***Serial Number***	***Manufacturer***
AC 220V to DC 24V Regulator	ANC220V24V	4536-9870	Astronics

EMISSIONS EXERCISE SOFTWARE DESCRIPTION

(Describe what software is running on the product under test and how it will exercise the system during emissions testing. Include the program cycle time once, in seconds, for all devices to be exercised.)

Only main software will be running. RS232 communnication port program will be running second phase
Program cycle is 125 nsec.

IMMUNITY EXERCISE SOFTWARE DESCRIPTION

(If different from emissions exercise software. Include the program cycle time once, in seconds, for all devices to be exercised.)

Program cycle is only 125 nsec.

IMMUNITY TESTING PERFORMANCE CRITERIA

(Describe the proper mode of operation of the equipment under test. Explain what the test operator should monitor during the testing to determine if the product is operating within specified parameters)

When the equipment run in the second phase in that case the software communicates with a computer to
supply and recieve some data that could be importants in order to work correctly.

FUNCTIONAL WIRING DIAGRAM OF DEVICE UNDER TEST

(to be provided prior to the day of test.)

The wiring of the TCI medical device will be given prior to the day of test.

RESOURCES

[1] **STMicroelectronics**, 2000. EMC Guidelines for Microcontroller-Based Applications, *by Microcontroller Division Applications, AN898,* United State of America.

[2] **STMicroelectronics**, 2000. EMC General Information, *by Microcontroller Division Applications, AN901,* United State of America.

[3] **ATMEL Corporation**, 2006. EMC Design Considerations, *by Microcontroller Division Applications, 8-Bit AVR Microcontrollers Application Note AN1619,* San Jose, United State of America.

[4] **FCC**, 1984. Understanding the FCC Regulations Concerning Computing Devices, *OST Bulletin, vol.62,* United State of America.

[5] **Mike Catherwood**, 2004. Designing for Electromagnetic Compability (EMC) with HCMOS Microcontrollers, *Freescale Inc. Application Note, AN1050,* Austin, Texas.

[6] **Joe Cocovich**, 2001. EMI/RFI Board Design, *National Semiconductor Application Note, AN643,* April 2001, United State of America.

[7] **STMicroelectronics**, 2001. Software Techniques for Improving Microcontroller EMC Performance, *by Microcontroller Division Applications, AN1015,* United State of America.

[8] **Queen's University,** 2007. *Queen's University EMI/EMC Laboratory Equipment*, Kingston, Ontario, Canada..

[9] **Freescale Semiconductor Corp.**, 2005. M68HC08 Microcontrollers, *Datasheet,* Rev.1.1 MC68HC908JL3/H August 2005, Colorado, United State of America.

[10] **National Semiconductor Corp.**, 2004. LM1575/LM2575/LM2575HV simple switcher ® 1A Step-Down Voltage Regulator, *Datasheet,* August 2004, United State of America.

