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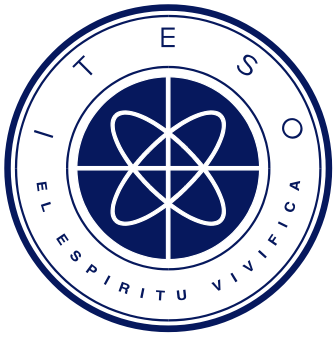

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Trabajo final que para obtener el diploma de

ESPECIALISTA EN SISTEMAS EMBEBIDOS

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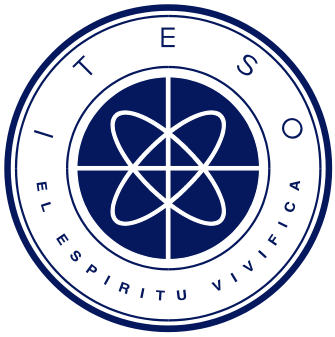

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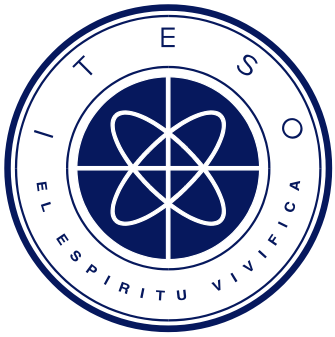

$CaCO_3$ SYNTHESIS FROM RESIDUAL EXHAUST CO_2

EMBEDDED CONTROL SYSTEM

Final report to earn the diploma of

EMBEDDED SYSTEM SPECIALIST

Presented by: Manuel Téllez Girón Enríquez
CONACYT Scholarship No. 591594

Advisor: Raúl Campos Rodríguez
Advisor: Adrián Navarro Diaz

Tlaquepaque, Jalisco. November 16th, 2016.

Thanks to

Author sincerely wants to thank to:

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- My beloved wife and kids, for supporting and encouraging me whenever I have needed time support and comprehension to let me complete this challenging endeavor.

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DEDICATION

Author wants to grant a sincere dedication of this work to my Family: Beba, Dan, Ana Laura and Alex for the love they always manifested to support me with this endeavor, even when it meant my to lessen my time shared to them, less vacation periods, and shorter weekends. God bless you all and gives all his Love forever to you.

RESUMEN

En este documento es el resultado de una conceptualización de una solución tecnológica cuyo objetivo es el de reducir y sintetizar emisiones de CO2 provenientes de vehículos automotores de combustible fósil. El concepto presentado en este documento es el de generar un subproducto desechable y reciclable sin riesgo ambiental o de salud (tal como el CaCO3), cuyo origen sean las emisiones contaminantes de CO2 de un vehículo automotor.

Se presenta inicialmente en la Introducción algunas soluciones empleadas actualmente para reducir emisiones de CO2 en ambientes industriales, tales como el burbujeo del gas en agua marina para forzar a una reacción con sales minerales del líquido; se presenta de igual manera una segunda solución que consiste en hacer pasar el gas a través de redes de arrecifes de coral o erizos de mar con objeto de forzar la combinación en ambientes calcáreos; y finalmente se presenta el concepto de convertidor catalítico empleando un dispositivo colocado en el sistema de emisión de vehículos por donde se hace circular los gases residuales con objeto de reducir las emisiones en lo posible.

Cabe comentar que los dos primeros métodos descritos, si bien se emplean actualmente en algunas industrias que tienen cercanía geográfica con mares, requieren una alta inversión e infraestructura para hacerlos funcionalmente viables, y en el caso del convertidor catalítico, como se expondrá posteriormente, ha sido diseñado como sistema pasivo de reacción química que ha resultado efectivo para reducir de manera importante emisiones de NOx y CO, pero queda fuera generalmente la reducción de emisiones de CO2, que lamentablemente es el gas que es responsable del efecto invernadero, reducción de capa de ozono y reduce la pureza del aire atmosférico dificultando que se desarrollen las condiciones normales de vida en el planeta tierra.

En los trabajos previos se le da especial enfoque al análisis del convertidor catalítico y se analizan algunas ventajas y desventajas de mantenibilidad, costo y disposición final; asimismo se mencionan algunos otros sistemas auxiliares de reducción de contaminantes pero de manera proactiva, es decir, antes de que se origine la combustión en el motor del vehículo, tales como: Recirculación de vapores de combustible (EGR), control de emisiones por optimización en la relación mezcla-tiempo de chispa- control del ángulo de encendido, todo esto a cargo de la computadora de control de combustión (ECU).

En el “estado del arte” se hace una presentación de 3 trabajos previos: El primero de ellos referente a tecnologías de control de emisiones previamente mencionadas y adicionalmente la propuesta de uso de combustibles alternativos de muy baja producción de contaminantes, y donde los subproductos principales son H2O y algo de CO2. En el segundo trabajo se propone la reducción de dimensiones de motores, considerando el sacrificio de potencia y torque pero simultáneamente empleando un diseño optimizado del motor con objeto de no sobre-reducir el rendimiento del mismo. El tercer sistema propone, finalmente, la síntesis de CO2 en metanol mediante métodos electroquímicos, sin embargo como el mismo texto propone, el sistema es de muy alto costo y de difícil implementación como dispositivo en un vehículo automotor.

El objetivo y la hipótesis de este documento versan sobre una solución de costo moderado, de sencillo mantenimiento y de demanda de pocos recursos del vehículo para sintetizar $CaCO_3$ a partir de una reacción química del CO_2, H_2O condensada del aire ambiental y un elemento reactivo base de CaO_2. El subproducto $CaCO_3$ es reciclable o desechable.

En la sección de Diseño de arquitectura, se ha propuesto el empleo de un sistema de Desarrollo de Microchip Inc., basado en el MCU PIC18F46K22 (DM164134), de 8 bits dado que contiene la arquitectura deseable para un sistema de la naturaleza de la solución prevista.

En el subsistema de Hardware se definen los componentes principales que corresponden a una plataforma embebida con un número definido de I/Os digitales y la posibilidad de interconectar a un sensor de temperatura y humedad relativa de 4 hilos, asimismo una etapa de salida de potencia para poder accionar un arreglo de celdas Peltier para producir condensación de humedad por algoritmo de error con el punto de rocío, una cámara de reacción donde se encontrará la muestra del material reactivo (CaO_2) y se combinará con H_2O y CO_2.

El subsistema de software propone el diseño basado en capas (modelo OSI), donde en la capa de HAL de desarrollan drivers para el bus SPI de 4 hilos para el sensor de temperatura (SHT11), un segundo bus SPI para el control de la pantalla OLED integrada. En la capa de aplicación se propone módulo de manejo de gráficos en la pantalla OLED, módulo de manejo del sensor de temperatura con funciones de cálculo de traducción de protocolo, cálculo de punto de rocío y control discreto de actuadores de arreglo Peltier y un posible actuador de ingreso/purga de humedad. Asimismo en las funciones de la aplicación se incorporan algoritmos para linearizar las lecturas del sensor, de-saturación de membrana del sensor SHT11 y control de indicadores discretos.

Derivado de un análisis de eficiencia, portabilidad, costo de implementación y robustez del código, se elige como plataforma de Desarrollo el IDE MPLAB V8.90, el compilador CCS V4.75 que tiene como ventaja la implementación rápida de un RTOS nativo, configurable a pre-emptive o colaborativo, y las herramientas ICD3 y PICkit3 que permiten programación y depuración en tiempo real y en circuito.

Finalmente si bien no se alcanzó a construir o validar un prototipo físico del concepto, las pruebas funcionales a nivel concepto arrojan que el sistema es factible de llevar a implementación y conclusión como un dispositivo, ya sea de implementación de fábrica en el vehículo, o alternativamente como un dispositivo post-venta (aftermarket) para ser adaptado a cualquier vehículo automotor.

ABSTRACT

This work obeys to the crescent need on thinking “out of the box” with innovative solutions to the environmental challenges the world is facing from some years to date. This document tries to address an effective implementation of an embedded control system, as part of a major system, to recycle residual Carbon dioxide ($CaCo_2$) exhaust emissions from a gas fueled vehicle in order to synthesize, with the aid of low cost and easily acquirable and non-hazardous chemicals such as Calcium Oxide (CaO) , into a bio-degradable aside non health hazard sub-product like Calcium Carbonate ($CaCo_3$) which can be re-used otherwise safely and environmentally friendly disposed.

First part of this Thesis states the objectives and theoretical framework as well as state of the art of existing solutions. Second part will get into details of the embedded system implementation scoping the hardware proposal, as well as the technical Embedded Software Engineering, design, validation and code implementation phases, and finally a third part will focus on the future work which will be aimed to lead to an interest of continuing the work in future system level implementations, including chemical reservoir design, environmental humidity acquisition chamber and a means of disposing of the non-toxic final product that should be freely either recycled or disposed easily without representing a bio or health hazard.

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ACRONYMS AND SYMBOLS

CO_2	Carbon Dioxide
$CaCO_3$	Calcium Carbonate
O_2	Molecular Oxygen
CO	Carbon Monoxide
NOx	Nitrogen Oxides
H_2	Molecular Hydrogen
H_2O	Water
RH%	Relative Humidity (percent)
HC	Hydrocarbons
kW	kilowatts
kWh	Kilowatt-hour
g	grams
MPa	Mega Pascal
rpm	Revolutions per minute
BMEP	Brake Mean Effective Pressure
DP	Dew Point
PCB	Printed Circuit Board
I^2C	Inter Integrated Circuit (Protocol)
MCLR	Main Clear (Microcontroller signal)
ICSP	In Circuit Serial Programming
MCU	Microcontroller Unit
µCU	Microcontroller Unit
EEPROM	Electrically Erasable Programmable Read Only Memory
ROM	Read Only Memory
SRAM	Static Random Access Memory
LED	Light Emitting Diode
OLED	Organic Light Emitting Diode
I/O	Input/output
DI/O	Digital Input/output
EMI	Electromagnetic Interference
MHz	Megahertz
ICSPDAT	In Circuit Serial Programming Data (Line)
ICSPCLK	In Circuit Serial Programming Clock (Line)
Vpp	Voltage Programming Pulse
SCK or SCLK	Serial Clock (Signal)
SDA	Serial Data (Signal)
D/C	Data/Control
BSW	Basic Software
CPU	Central Processing Unit
PLL	Phase Locked Loop
WDT	Watchdog Timer
MAL	Micro application Layer
PID	Proportional-Integral-Derivative
CCS®	Custom Computer Services
RTOS	Real Time Operating System
ANSI	American National Standards Institute
SO_{RH}	Sensor Output Relative Humidity (readout)
SO_T	Sensor Output Temperature (readout)
UART	Universal Asynchronous Receiver-Transmitter

IDC	Insulator Displacement Connector
SPI	Serial Peripheral Interface
ADC	Analog to Digital Converter
DAC	Digital to Analog Converter
ASCII	American Standard Code for Interchange of Information
IDE	Integrated Development Environment
SoC	System on Chip
PTAT	Proportional to Absolute
USB	Universal Serial Bus
SAT	Saturated
DESAT	Desaturated
EOL	End of Life

1. INTRODUCTION

Abstract: *This chapter briefly presents the background of this project, the problem definition, justification, and objectives.*

In the latest years the ozone layer depletion as well as other serious consequences derived from global pollution have been an important discussion and action trigger topic across governments, society and private institutions. This project and this derived thesis is based on existing, and other inspirational research works aiming to synthesize the fossil fuels emissions, specifically Carbon Dioxide (CO_2) to a less pollutant as well as recyclable or safely disposable substance such as Calcium Carbonate ($CaCo_3$) which can have several non-hazardous end uses such as:

- Masonry and building
- Gardening and non-hazardous/ non-toxic inorganic fertilizers
- Landfilling
- Painting
- Forest bugs plague prevention

Several efforts have been already developed, and some actually under experimental use, mainly for industrial applications, which worth the value to mention preliminarily:

- Bubbling CO_2 into salted water (marine water) in order to allow a chemical reaction to synthesize gasses into other non-hazardous minerals
- Filtering CO_2 through a "network" of natural organisms such as algae and urchins (ecchinaccei)

  In order to let gasses react with their Calcium shells and absorb most pollutants by synthesizing them onto $CaCO_3$
- Letting CO_2 react onto artificial catalytic converters in order to get tem mixed with other minerals.

As can be seen, such solutions are practical for big volume, high infrastructure investments so only focused to transformation industry, however there is not yet available a lower volume solution for mobile pollutant systems, such as vehicular combustion systems.

This document will explain in detail the embedded control system development for mobile aftermarket solution proposal, that can address the treatment of emissions in vehicles, and which can be interfaced to the chemical and physical means of treating the emissions.

1.1. Background Work

CO2 emissions reduction applied to industry and transformation processes have been a concern during the last two decades. A research applied to such efforts outcome a series of devices and processes mainly applied to transformation industry, however the automotive industry still keeps applying the already known methods that are designed and built along the development lifecycle of a vehicle:

+ CATALYTIC CONVERTERS:

A catalytic converter is a device devote to the conversion of toxic gases to a less pollutants products by a catalytic process, with an oxidation procedure of the hazardous gas. Typically, catalytic converters are used with engines that use petrol, diesel, and other fossil fuel.

The catalytic converters are quite important nowadays that it is very common information about its functionality. Typically, there are two types of converters. A two-way converter has two simultaneous tasks. By the one hand, an oxidation of carbon monoxide to carbon dioxide, represented by the well-known formula $2CO + O_2 \rightarrow 2CO_2$. On the other hand, an oxidation process of hydrocarbons to the carbon dioxide and residual water. This reaction is captured by the formula $CxH2x+2 + [(3x+1)/2]\ O_2 \rightarrow xCO_2 + (x+1)\ H_2O$.

A two-way catalytic converter is widely used on engines based on diesel. However, this converter lack of the ability to control the nitrogen oxidation.

A three-way converters have been designed to overcome the disadvantages of the two-way converters. A three-way converter has the ability of controlling the emission of nitric oxide and nitrogen dioxide. These two components contributes to the acid rain and hazardous smog.

As its name suggests, a three-way catalytic converter performs three simultaneous conversion tasks. Firstly, it makes a reduction process of nitrogen oxides to nitrogen and oxygen ($2NOx \rightarrow xO2 + N2$). Secondly, it does an oxidation of carbon monoxide to carbon dioxide ($2CO + O_2 \rightarrow 2CO_2$). Finally, it achieves an oxidation of unburnt hydrocarbons to carbon dioxide and water ($CxH2x+2 + [(3x+1)/2]O2 \rightarrow xCO_2 + (x+1)H_2O$). More information on catalytic converters can be found in **Error! Reference source ot found.**.

DISADVANTAGES:

- Design of catalyzer involves precious or costly metals at some stage of the process (Rhodium, Palladium, Cerium, Platinum), which in turn makes the device per se in a costly add-on, and which recycling process, results not to be not cost effective.
- As seen, the device per se, is aimed to reduce both CO and HC emissions. However, the aim of the global warming solution resides to reduce the CO_2 emissions, which in any case are the residuals for existing catalytic converters (aside of H_2O).
- As the internal components of a catalyzer have a natural residuals absorption process, there is a limited life expectancy for a catalyzer which rounds **10 years**, so after such period, the user needs to consider replacing, refurbishing or discarding the catalyzer.
- Some minor contaminants of the fuel can progressively change the chemical and red-ox properties of a catalyzer which in turn makes the catalyzer into a pollutant device. Lead and other heavy metals contained in any amount in the fuels will lead to this degradation process.

The reduction of CO2 emissions is of global interest. Some of the efforts are reflected in patents and patent applications. An interested reader may refer to the following list to get further information, only to mention a few:

- Keith, C. D., et al. U.S. Patent 3,441,381: "Apparatus for purifying exhaust gases of an internal combustion engine". 29 April 1969
- Lachman, I. M. et al. U.S. Patent 3,885,977: "Anisotropic Cordierite Monolith" (Ceramic substrate). 5 November 1973
- Charles H. Bailey. U.S. Patent 4,094,645: "Combination muffler and catalytic converter having low backpressure". 13 June 1978
- Charles H. Bailey. U.S. Patent 4,250,146: "'Caseless monolithic catalytic converter". 10 February 1981
- Srinivasan Gopalakrishnan. GB 2397782: "Process and Synthesizer for Molecular Engineering of Materials". 13 March 2002

1.2 Justification

- The need of an aftermarket and pre-market device to be incorporated on fossil fueled vehicles in order not to reduce just the CO and HC emissions, but aside CO2, which is the main cause of the global warming;
- The need of a moderated cost CO2 reduction device which can be incorporated a design time on almost any vehicle in order to be mechanically interfaced to accomplish the intended usage;
- And which can be replaced, maintained, disposed and refurbished by user or specialized workshops

1.3. Problem to be solved

- In order to contribute to CO_2 reduction from fossil fueled vehicles ,by means of a vehicle internal device synthesize CO_2 emissions ,and ,by a chemical reaction with an alkaline oxide reactive and condensed water, outcome a nonhazardous sub-product such as CaCO3 which can be safely disposed or recycled for several uses.

1.4. Hypothesis

- A device that can be incorporated in a fossil fueled vehicle that shall outcome a nonhazardous sub product based on the following chemical formula (which aim is to reduce CO_2 exhaust emissions):
    - $CaO + H_2O + CO_2 \rightarrow CaC0_3 + H2O$
    - Where H2O can be condensed from air humidity
    - Where CaO can be supplied as a consumable from user
    - Where $CaCO_3$ is the sub product obtained from chemical reaction

1.5. Objectives

1.5.1. General Objective:

1.5.1.1 To develop an aftermarket or premarket device to recycle/reduce CO2 emissions from fossil fueled vehicles, and synthesize exhaust gasses onto a nonhazardous sub product that can be safely disposed or recycled by user.

1.5.2. Specific Objectives:

1.5.2.1. To design a device that can be fitted by design in the exhaust pipeline in a fossil fueled vehicle and which significantly reduces the amount of CO_2 from combustion emissions,

1.5.2.2.- To design a device that needs only an alkaline oxide reactive, atmospheric air extracted humidity supply ,and which chemical reactions outcome a disposable product can easily be retrieved by user.

1.6. Scientific novelty / scientific contribution

- A device that additionally or in lieu of the traditional catalytic converters, takes the chore of reducing and/or synthesizing CO_2 emissions from automotive exhausts. Actual catalyzers do just work on CO, NOx and HC emissions,
- A device that relies on an embedded control to allow environmental humidity condensing, by monitoring RH% and controlling a condensing unit (by calculating the Dew point) such as a reservoir with a Peltier array that permits extracting humidity from air, thus aimed to be easily fitted by design otherwise as an aftermarket device to most existing makes of vehicles.

2. STATE OF THE TECHNIQUE

Abstract: *This chapter briefly presents current developments reported in the literature that are related with this work.*

As a context for this project, some works related to the reduction of CO2 emissions are reviewed. The emphasis is on those works that are closer to the line and objectives of this work. The full reference to the original work is provided in such a way that further information could be accessed.

2.1 Related Work No.1:

"Reduction of CO_2 Emissions for Automotive Systems"

By Junichi Ishii, Minoru Osuga, Takashi Okada, Hideky Miyazaki, Mitsuru Koseki, and Koichiro Tanikoshi. Hitachi Automotive Systems, Ltd., 2013.

In this work some actual and WIP technologies are described. The state of the art technologies considered in this paper are:

- Vehicle performance by-design technologies: Reduction of Engine losses in power train, hybrid power train technologies or electrical supply technologies,
- Alternative fuels technologies: Ethanol, Propanol, Water electrolysis powering, Bio-fuels, etc.
- Infrastructure improvement technologies (ITS)
- Fuel consumption optimization techniques: Vapor recirculation, Catalytic converters new technologies (however still focused to NOx , HC and COx),

The Figure 1 details the typical measurement of the CO2 emissions in utilitarian cars.

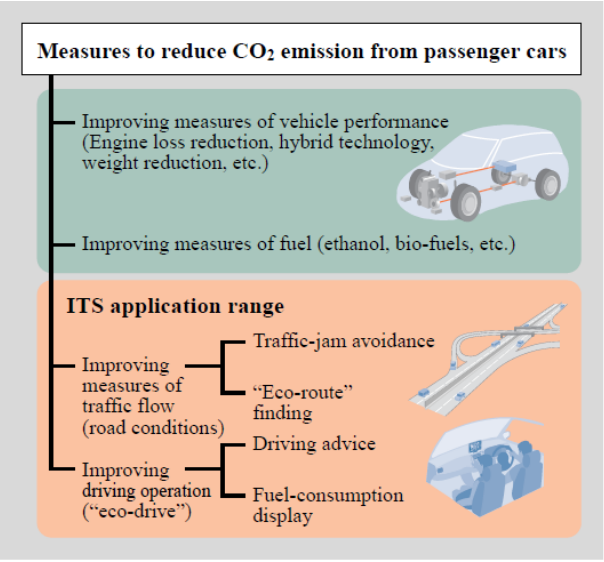

Figure 1. Measurement of the CO2 from passenger cars

2.2 Related Work No. 2

"Downsizing of Gasoline Engine: an Efficient Way to Reduce CO2 Emissions"

By P. Leduc, B. Dubar, A. Ranini and G. Monnier. Institut français du pétrole, division Techniques d'applications énergétiques, 92852 Rueil-Malmaison Cedex – France

Size reduction of the gasoline engine has shown been an efficient way to reduce CO_2 emissions. The next is the abstract information in the cited work:

"Abstract: *In order to meet commitments in terms of vehicle CO_2 emission reduction for the whole fleet of cars for the year 2008, engine research and development is today exploring several fields. From CO_2 point of view, gasoline engines suffer from a handicap in comparison to Diesel engines.*

Engine (downsizing) appears to be a promising way to improve engine efficiency and is subject to extensive research. Having a look to the long term, the aim should be to reduce by half the engine displacement volume."

2.3 Related Work No. 3

"Assessment of Methanol Synthesis Utilizing Exhaust CO_2 for Chemical Storage of Electrical Energy"

By Liisa K. Rihko-Struckmann, Andreas Peschel, Richard Hanke-Rauschenbach, and Kai Sundmacher. Max Planck Institute for Dynamics of Complex Technical Systems, and Otto-von-Guericke University Magdeburg, D-39106 Magdeburg, Germany, Sep 2010.

This work focuses on the production of methanol from residual CO2 is one of the main contribution of this work. The efficiency of different conversion techniques of the system is analyzed. The following information could be found in the cited work:

*"**Abstract:** This work deals with the thermodynamic and operational boundaries to store electrical energy chemically. Methanol is considered as a candidate for chemical energy storage.*

The production of methanol from exhaust CO2 could be one way to recycle CO2 and lower the global CO2 emissions in automotive engines. Energetic analysis reveals that exergy losses are most severe in the parts of the system when electrical energy is converted to chemical, by electrolysis, and when chemical energy is converted to electrical."

As could be noticed, there are several efforts to cope the problems related with the pollution reduction, with a special focus on the CO2 emissions. An interested reader may refer to the provided sources for more information.

3. ARCHITECTURAL DESIGN

Abstract: *This chapter describes the architectural design of the solution proposed and the main technical aspects of the implementation.*

3.1. LAYOUT ARCHITECTURE

As previously remarked, the aim of this work is to provide a solution for reducing CO2 emissions in a vehicle. The Figure 2 provides a layout of the proposed architectural solution.

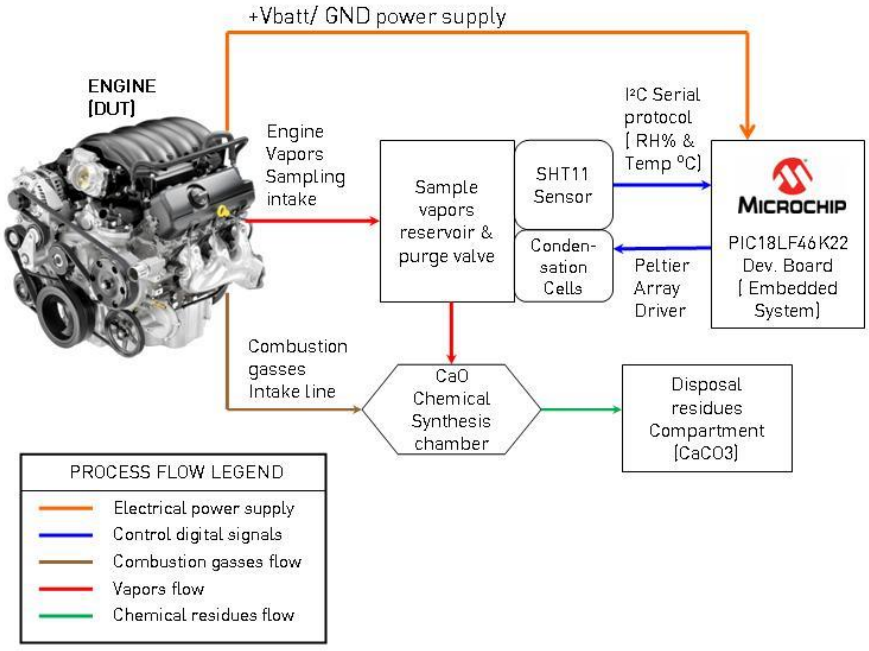

Figure 2. General layout of the proposed solution

The diagram is described as a flow the process in the following terms:

1. Exhaust CO2 is directed to the reaction reservoir all the time
2. Embedded system is monitoring air temperature, RH% and calculated Dew point in real time, so
3. If DP is less than air temperature, turns Peltier cells array on to cool down air to DP, thus humidity condensing is achieved.
4. Exhaust CO2 reacts chemically with condensed water and sample reactive (CaO).
5. Embedded system detects RH% saturation, then turns purge valve on and signals user to provide maintenance to reaction chamber, which means to check the sample and decide whether is necessary to dispose and replace for a new sample.