APPENDIX

A – Gerber files

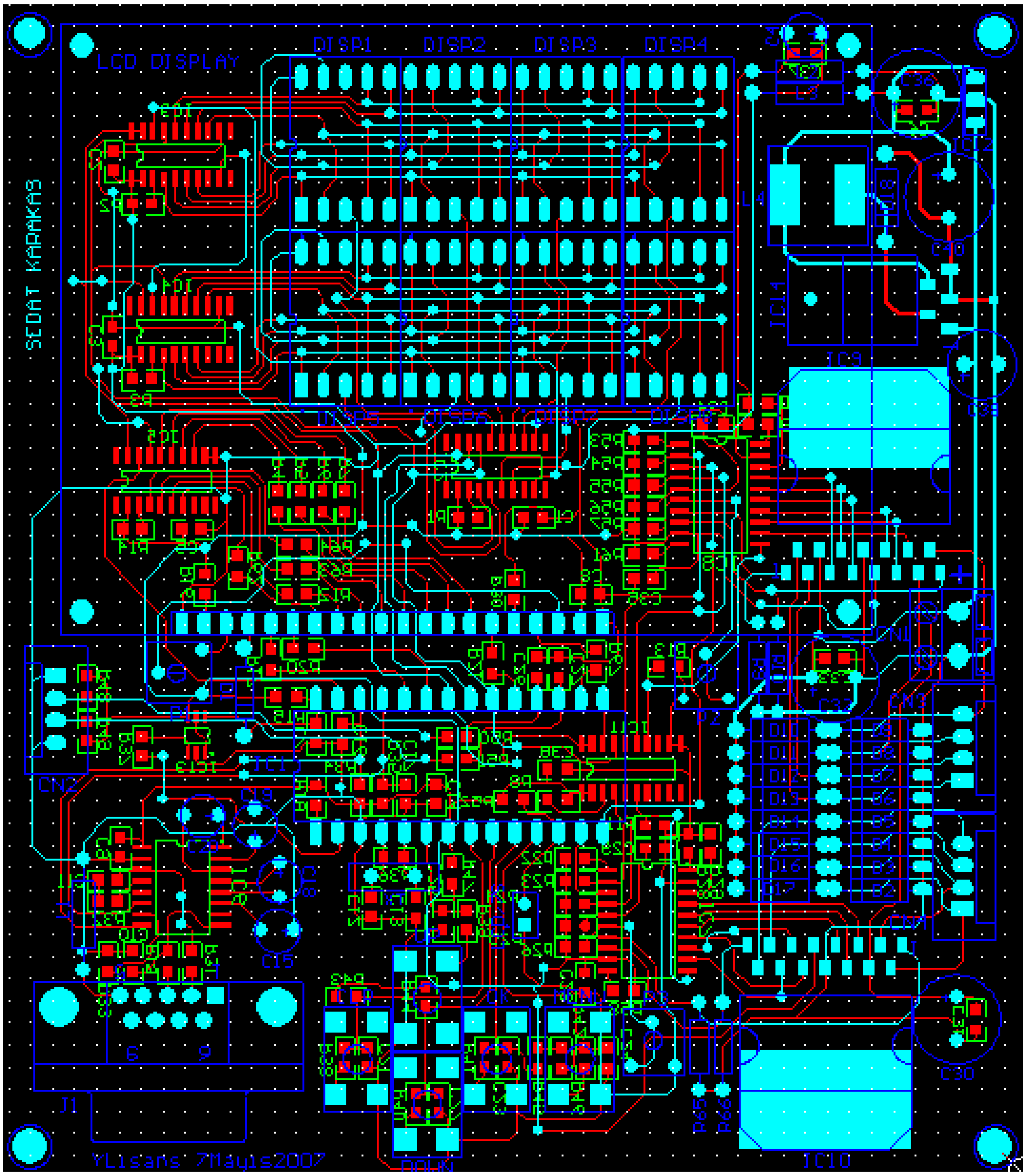


Figure A.1: All layer of theTCI medical application gerber file

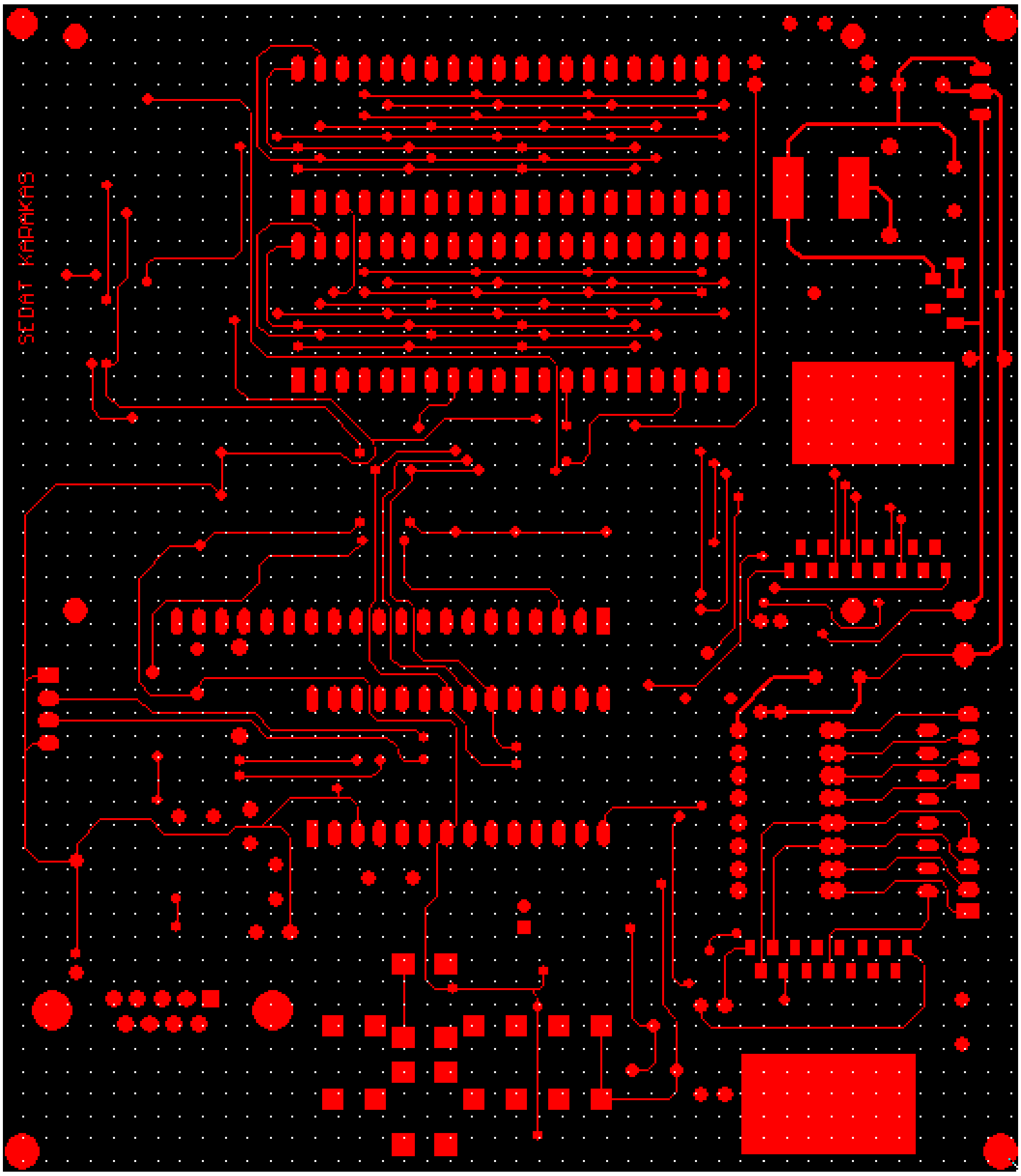


Figure A.2: Top layer of theTCI medical application gerber file

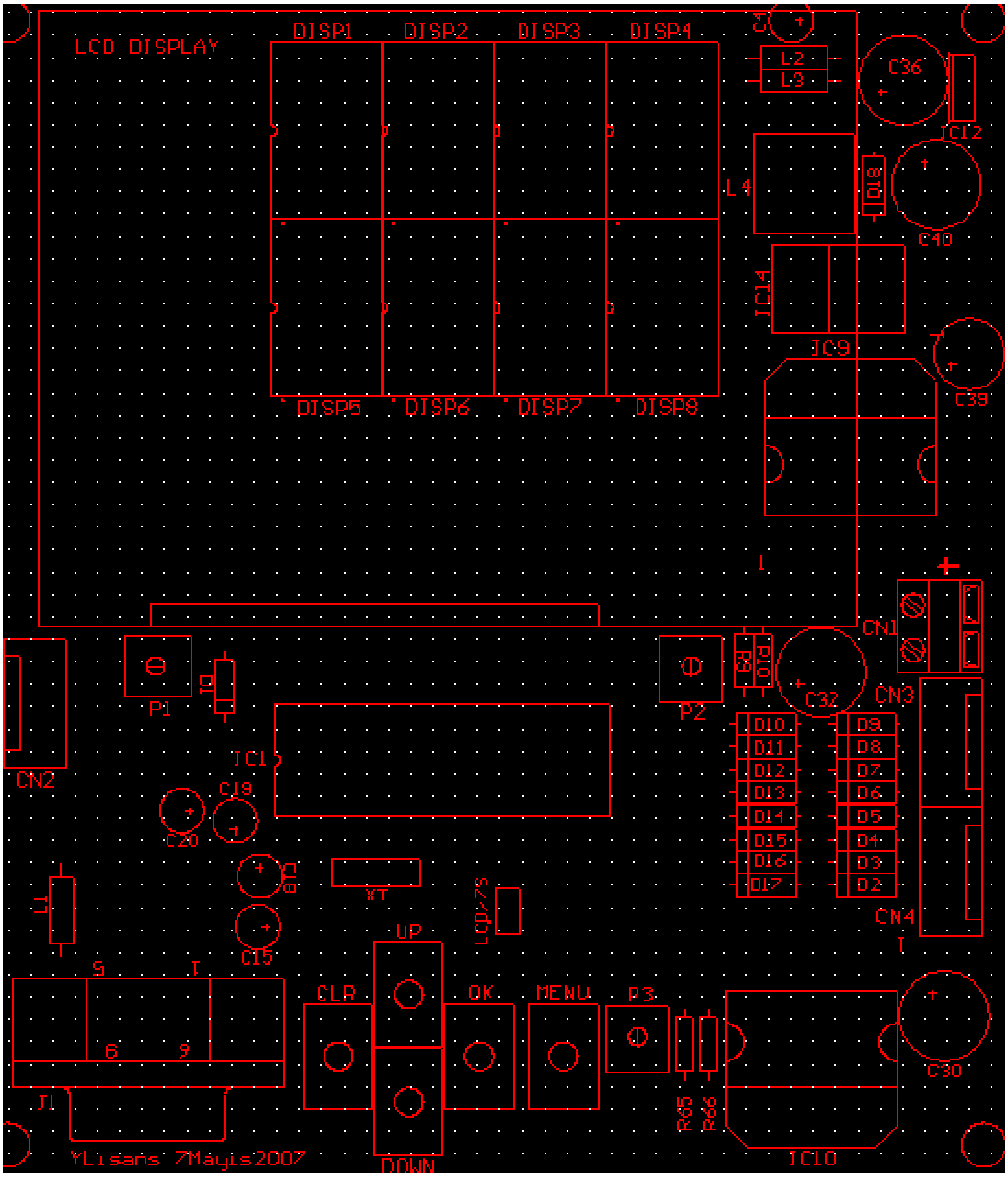


Figure A.3: Top overlayer of theTCI medical application gerber file

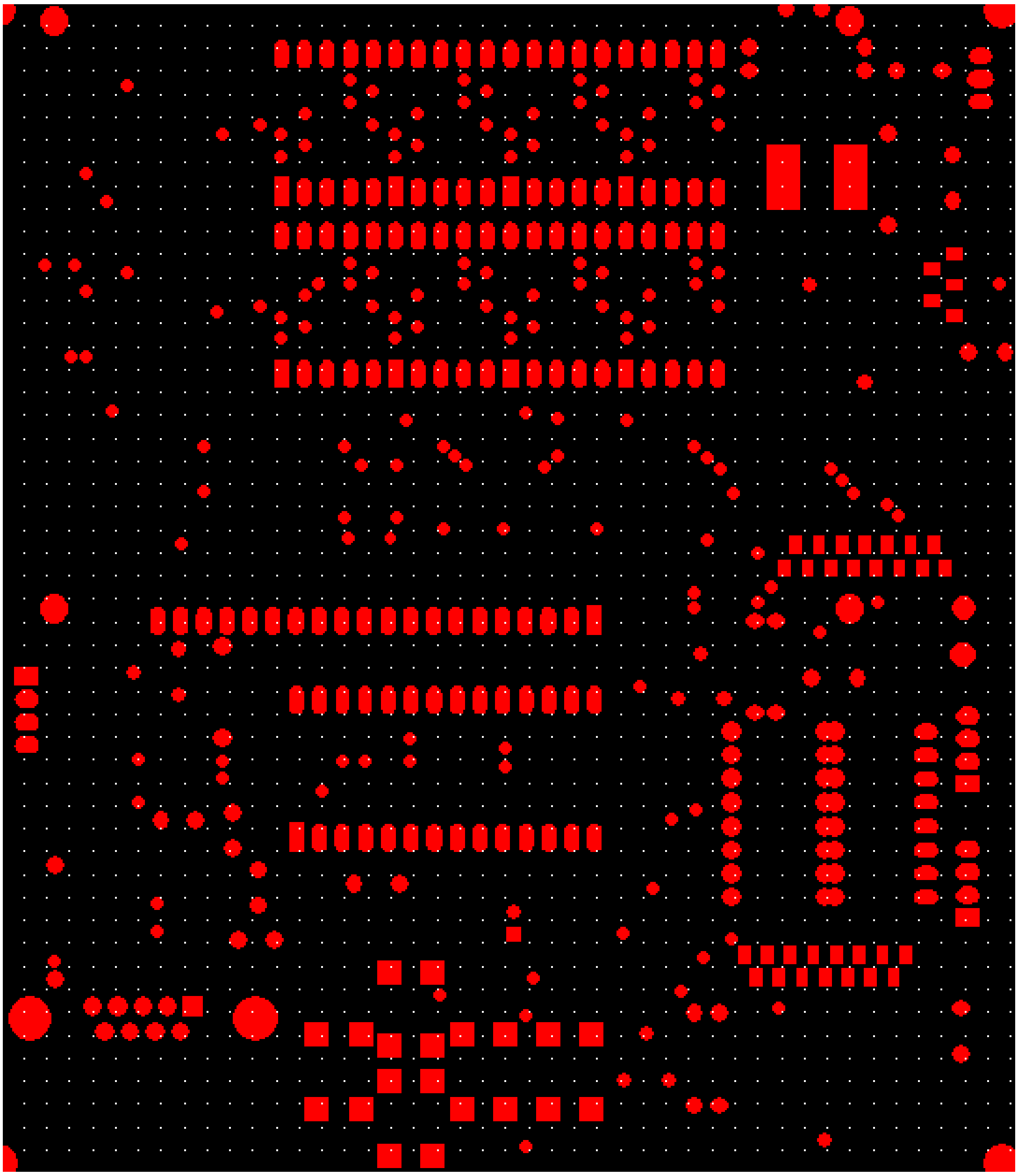