3.1.1. SYSTEM LEVEL REQUIREMENTS

The following table captures the system level requirements considered for this project.

Table 1. System Level Functional Requirements

SYS-01	SYSTEM	System shall interface automotive signals, emmisions and power supply in a non invasive nor disturbing way to normal vehicle functions
SYS-02	SYSTEM	System shall handle and store all intaken emmisions , outcame products and subproducts in a safe and non hazardous way
SYS-03	SYSTEM	System shall count on means of disposing products and subproducts in a way that is not hazardous to user nor to other persons, plants or animals in eventual contact with such substances
SYS-04	SYSTEM	System shall count on consumable and replaceable/ serviceable parts in a way not representing use of special tools nor requiring specialized training nor skills to vehicle user
SYS-05	SYSTEM	System shall function in a way that in the event of a malfunction or non recoverable failure, does not interfere with vehicle normal functions
SYS-06	SYSTEM	System shall not create significant fuel nor power consumption increase for drawing power from vehicle power supply
SYS-07	SYSTEM	System shall have an audible or visual means of indication of service needed, malfunction or any other indication needing user attention
SYS-08	SYSTEM	System shall count on a self-means of recalibrating upon humidity saturation or emmisions excess that disturb normal parameters sensing/monitoring
SYS-09	SYSTEM	System shall not generate significant heat increase during normal functions
SYS-10	SYSTEM	System shall not generate noticieable noise nor added vibrations at normal functioning
SYS-11	SYSTEM	System main product shall be CaCO3 and it's subproducts shall not exceed legal levels of hazardous materials that a person can be exposed to

3.2. HARDWARE ARCHITECTURE

3.2.1. HARDWARE REQUIREMENTS

The following table captures the hardware requirements considered for this project.

Table 2. System Level Functional Requirements

HW-01	HARDWARE	Control module shall be based on an 8 bit embedded system board capable of interfacing all incoming and outgoing logic, analog , communications and power electrical signals
HW-02	HARDWARE	Control module shall be capable of working inside either a sealed or non sealed case
HW-03	HARDWARE	Controle module shall not add significant EMI interference to overall vehicular network, analog signals nor digital control vehicle signals
HW-04	HARDWARE	Control module shall be working in an stand-alone mode , non depending on vehicular control nor power signals
HW-05	HARDWARE	Valve electrical actuators shall not produce significant EMI interference in vehicualr network nor signals
HW-06	HARDWARE	Control module wiring and harnesses shall not require additional environmental and working specifications that normal vehicular cabling specs
HW-07	HARDWARE	Valves and actuators shall be compliant with automotive exhaust section operating temperatures, vibration and humidity specifications
HW-08	HARDWARE	Humidity and temperature sensing shall be implemented using a single chip sensor mounted in a PCB
HW-09	HARDWARE	Humidity and temperature sensor shall be tolerant to automotive exhaust humidity and temperature ranges
HW-10	HARDWARE	Humidity and temperature sensor shall count on a means of self-de-saturation when it's sensing membrane causes out-of-calibration function
HW-11	HARDWARE	Decondensing process shall be controlled and monitored by control unit
HW-12	HARDWARE	Sensor interface to Embedded controller shall be a serial 2 wire protocol, electrically compliant with I2C protocol standard
HW-13	HARDWARE	Sensor interface shall have a mounting means in system in a non-invasive way towards humidity and emmisions flows
HW-14	HARDWARE	Controlling unit shall be fully capable of self-calibrating and auto-calibration of valves actuators
HW-15	HARDWARE	Sensor shall be compliant with constant exposure to exhaust gasses not limited to CO2 but also CO2, HC, Nox,
HW-16	HARDWARE	Control unit shall have an electrical connection means of being re-flashed in field
HW-17	HARDWARE	Control unit shall be capable of being accesed for reflashing while not requiring specialized tools nor complicated access to the ICSP connection
HW-18	HARDWARE	Microcontroller shall have a minimum of 16 Kwords of FLASH ROM
HW-19	HARDWARE	Microcontroller shall have not less than 512 bytes of SRAM
HW-20	HARDWARE	Microcontroller shall have not less than 128 bytes of EEPROM
HW-21	HARDWARE	Microcontroller shall be compliant with automotive temperature range
HW-22	HARDWARE	Microcontroller shall incorporate a minimum of 2x16 bits counters
HW-23	HARDWARE	MCU shall not require an external oscillator but an internal oscillator module not exceeding 5% tolerance
HW-24	HARDWARE	MCU shall count on a minimum of 10 Digital I/Os not counting the ICSP nor MCLR pins

3.3. FUNCTION DIAGRAM

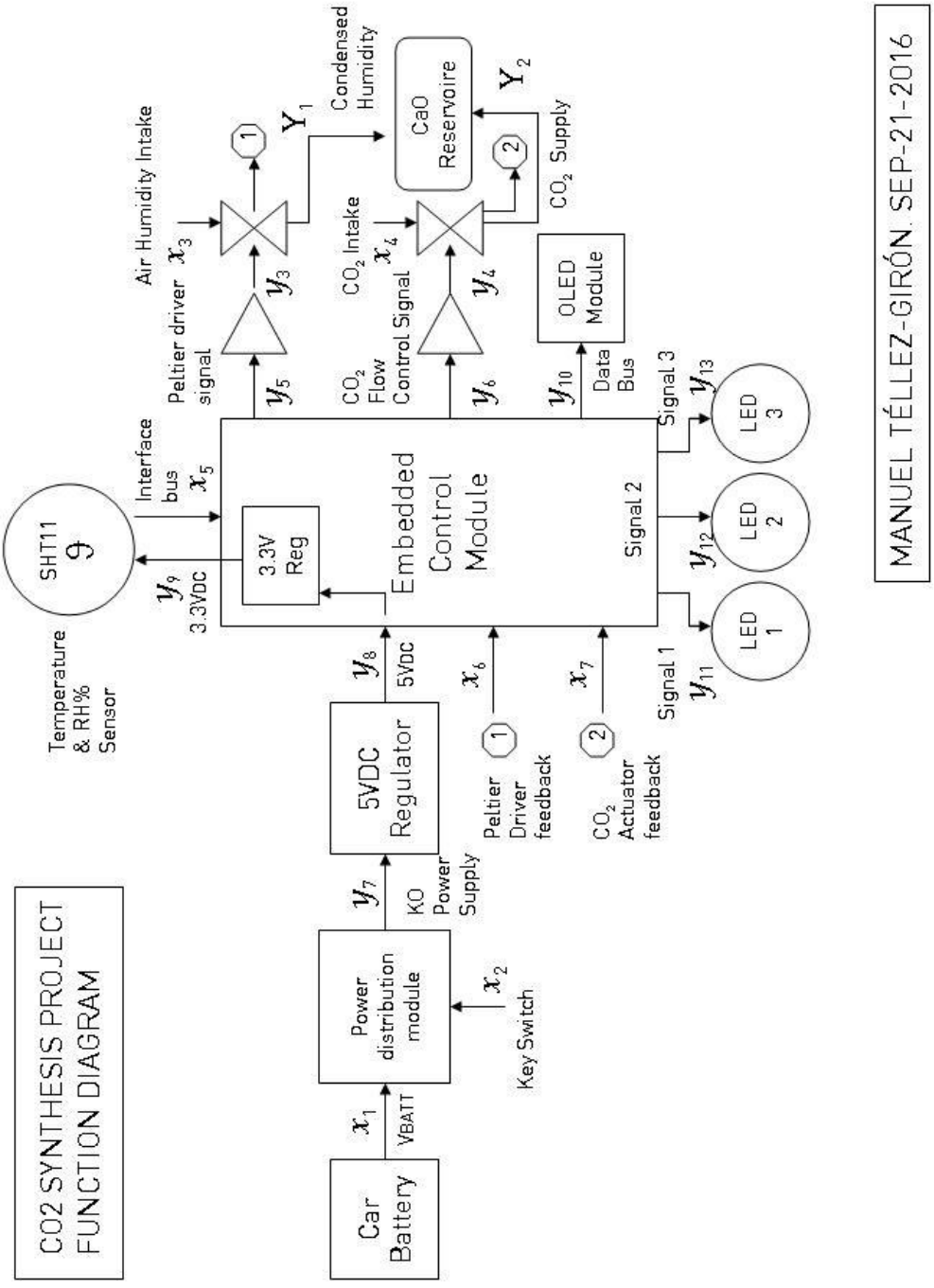

Figure 3. System concept Function Diagram

3.4. P-DIAGRAM

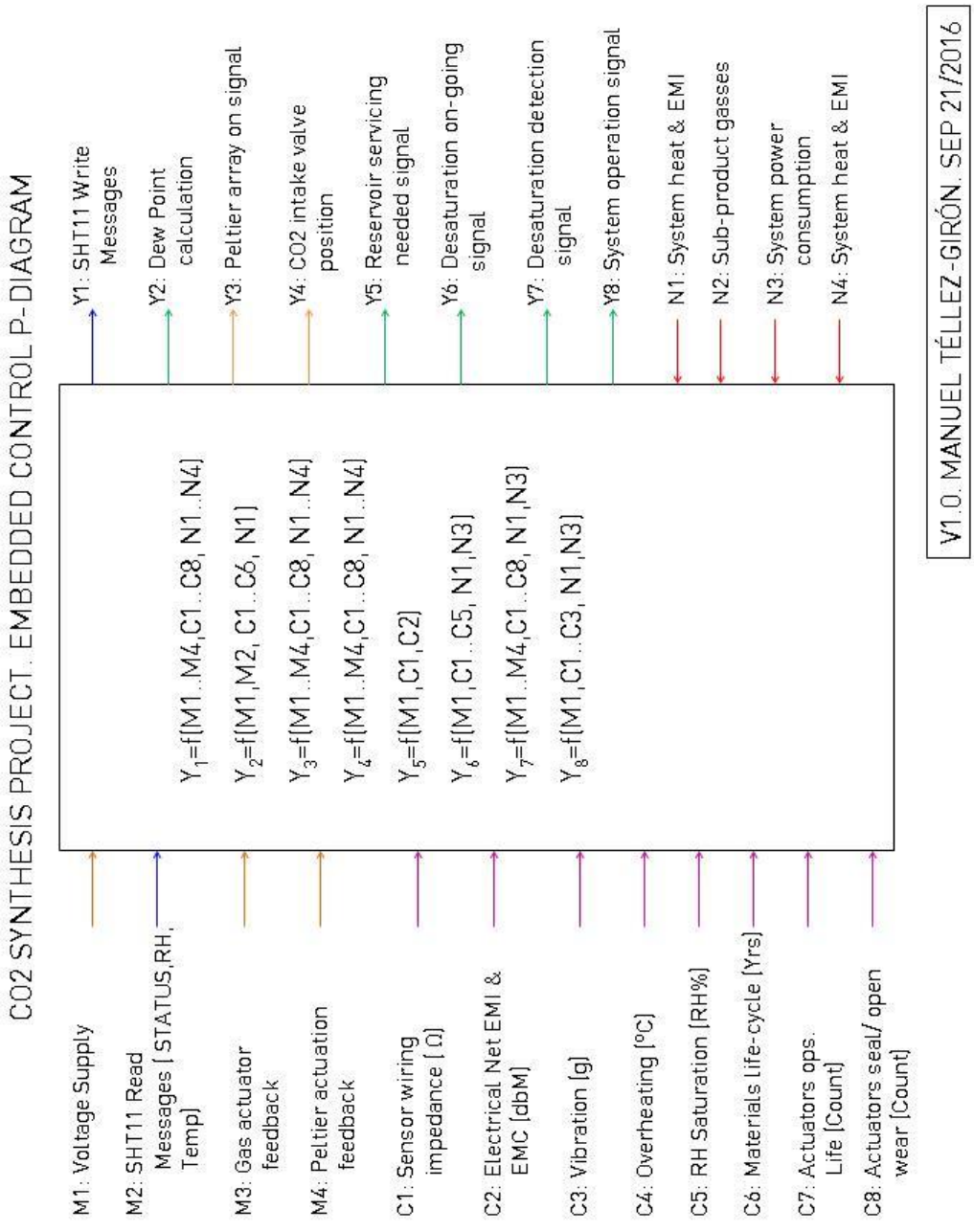

Figure 4. Embedded Control P- Diagram

3.5. BOUNDARY DIAGRAM

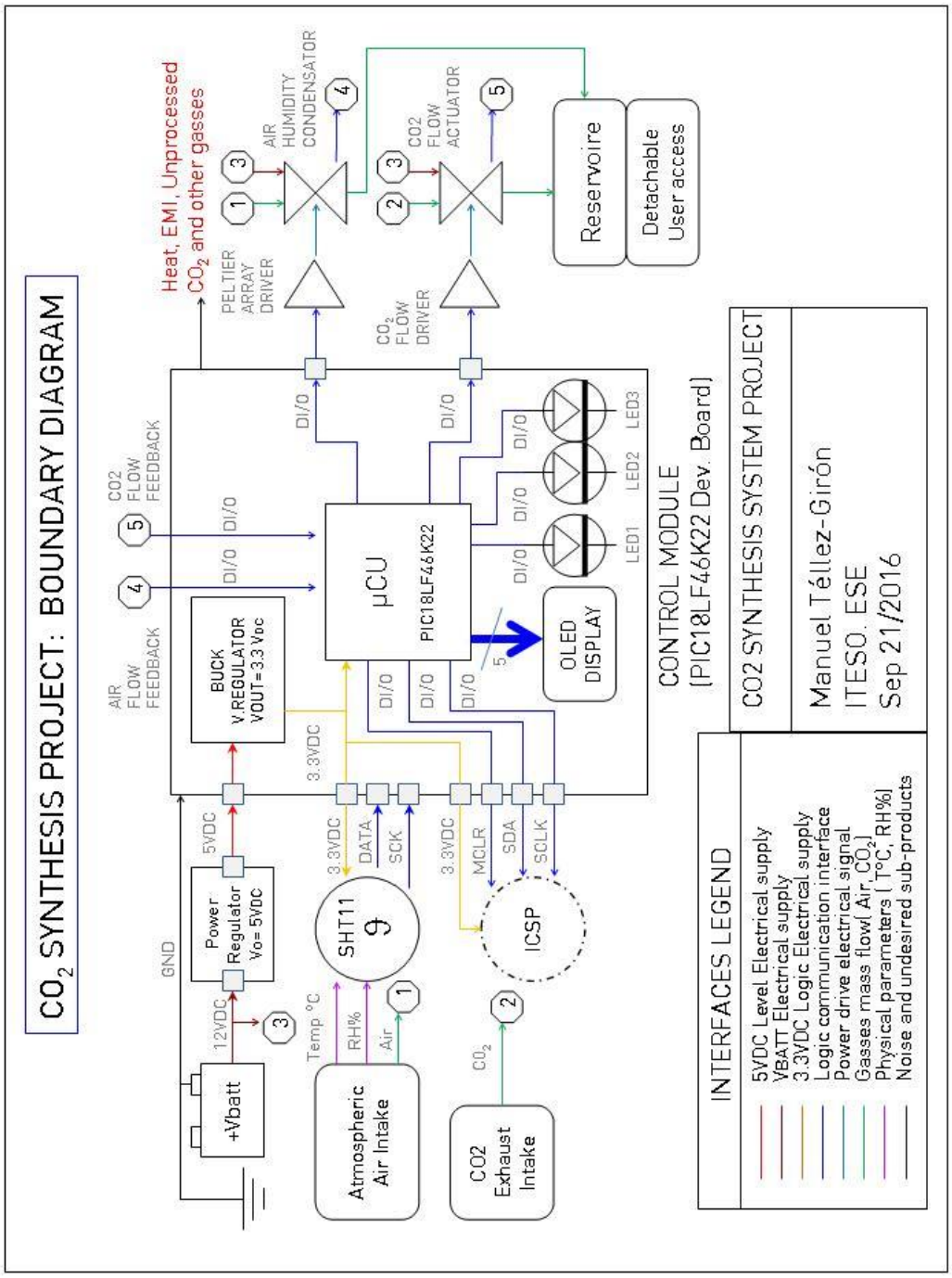

Figure 5. Embedded Control Boundary Diagram

3.1. SIMPLIFIED ELECTRICAL INTERFACE SCHEMATICS

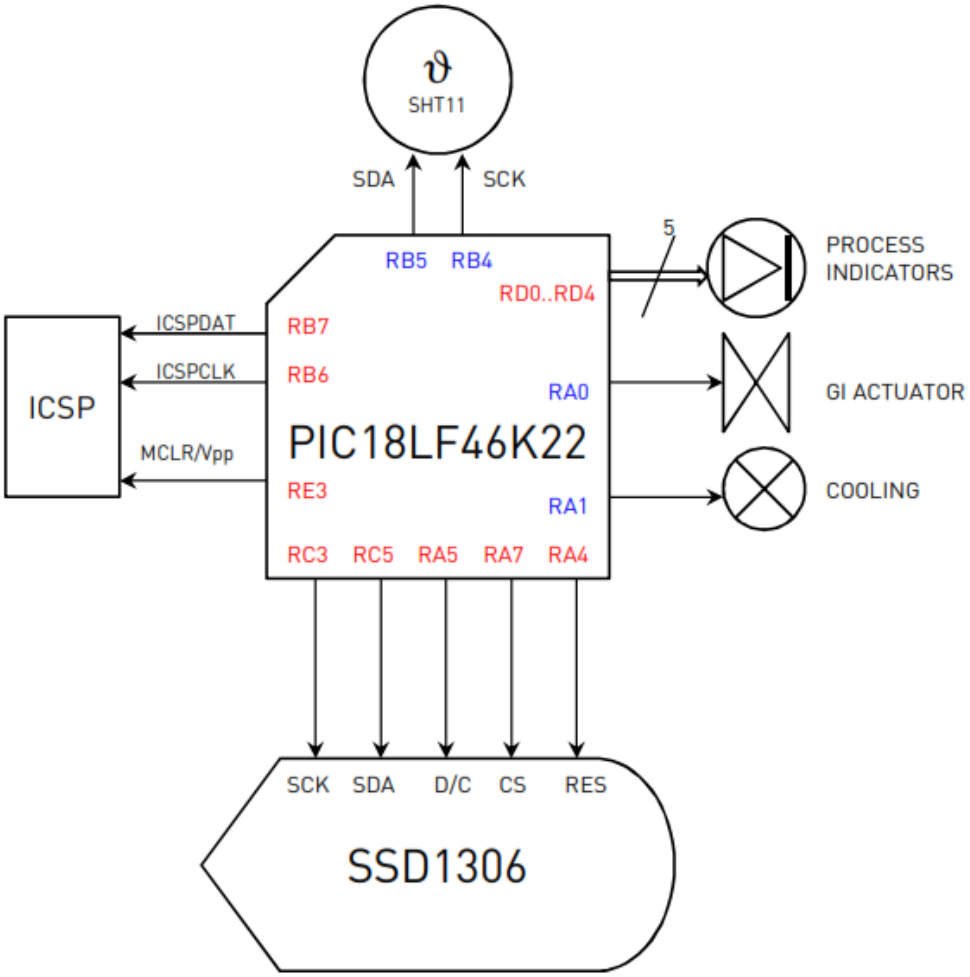

Figure 6. Simplified Electrical Interface Schematics

3.2. SOFTWARE ARCHITECTURE

3.2.1. SOFTWARE REQUIREMENTS

The following tables shows the software requirements of this project.

Table 3. Software Level Requirements

SW-01	**SOFTWARE**	Control software shall be based on a task scheduler that incorporates sensing/monitoring tasks, algorithm process tasks, actuators control tasks, diagnostics tasks
SW-02	**SOFTWARE**	Interface protocol towards SHT11 sensor shall be compliant with Sensirion SHTxx protocol specification
SW-03	**SOFTWARE**	Task scheduler shall implement a 1000 mS task for monitoring humidity sensor and temperature sensing
SW-04	**SOFTWARE**	Task scheduler shall implement a 10,000 mS task for detecting condensation/saturation in RH% sensor and executing desaturation procedure
SW-05	**SOFTWARE**	During desaturation procedure actuators shall be in a state of closure to avoid admitting gasses nor humidity to reservoire
SW-06	**SOFTWARE**	A self calibration procedure shall be executed at control start-up without disturbing any operation in vehicle
SW-07	**SOFTWARE**	Using an OLED visual alarm, program shall notify user when a saturation event is detected
SW-08	**SOFTWARE**	Using an OLED visual indication, program shall notify user when a de-saturation process is undergoing
SW-09	**SOFTWARE**	Using an OLED visual indication, program shall notify user when disposable products need to be removed from reservoire
SW-10	**SOFTWARE**	Using an OLED visual indication, program shall notify user that system is operating
SW-11	**SOFTWARE**	MCU internal clock working frequency shall be configured to be 4.0000 MHz
SW-12	**SOFTWARE**	Main internal oscillator shall not invoke PLL configuration to work
SW-13	**SOFTWARE**	Controll shall not need additional interrupts not events handlers aside the scheduler tasks driven ones
SW-14	**SOFTWARE**	Control unit shall have an internal WDT implementation not requiring external circuitry
SW-15	**SOFTWARE**	Embedded system shall be compliant to be flashed, debugged and updated via Microchip ICSP Protocol
SW-16	**SOFTWARE**	Source code shall be compilable using PICC CCS Compiler V4.140
SW-17	**SOFTWARE**	Source Code shall be capable of handling at least 5 Interrupt vectors
SW-18	**SOFTWARE**	Source code shall de structured to incorporate as minimum: MAL, Services and application layers
SW-19	**SOFTWARE**	Actuators position shall be based on a PID type control

Table 4. Software Level Requirements (cont.)

<table>
<tr><td>SW-20</td><td>SOFTWARE</td><td>Dew point calculation shall be based on the following algorithm
$$T_d(RH,T) = T_n \cdot \frac{\ln\left(\frac{RH}{100\%}\right) + \frac{m \cdot T}{T_n + T}}{m - \ln\left(\frac{RH}{100\%}\right) - \frac{m \cdot T}{T_n + T}}$$
<table>
<tr><th>Temperature Range</th><th>Tn (°C)</th><th>m</th></tr>
<tr><td>Above water, 0 – 50°C</td><td>243.12</td><td>17.62</td></tr>
<tr><td>Above ice, -40 – 0°C</td><td>272.62</td><td>22.46</td></tr>
</table></td></tr>
<tr><td>SW-21</td><td>SOFTWARE</td><td>Program shall scope a linearization/compensation procedure for the specific operation conditions of the SHT sensor and adhered to the following formula:
$$RH_{linear} = c_1 + c_2 \cdot SO_{RH} + c_3 \cdot SO_{RH}^{\ 2} \ (\%RH)$$
<table>
<tr><th>SO_{RH}</th><th>c_1</th><th>c_2</th><th>c_3</th></tr>
<tr><td>12 bit</td><td>-2.0468</td><td>0.0367</td><td>-1.5955E-6</td></tr>
<tr><td>8 bit</td><td>-2.0468</td><td>0.5872</td><td>-4.0845E-4</td></tr>
</table></td></tr>
<tr><td>SW-22</td><td>SOFTWARE</td><td>Program shall apply the following additional Temperature compensation for operation conditions very above of 25°C
$$RH_{true} = (T_{°C} - 25) \cdot (t_1 + t_2 \cdot SO_{RH}) + RH_{linear}$$
<table>
<tr><th>SO_{RH}</th><th>t_1</th><th>t_2</th></tr>
<tr><td>12 bit</td><td>0.01</td><td>0.00008</td></tr>
<tr><td>8 bit</td><td>0.01</td><td>0.00128</td></tr>
</table></td></tr>
<tr><td>SW-23</td><td>SOFTWARE</td><td>Temperature conversion from readout shall be obtained using the follwing formulae:
$$T = d_1 + d_2 \cdot SO_T$$
<table>
<tr><th>VDD</th><th>d_1 (°C)</th><th>d_1 (°F)</th></tr>
<tr><td>5V</td><td>-40.1</td><td>-40.2</td></tr>
<tr><td>4V</td><td>-39.8</td><td>-39.6</td></tr>
<tr><td>3.5V</td><td>-39.7</td><td>-39.5</td></tr>
<tr><td>3V</td><td>-39.6</td><td>-39.3</td></tr>
<tr><td>2.5V</td><td>-39.4</td><td>-38.9</td></tr>
</table>
<table>
<tr><th>SO_T</th><th>d_2 (°C)</th><th>d_2 (°F)</th></tr>
<tr><td>14bit</td><td>0.01</td><td>0.018</td></tr>
<tr><td>12bit</td><td>0.04</td><td>0.072</td></tr>
</table></td></tr>
<tr><td>SW-24</td><td>SOFTWARE</td><td>RTOS shall be of pre-emptive type to allow algorithms to handle semaphors</td></tr>
</table>

3.2.2. AUTOSAR SOFTWARE ARCHITECTURE

Microcontroller abstraction Layer:

SHT11_Driver_V1.h & SHT11_Driver_V1.c
- SHT11 RH% & Temp sensor Hardware driver

SPI_Driver_V1.h & SPI_Driver_V1.c
- Organic LED (OLED) Display Hardware driver

ECU Abstraction Layer:

SHT11_Handler_V1.h & SHT11_Handler_V1.c
- SHT11 RH% & Temp sensor basic protocol layer

OLED_Handler_V1.h & OLED_Handler_V1.c
- Organic LED (OLED) Display chars , columns & rows handler

OLED_Chartable_V1.h
- OLED Character generator table

Application Layer:

CO2_Synth_V10.c & CO2_Synth_V10.h
- Main application, system configuration , application macros and definitions