Figure A.4: Top solder of theTCI medical application gerber file

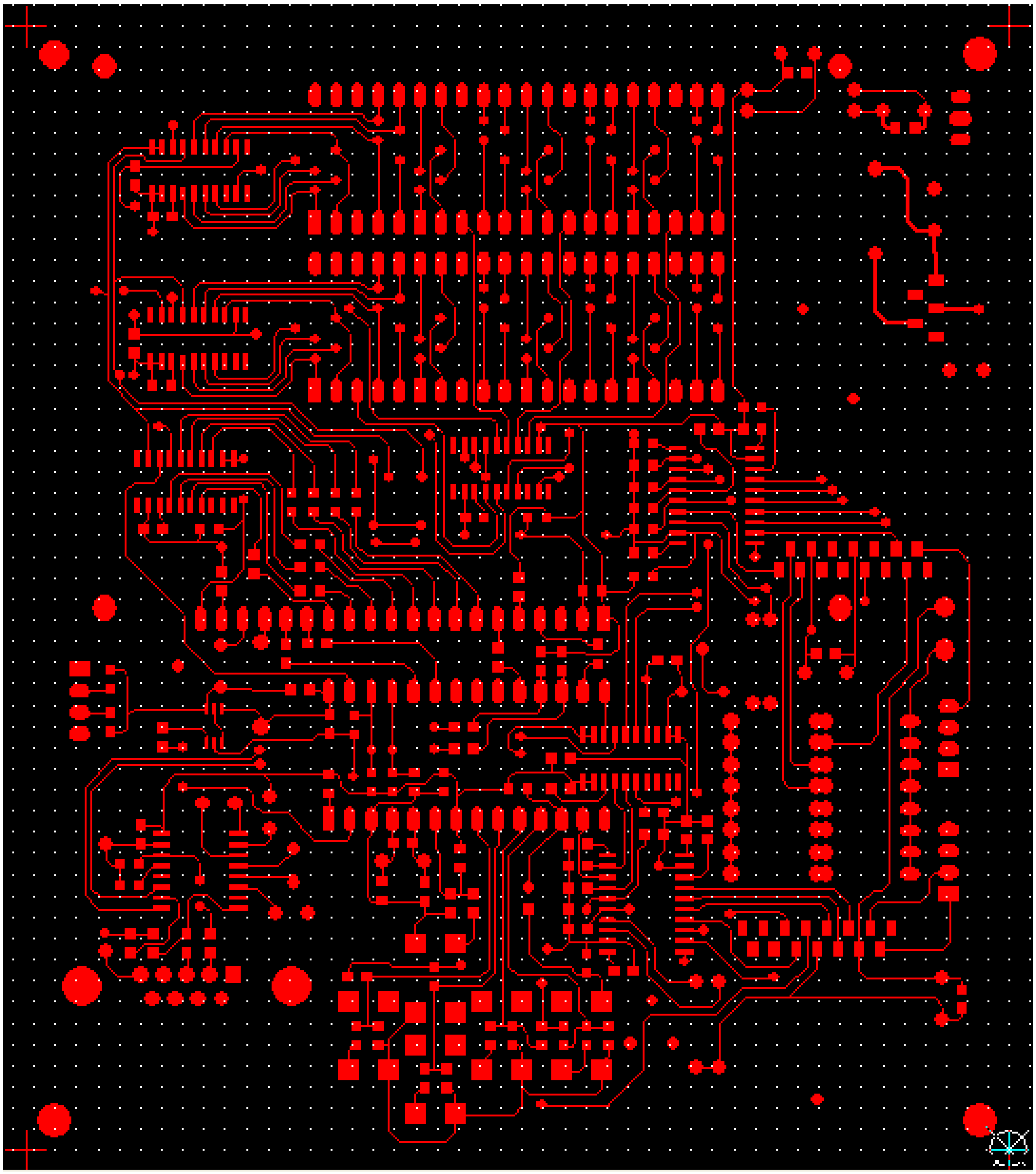


Figure A.5: Bottom layer of theTCI medical application gerber file

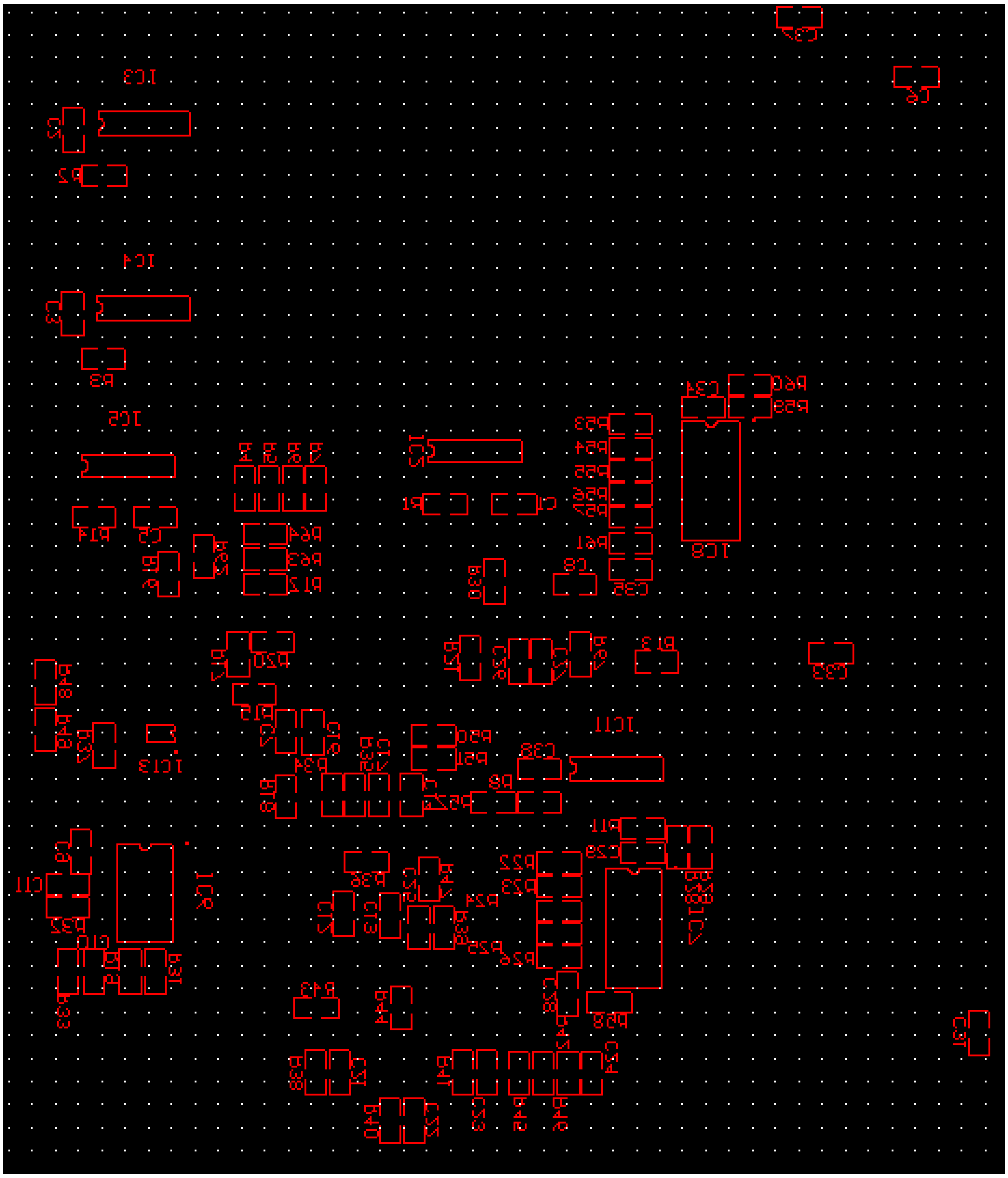


Figure A.6: Bottom overlayer of theTCI medical application gerber file

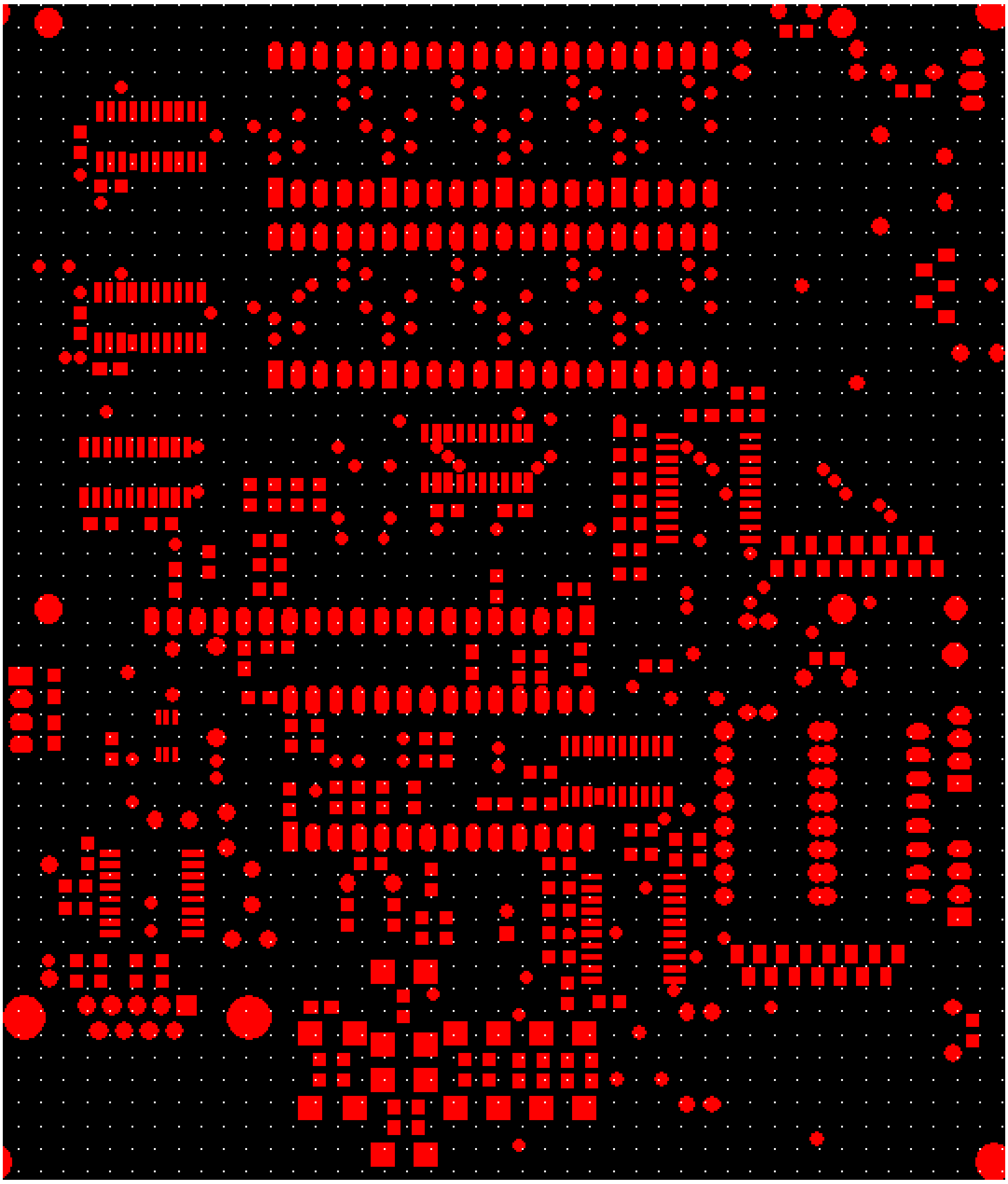


Figure A.7: Bottom solder of theTCI medical application gerber file

B – Program Software