CO2_Synth_Tasks_V10.c
- RTOS Tasks definition

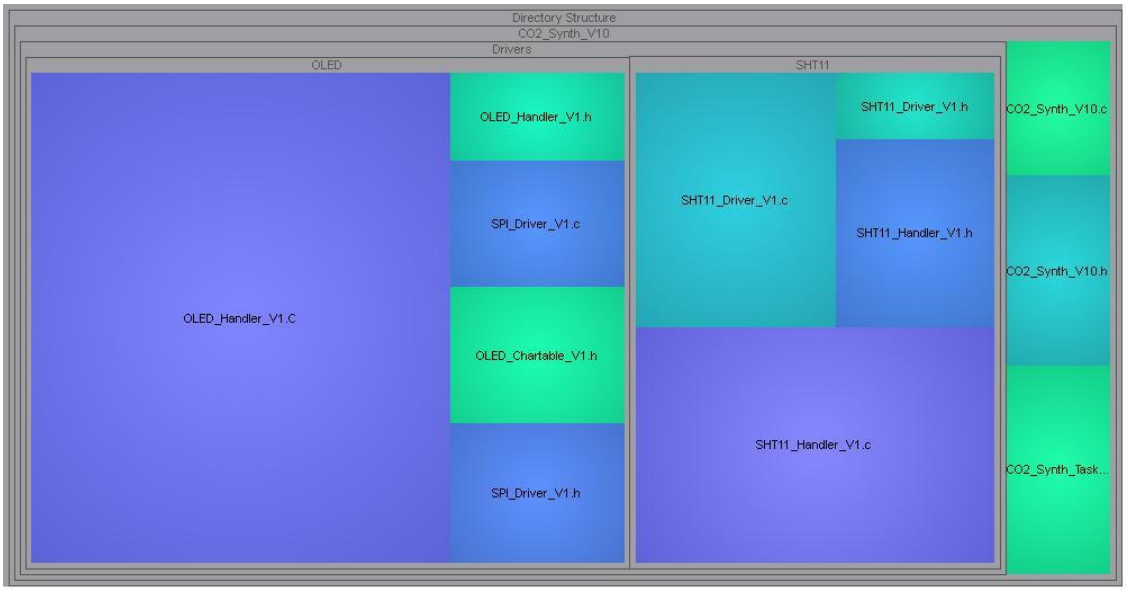

Figure 7. AUTOSAR Model for embedded software architecture

3.2.3. BUTTERFLY DIAGRAM SOFTWARE ARCHITECTURE

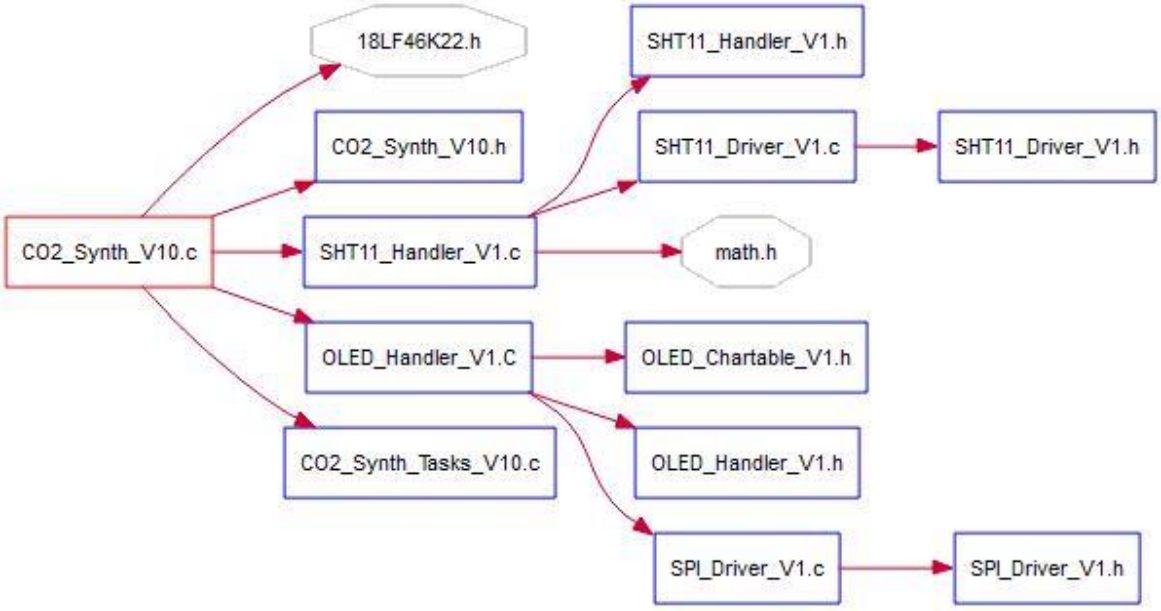

Figure 8. Butterfly Diagram of software architecture

Notes:

1. - 18LF46K22.h is a header file provided by CCS Compiler, contains definitions for Registers, I/O pins, macros for CPU configuration, etc.

2. - math.h is a header library provided by CCS Compiler and adhered to ANSI C library standards, defines mathematical macros such as double precision, floating point, complex and trigonometric math functions, etc.

3.2.1. EMBEDDED SOFTWARE FLOWCHART

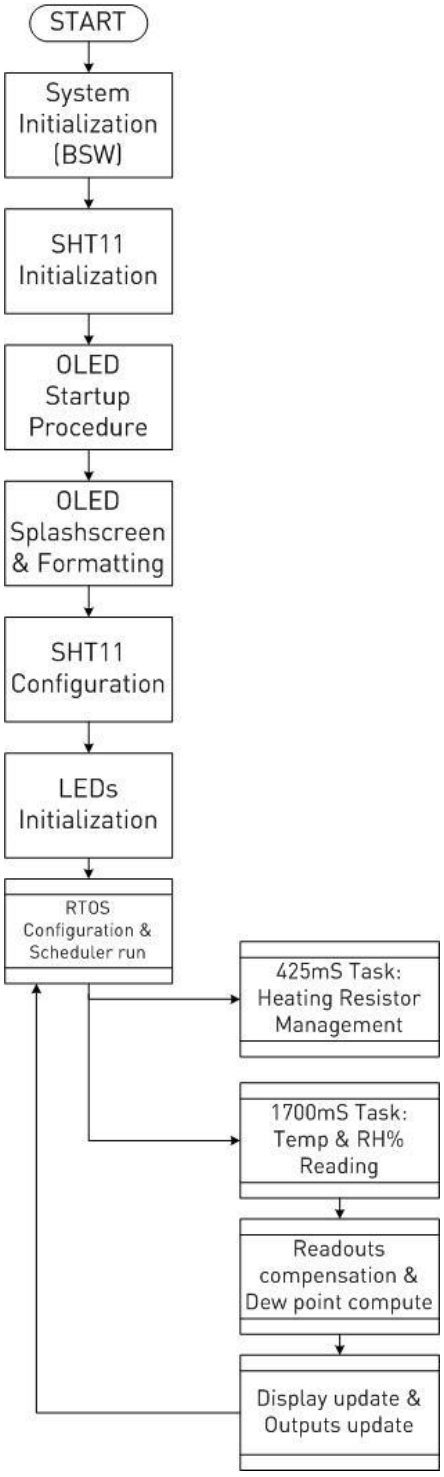

Figure 9. Software implementation flowchart

4. IMPLEMENTATION

Abstract: *This chapter describes the main aspects of the implementations developed in this work. It describes the development tools as well as the integrated development environment, compilation tools and sensors interfacing.*

4.1. IMPLEMENTATION FRAMEWORK

Keeping in mind the Software requirements, key elements were identified in order to select the development toolchain and infrastructure that meets the best possible the needs for the prototype development and validation phases.

4.1.1 CPU Selection

A benchmark for selecting CPU (thus platform and toolchain) were took in consideration:

a) Reputable brand, web based support and developer libraries and available resources
b) Ease of acquisition, available in Mexico, ease of implementation nor close to EOL part
c) Cost of CPU affordable for massive production, not close to EOL
d) ANSI C support and RTOS support
e) At least one SPI port available
f) At least one UART available (for development support purposes)
g) Real time programming, debugging and simulation (In circuit)
h) Reasonable pricing of CPU, development platform, embedded software dev tools
i) Reasonable board size and reasonable form factor
j) External interfacing and connecting capabilities via IDC ports (DuPont cabling)

Selected part resulted to be the PIC18LF46K22, which is a low power variant of the PIC18FxxKxx family from Microchip Technology Inc., Semiconductor manufacturer based in Chandler Az.

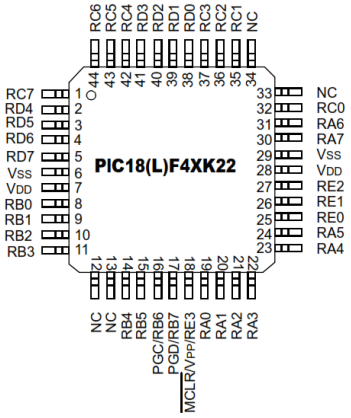

Figure 10. Selected Project MCU Pinout

4.1.2 Development hardware selection

Based on previous CPU criteria the selected development board is the DM164134 which incorporates an on-board OLED display, a 32KHz tuning fork oscillator, ADC and DAC circuitry, Low resolution temperature sensor, auxiliary LED indicators and pushbuttons, current monitor and on-board voltage regulator.

As usual in Microchip development boards, the platform incorporated an ICSP interface to let real time programming and debugging from the IDE using the standard development tools such as MPLAB ICD 2, ICD3 or PickIT3

This board incorporates aside 0.1 inch pitch female connectors compatible with DuPont style prototyping connectors, so it is available to interface with external boards or prototyping boards by using a simple insert type wiring.

For this project purposes, an external prototyping board where the SHT11 sensor was inserted, was the choice in order to keep prototyping modularity.

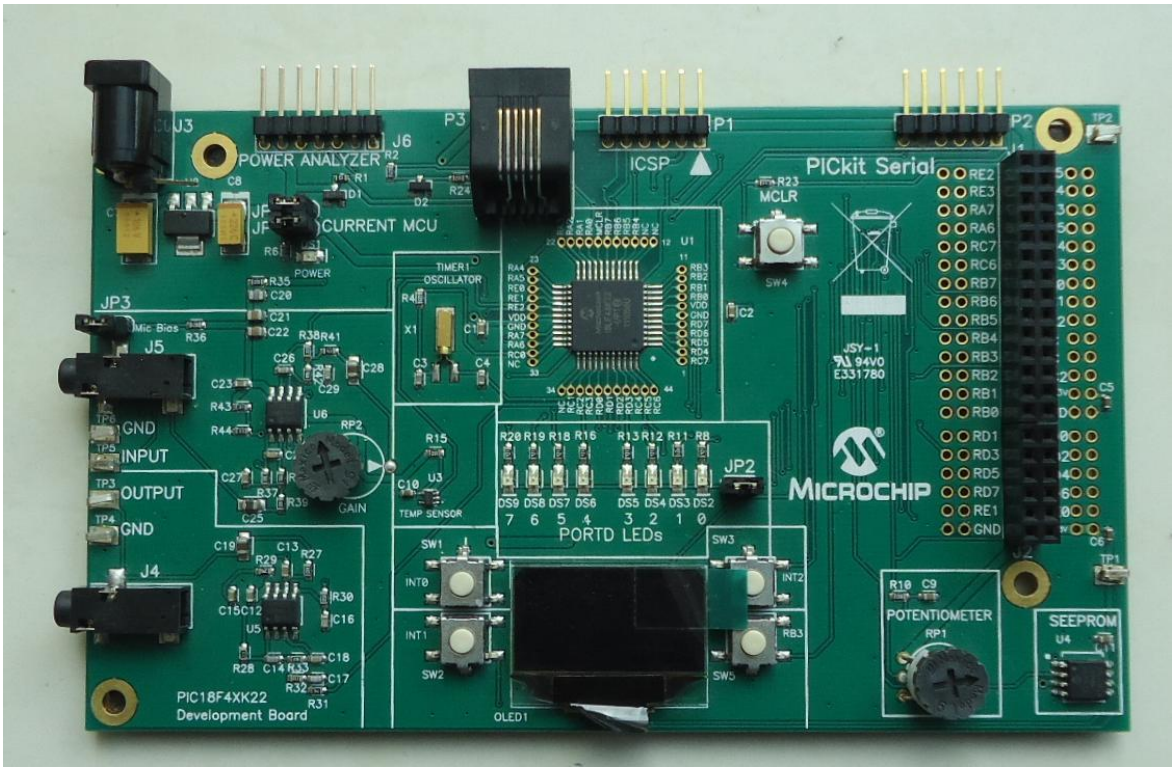

Figure 11. Microchip Development board (DM164134)

4.1.3 Integrated Development Environment (IDE)

Since a Microchip part was selected, an adequate IDE is needed. Microchip base development IDE is the MPLAB platform thus, such platform was selected. The latest IDE version (as of September 2016) is the MPLABX V3.40, however does not run appropriately on all computing environments/ OS, so a rollback to MPLAB V8.90 was decided in order to provide the most flexibility during the development cycle.

Basic platform incorporates an editor, an integrated assembler (MPASM) and simulator. MPLAB natively interfaces ICSP protocol based tools such as ICD2, ICD3 and Pickit3.

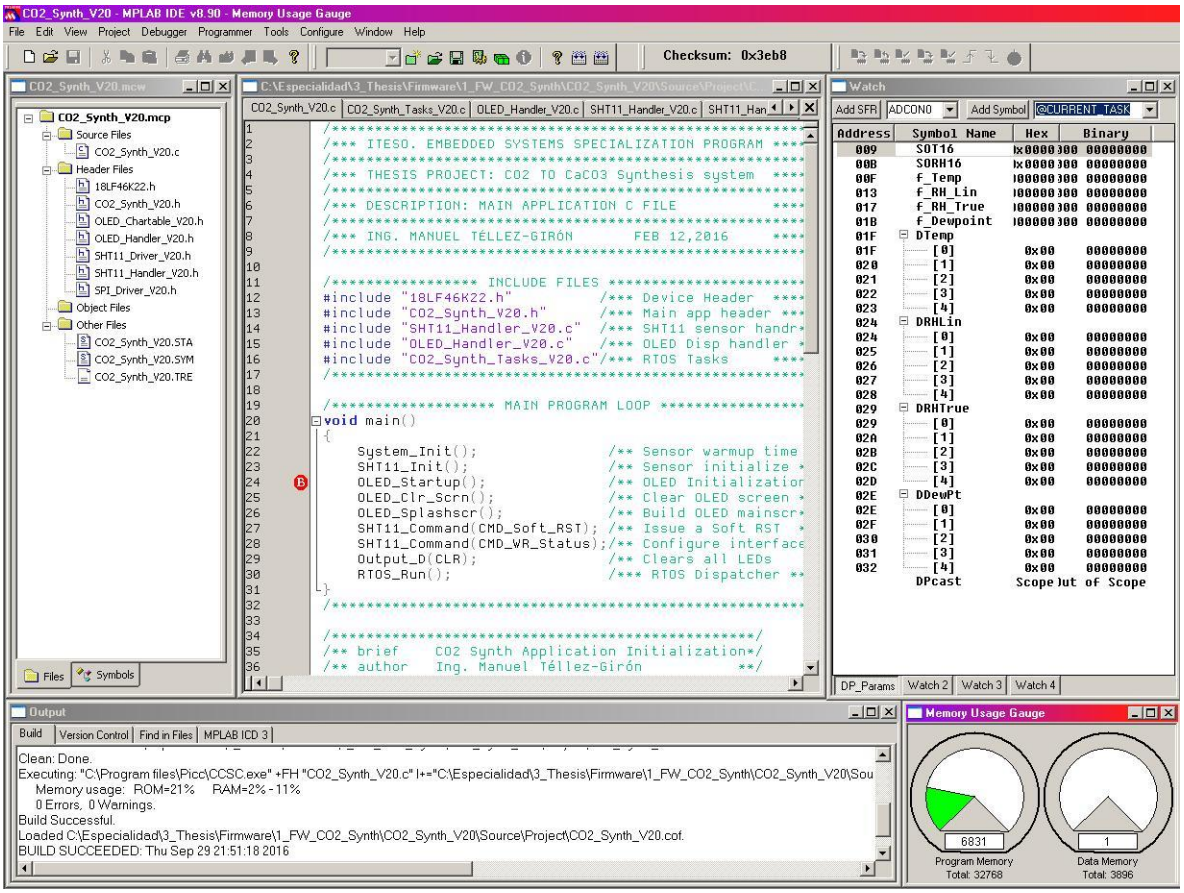

Figure 12. MPLAB IDE V8.90 Screenshot

4.1.4 C Compiler

Based on experiences, was determined that A compiler that offers an appropriate balance cost- ease of implementation and use, is the Custom Computer Services C Compiler which is a modular compiler environment that also has integrated auxiliary tools such as ASCII Terminal, Chip configurator/ Editor etc., and can work both as a command line compiler with a rich set of compilation switches, as well as a standalone IDE compiler. CCS Compiler, when used in standalone mode, can also incorporate a plugin for debugging and emulating in real time using ICD3 and other Microchip tools.

CCS Compiler offers also an integrated RTOS that can be configured to be either Preemptive or Collaborative. In this project the Preemptive mode was employed.

For this project purposes, CCS C compiler V4.1.0 was used as a line command compiler, directly and transparently interfaces to the MPLAB IDE platform.

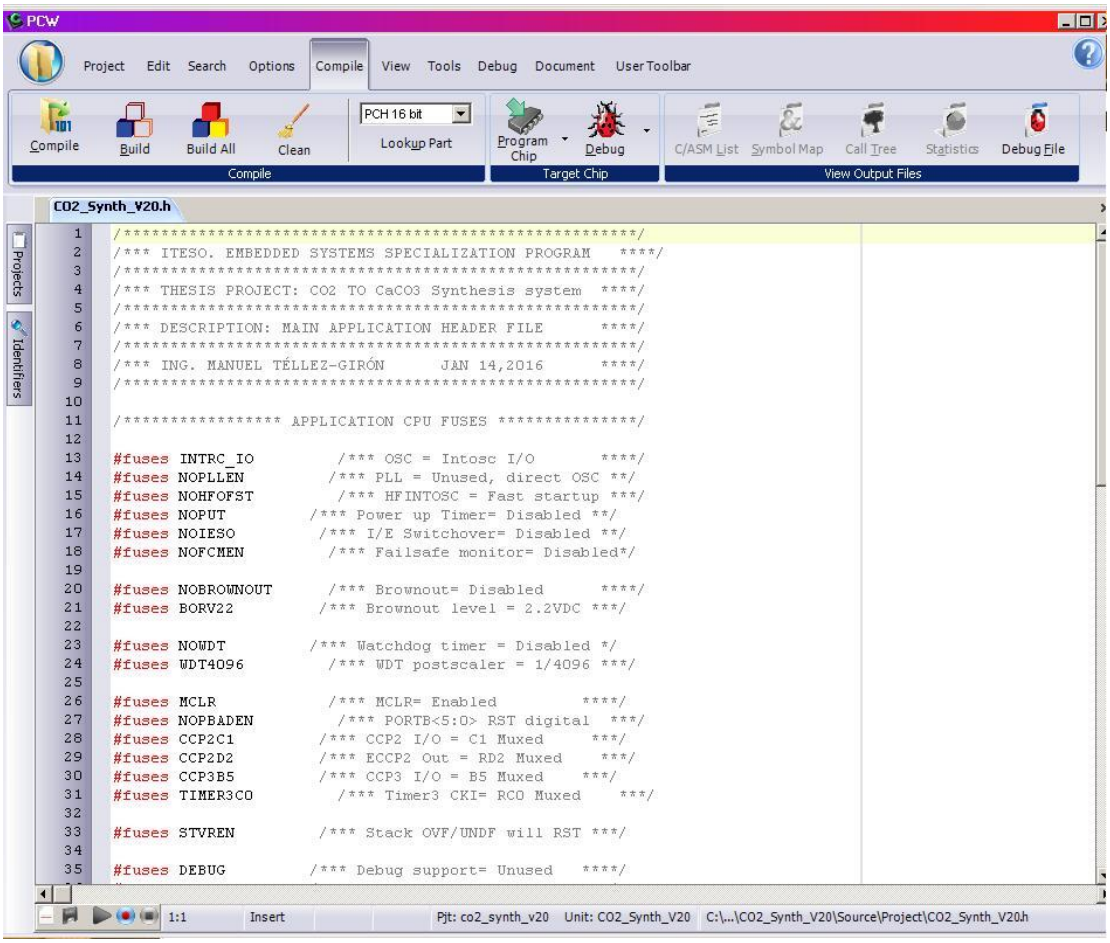

Figure 13. CCS Compiler screenshot run at standalone mode

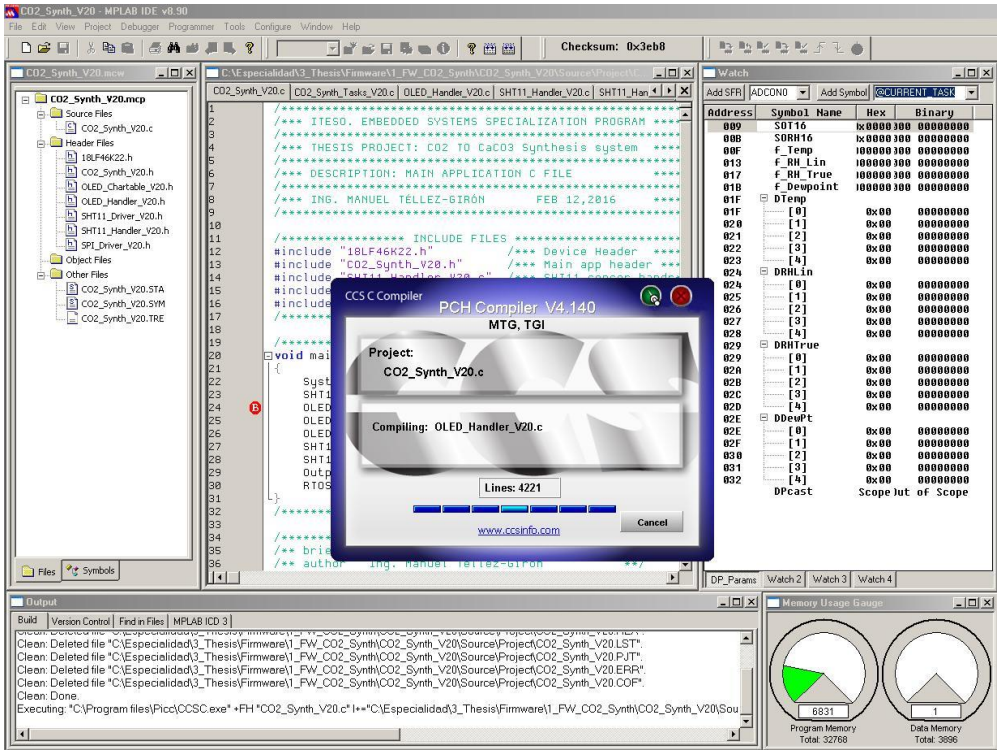

Figure 14. CCS Compiler run at MPLAB plugin mode

4.1.5 Debugging tools

As mentioned previously, preferred debugging tools are the ones that interface natively and transparently to MPLAB environment. In this project was mainly used the In Circuit 3 (ICD3) debugger which supports up to 5 breakpoints, can debug in real time and is compatible with CCS compiler (using the appropriate plug-in).

As an auxiliary tool a low cost PICkIT 3 tool was used, that has basic debugging features but has the advantage of working as a "semi"-standalone flasher, which means that can download new firmware to the target without needing to open an MPLAB session, but using a basic field programming software.

Figure 15. PICKit 3 and ICD3 Flash/ Debugging tools

4.1.6 Temperature & RH% Sensor

Considering that the real work environment of the sensing devices is quite harsh, i.e. environmental conditions, electrical noise as well as a desired low power consumption, which are typical of an automotive application the selected device is a SHT11 from Sensirion.

This family of sensors provide a two wire digital interface towards the MCU (I^2C like but slightly different regarding protocol layer). The means of sensing is a capacitive device and the SOC integrates also the needed signal conditioning circuitry, ADC, and all needed peripherals to interface the device to a microcontroller serial interface bus.

The sensor provides a resolution up to 12 bits for RH% measurements, and 14 bits for temperature measurements. Developer is responsible for processing the received raw data (SO_T & SO_{RH}) by linearizing and compensating according some coefficients and equations provided by manufacturer, thus letting user to get up to an 0.4°C error when measuring temperature, and 3 % accuracy when RH% is being measured.

This family of sensor also provide an integrated resistor for desaturation purposes, as well as for testing evaluation purposes when developer simply wants to exercise a self-check of the sensor working OK.