The software of the TCI application is included in the Thesis CD-ROM because of the pages of the software is bigger than five pages.

C – TCI Layout and Schematic Output

The application of the TCI has layout outputs which are also included in the Thesis CD-ROM.

CURRICULUM VITAE

Educational Background

- MSc., İstanbul Technical University, Department of Electronic and Telecommunication Eng., Biomedical Eng. Prog. (Current),
- BSc, İstanbul Technical University, Department of Electronic and Teleccommunication Engineering (1996-2001),
- HS, Adana Karşıyaka Technical High School, Electronic Programme (1990-1994).

Work Experience

- MEGA Electronic Company / Topkapı, İstanbul, Turkey / (2000-2002),
- ROTA Electronic Company / Dudullu, İstanbul, Turkey / (2002 -2004),
- THY Technic / Yeşilköy, İstanbul, Turkey / (2004 -).

Traning

- Motorola Digital Signal Processor (DSP) using and application course, 2002
- Motorola EMC designing rules in Microcontroller Based Systems, 2003
- 3M Company EMC Preventive Techniques Course, 2005
- Aircraft Maintenance Human Factors, 2005
- Boeing Safety Management in Civil Aviation Seminar, 2005
- Airbus Electrical Wiring Interconnections Systems, 2005
- Panasonic System 3000i Line Maintenance Course, 2005
- JAR-OPS 1 Subpart M and SHY-M Regulations Seminar, 2005
- ESD Awareness Traning Course, 2006
- LVO Authorized Recurrent Course, 2006
- Boeing 737-800 Avionic Systems Course, 2006

Foreign Languages

- English

Computer Skills

- Programming languages (Assembly, C, Matlab, Visual Basic)
- Engineering and design programs (Protel, Orcad, Eagle)
- Operating systems (MS-DOS, Windows, Ms Office)

Prepared Designs

- Microcontroller Based Electronic Control Card, Demirdöküm Aden Model
- Microcontroller Based Electronic Control Card, Demirdöküm DD2 Model
- Solar Control Panel, Final Project in Motorola Design Contest
- Solid Fuel Control Card for Demidöküm Company

Hobbies & Activities

- Searching the web for educational purposes, reading articles about work life, listenning to Classical Music

References

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