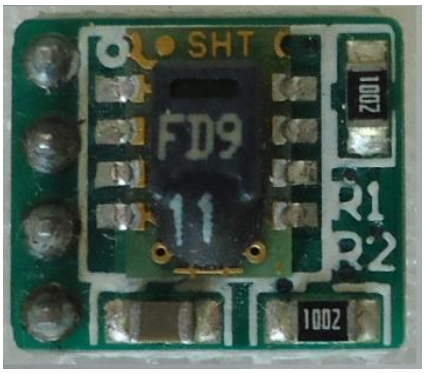

Figure 16. SHT11 Sensor mounted on an interposer for development purposes

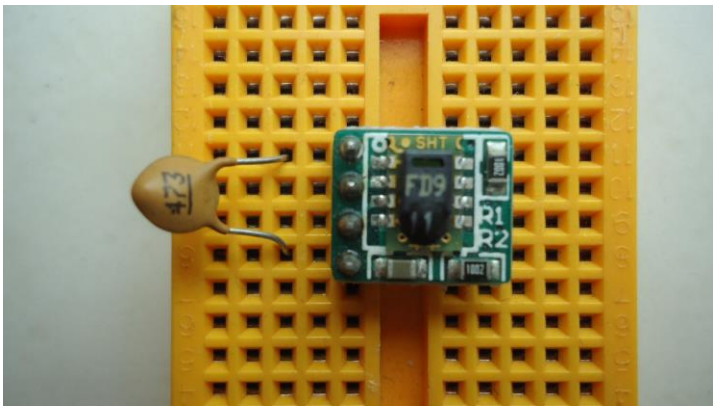

Figure 17. SHT11 Assembly mounted on a breadboard

4.2 EMBEDDED SOFTWARE IMPLEMENTATION

4.2.1 Development environment implementation

Software development environment is set-up following the steps:

a) Install MPLAB IDE (as said in previous sections, it is recommended for compatibility and portability purposes that MPLAB IDE legacy V8.90 is installed). All MPLAB tools can be downloaded directly from Microchip Inc. website www.microchip.com

b) Install CCS PICC Compiler, either full IDE version otherwise Line command version. Make sure that at least the **PCWH** family compiler is installed, and the installed version supports specifically the PIC18F46K22 and/or PIC18LF46K22 parts. CCS Compiler can be acquired from Custom Computer Services website www.ccsinfo.com

c) Install MPLAB IDE Plug in also from CCS Inc., make sure that plug in is installed prior to creating an MPLAB project based for the first time

d) Install MPLAB ICD3 Plug in also from CCS Inc., make sure that plug in is installed prior to creating an MPLAB project based for the first time whether developer will use any MPLAB commanded development tools (ICD2, ICD3, Pickit3, Real ICE, MP3 etc).

e) Create a new project in MPLAB IDE selecting 18LF46K22 as CPU, and CCS suite (PICC.exe) as tool suite.

f) If reusing software modules, make sure are selected when using the browser dialog window to select files to be included, otherwise simply let MPLAB create the project with no source files included, and add them later to project

g) In an open MPLAB IDE session configure, inside Project configuration menu, the linker path, the include files path and intermediate files path (object files). Make sure that linker file is the one provided by CCS Compiler and not the one from MPLAB installation.

h) Make sure that when using an ICD or a PICKit3 device as programmer, IDE is set as RELEASE, otherwise in debugging mode DEBUG should be selected

i) Make sure that, even though developer can have many tabs with source files open in a project, the only c source file in the Project Manager File tree is the main.c file, otherwise the build will contain errors and will not be completed. Header (.h) files, linker files (.lkr), assembly files and other files have no limitations to be included in Project manager tree window.

j) Make sure also that main.c file calls CPU header file to the CCS provided one and not the one provided by MPLAB IDE Installation

k) When using ICD3 as programmer debugger, remember that target board can be powered from debugger only if an external Power supply is attached to ICD3. For PICKit3 case, it is not necessary to attach an external power supply to power the target from PICKit3 while power demand is below limits. Also check always the right VCC level upon CPU selection.

4.2.1 Embedded software sections implementation

4.2.1.1 Main file (CO2_Synth_V20.c)

The main file is the axis for the application layer of embedded software. It contains the following elements:

a) Include handler level modules (.c) and headers (.h) for the main application layer
b) CPU & Peripherals initialization calls
c) RTOS Startup instructions & configuration

4.2.1.2 Main header file (CO2_Synth_V20.h)

This file will provide configuration for the following elements:

a) Program-time (flash) FUSES configuration such as: Oscillator configuration, Watchdog timer configuration, Memory zones protection configuration, Capture- Compare I/Os mapping, Brownout configuration, etc.

b) Application Macros & defines: I/Os alias

4.2.1.3 Driver for SHT11 Sensor (SHT11_Driver_V20.c/ SHT11_Driver_V20.h)

These files provide the basic software layer interface to control the SPI communications to and from SHT11 sensor.

4.2.1.4 SPI interface (4-wire) for SSD1306 chip (SPI_Driver_V20.c/ SPI_Driver_V20.h)

These files provide the basic software layer to interface the 4 line SPI bus to communicate to and from OLED controller chip (SSD1306).

4.2.1.5 Handler for SHT11 Sensor (SHT11_Handler_V20.c/ SHT11_Handler_V20.h)

These files provide the handler routines having SHT11 raw data as input:

a) Sensor SPI port initialization and configuration calls
b) SPI port Command processor
c) Temperature & Humidity readout management
d) Temperature & Humidity data compensation, linearization and conversion to readable characters
e) Dew point calculation
f) Floating point management routines

4.2.1.6 Handler for OLED display (OLED_Handler_V20.c/ OLED_Handler_V20.h)

These files provide the handler routines for displaying updated data and status onto OLED display.

4.2.1.7 OLED Display character map (OLED_Chartable_V20.h)

This file provides the dot matrix map for displaying readable characters in OLED Display

4.2.1.8 RTOS Tasks definition (CO2_Synth_Tasks_V20.c)

This file provides the code for each one of the implemented RTOS Tasks (425mS & 1700mS);

a) 425mS: Forced Heater handler
b) 1700mS: Periodic data samplig process

4.2.2 SHT11 Readout data Compensation & Linearization

As said previously, incoming data from SHT11 sensor needs to undergo both compensation and linearization procedures since readouts are affected by Temperature intrinsically as shown in the following charts:

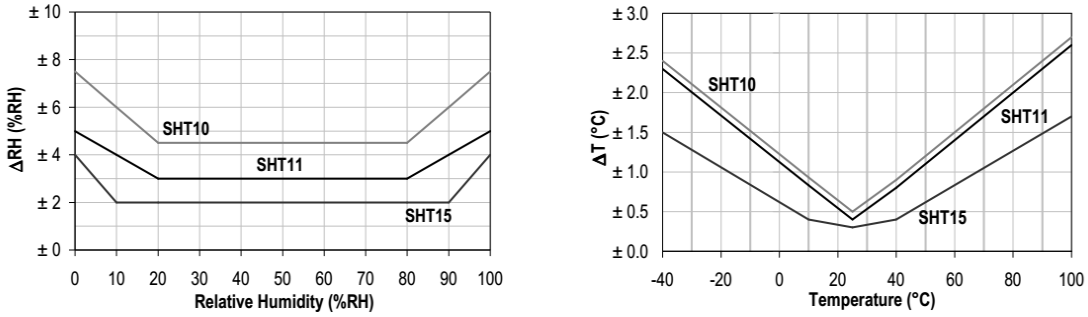

Figure 18. SHT11 Sensor normalization curves affected by T & RH%

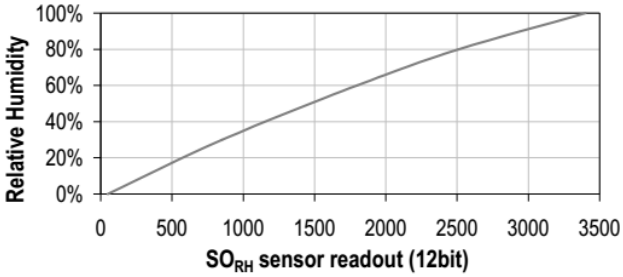

Figure 19. SHT11 Sensor transfer function for RH% Readout

4.2.2.1 Temperature compensation

Despite Proportional to Absolute (PTAT) bandgap temperature sensor is very linear, best accuracy is achieved using the following equation and coefficients:

$$T = d_1 + d_2 \cdot SO_T$$

Where:

T= Compensated Temperature readout
SO_T= "Raw" Sensor temperature readout
d1= Compensation offset depending on Voltage supply to sensor
d2= Compensation slope coefficient depending on readout selected resolution

Table 5. SHT11 Temperature compensation coefficients upon VDD and resolution

VDD	d_1 (°C)	d_1 (°F)
5V	-40.1	-40.2
4V	-39.8	-39.6
3.5V	-39.7	-39.5
3V	-39.6	-39.3
2.5V	-39.4	-38.9

SO_T	d_2 (°C)	d_2 (°F)
14bit	0.01	0.018
12bit	0.04	0.072

4.2.2.2 RH% linearization

Table 6. SHT11 RH% Linearization coefficients upon resolution

$$RH_{linear} = c_1 + c_2 \cdot SO_{RH} + c_3 \cdot SO_{RH}^{\ 2} \ (\%RH)$$

SO_{RH}	c_1	c_2	c_3
12 bit	-2.0468	0.0367	-1.5955E-6
8 bit	-2.0468	0.5872	-4.0845E-4

Where:

RH_{linear}= Linearized RH% Readout
SO_{RH}= "Raw" Sensor RH% readout
C1= Compensation offset depending on readout selected resolution
C2= Compensation slope linear coefficient depending on readout selected resolution
C3= Compensation slope quadratic coefficient depending on readout selected resolution

4.2.2.3 RH% true readout compensation

Table 7. SHT11 RH% True readout coefficients upon resolution

$$RH_{true} = (T_{°C} - 25) \cdot (t_1 + t_2 \cdot SO_{RH}) + RH_{linear}$$

SO_{RH}	t_1	t_2
12 bit	0.01	0.00008
8 bit	0.01	0.00128

Where:

RH_{true}=	Compensated RH% Readout
SO_{RH}=	"Raw" Sensor RH% readout
RH_{LINEAR}=	Linearized RH% readout
$T_{°C}$=	Compensated Temperature readout
t1=	Compensation offset depending on readout selected resolution
t2=	Compensation slope linear coefficient depending on readout selected resolution

4.2.3 Dew Point calculation

The following formula (Magnus formula) provides a good approximation for a Dew point calculation, once both Temp and RH% have been readout, linearized and compensated:

$$T_d(RH,T) = T_n \cdot \frac{\ln\left(\frac{RH}{100\%}\right) + \frac{m \cdot T}{T_n + T}}{m - \ln\left(\frac{RH}{100\%}\right) - \frac{m \cdot T}{T_n + T}}$$

Table 8. Dew Point Calculation Magnus formula coefficients upon Temp range

Temperature Range	Tn (°C)	m
Above water, 0 – 50°C	243.12	17.62
Above ice, -40 – 0°C	272.62	22.46

Where:

Td(RH,T) =	Dew point temperature
T =	Compensated temperature readout (dry bulb temperature)

5. RESULTS

5.1.0 Embedded System solution

As described previously, the Project hardware solution is composed by

A) PIC18LF4646K22 Development board system
B) Temperature and RH% sensor chip + interface system
C) Gas intake and Cooling solution I/O drivers

For the sake of the solution and the timeline availability, section C) was not physically implemented but only signaled using LEDs in the dev board. It is convenient to remark that for experimentation purposes, an external portable cellphone battery backup was used as power supply, an adapted USB to 2.1mm inverted plug connector was also implemented.

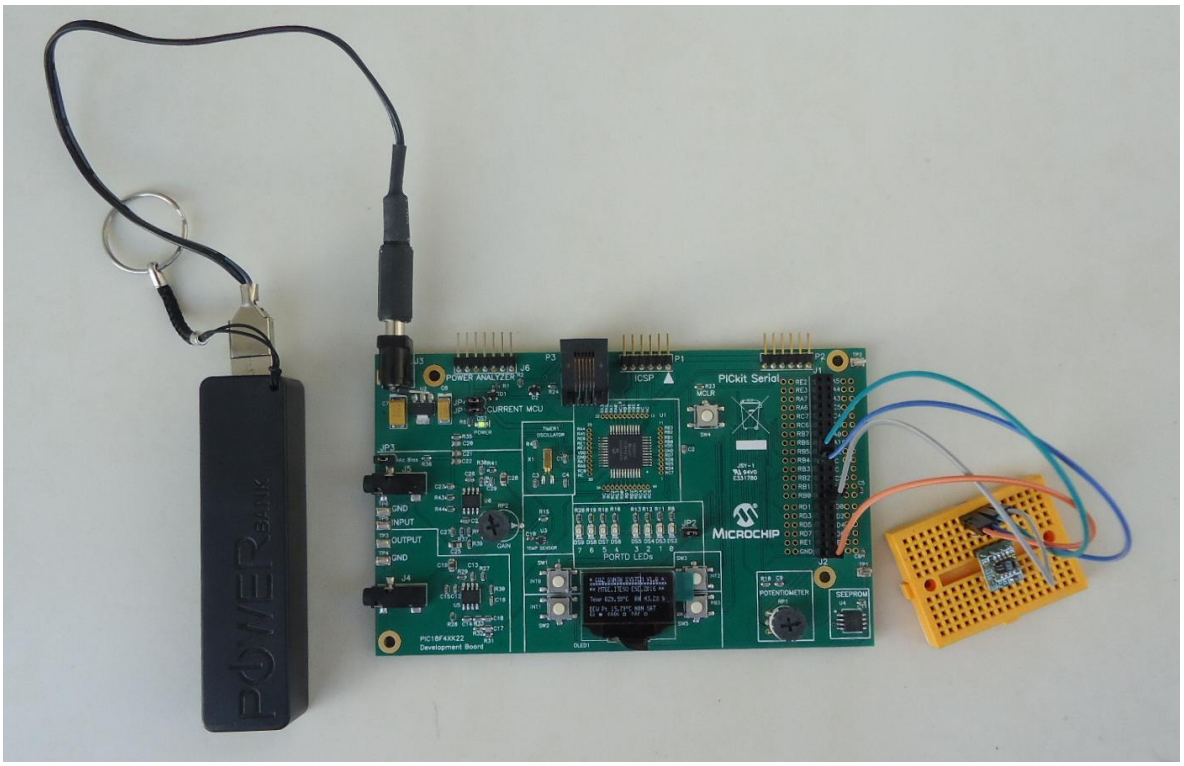

Figure 20. Project minimum system: Dev board, sensor breadboard and portable power supply

5.1.1 I/O basic testing

As a preliminary functional testing, the system was exposed to the following conditions:

A) Measuring room temperature and RH% at any given date/ time. Expected results are
0°C < Temp < 42°C (baseline is temp in Guadalajara, Jalisco México)
20% < RH < 80%
No desaturation indication
No forced desaturation activation

B) Soaking system inside a freezer for 10 mins and taking immediate readings and I/O state. Expected results are:
-10°C < Temp < 5°C
20% < RH < 80%
If RH > 85%, desaturation indication and activation shall be true

C) Waiting other 30 mins to await for system to complete the desaturation cycle and reach again the room conditions

D) Forced heating using INT0 shall provoke that system starts reading out temperature increase aside RH% decrease

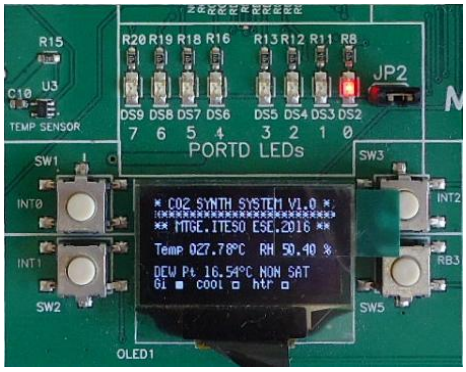

Figure 21. System operating "soaked" at room Temp and room RH% (baseline)

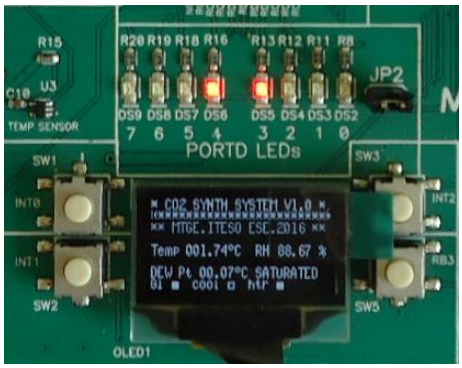

Figure 22. System operating as soon as removed from freezer: Heater ON, SAT indicator ON

Figure 23. System captured 5 mins later: Temp increasing and RH% decreasing

Figure 24. System at 30 mins later: Room temp reached, nominal RH% reached, DESAT OFF

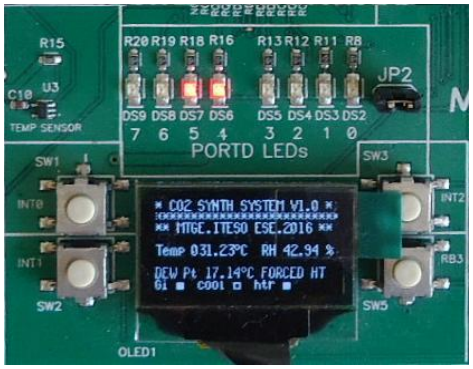

Figure 25. DESAT enforced test: Temperature readout increased, RH% readout decreased

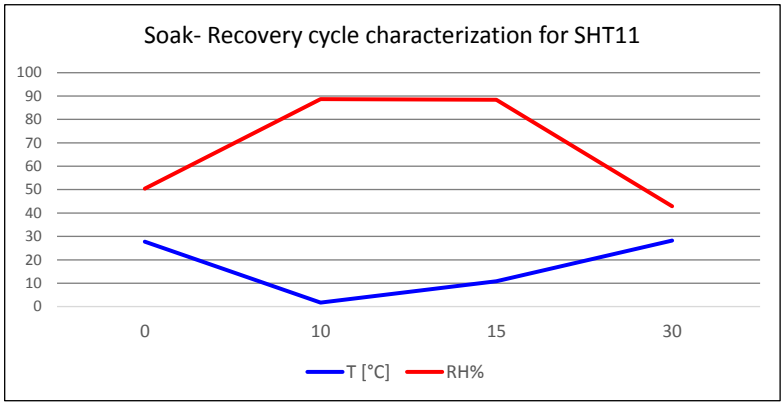

Figure 26. Basic I/O Testing numeric results

5.1.2 Sample measurements taken & dew point modeling

DUT was subject of daily measurements through the month of February 2016 (winter season) In order to detect whether worst cases in early morning (where temp is lower and RH is high) and determine operational range for Peltier cells array.

Table 9. Sample Temp & RH% Readings taken during Feb 2016

DATE	HOUR	TEMP [°C]	RH%	DP [°C]	ΔT [°C]
2-Feb	6:25	8.85	28.33	-8.55	-17.4
3-Feb	6:32	6.12	32.25	-9.28	-15.4
4-Feb	6:30	9.11	31.12	-7.12	-16.23
5-Feb	6:21	5.55	28.03	-11.55	-17.1
6-Feb	8:00	14.22	39.22	0.52	-13.7
7-Feb	10:25	19.12	42.32	5.82	-13.3
8-Feb	6:24	8.55	19.11	-13.75	-22.3
9-Feb	6:33	13.24	28.22	-4.79	-18.03
10-Feb	6:20	7.21	34.02	-7.58	-14.79
11-Feb	6:24	6.55	22.00	-13.61	-20.16
12-Feb	6:30	12.34	52.33	2.89	-9.45
13-Feb	10:25	17.55	45.55	5.66	-11.89
14-Feb	11:55	21.12	42.34	7.83	-13.29
15-Feb	6:28	12.53	36.78	-1.92	-14.45
16-Feb	6:34	14.55	39.28	0.91	-13.64
17-Feb	6:19	15.28	33.42	-0.74	-16.02
18-Feb	6:22	14.26	28.97	-3.48	-17.74
19-Feb	6:32	12.33	41.11	-0.43	-12.76
20-Feb	14:29	27.65	58.67	18.78	-8.87
21-Feb	11:42	19.23	49.44	8.45	-10.78
22-Feb	6:19	8.65	36.42	-5.39	-14.04
23-Feb	6:17	15.34	53.41	5.88	-9.46
24-Feb	6:28	13.23	64.56	6.71	-6.52
25-Feb	6:22	12.08	53.33	2.9	-9.18
26-Feb	6:15	12.51	39.88	-0.82	-13.33
27-Feb	10:13	21.98	68.22	15.79	-6.19
28-Feb	12:18	23.74	76.32	19.33	-4.41
29-Feb	6:23	12.50	54.55	3.64	-8.86

Results follow:
Where:
DP = Calculated Dew point to enforce humidity condensation at sampled weather conditions
ΔT = Temperature decrease needed to reach the calculated Dew point.

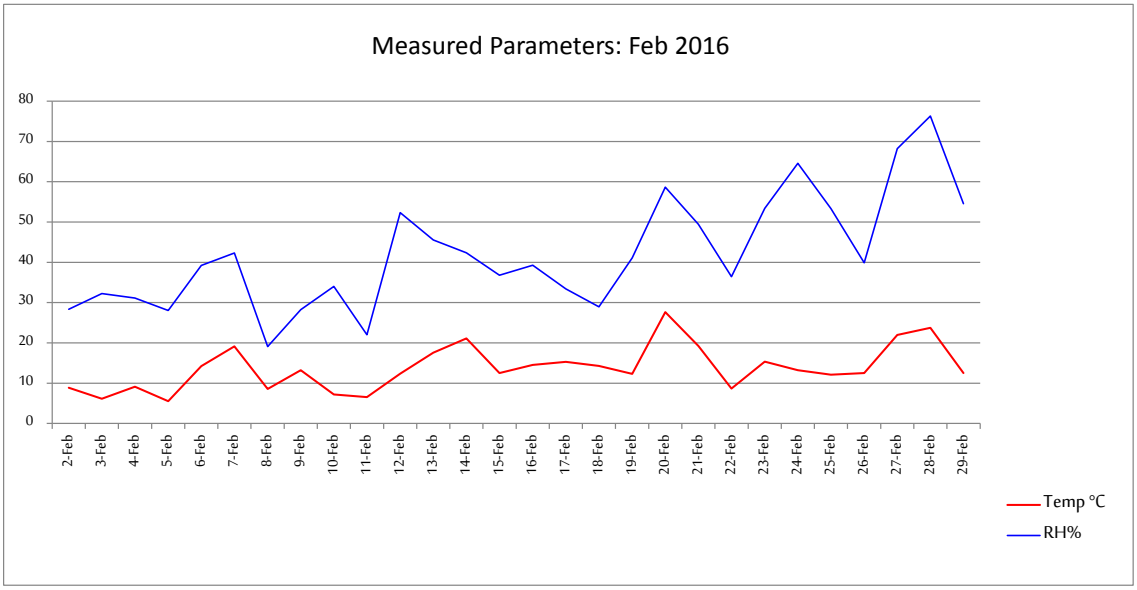

Figure 27. Sample readouts plot: February 2016

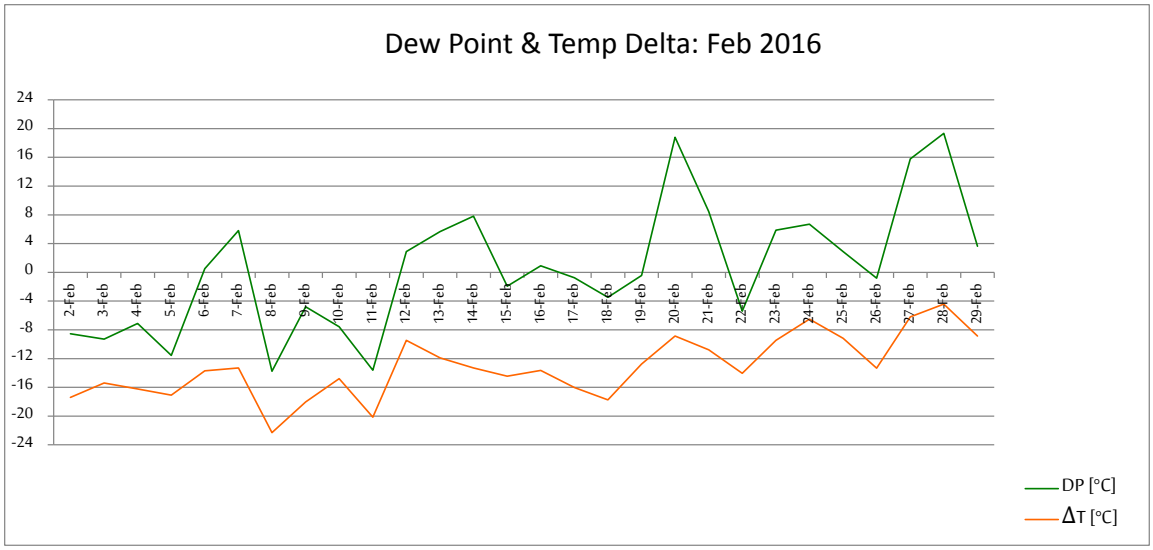

Figure 28. Calculated Dew point and needed temperature deltas for sample measurements

6. CONCLUSIONS

6.1. Conclusions

6.1.1.- Original scope of the project was to reach the stage of a working functional prototype, including, potentially, a way of getting electrical power without intrusion such as implementing a solar panel as an external accessory. It was unfeasible to accomplish the full envisioned scope due to some factors that were not identified at the start of the project, however this shortfall provided some learning for future project planning exercises. Some of the factors hence listed:

a) High cost of physical components such as the Peltier cells array otherwise another cooling solution for enforcing a dew point, Gas intake valve, chemical reservoir, etc.

b) Restrictions on the development board to provide the sufficient power to drive actuators: Valves typically require 2-5 amps to excite DC coils; sized Peltier cells require more than 2 amps to get energized, etc.; thus a non-scoped power driver section needs to be designed and implemented.

c) It got unfeasible to plan on a non-intrusive power supply system due to the big size of the solar panels that would be needed to provide the amount of power needed by system.

d) Chemical reservoir deserves a further detailed study, design and modeling of the solution in order to produce a working prototype, aside thinking on a solution that with minor modifications can be implemented as an aftermarket solution for vehicles, otherwise a factory-time solution.

6.1.2. - In the original concept, just a cold-producing device was considered, thus, a "fixed" single driver connection to the Peltier cells array was considered, and a simple ON/OFF Control scenario was envisioned. After doing the sampling of temperature and RH% readouts in the month of February, was found out that when the temperature falls below the water freezing point and, by hysteresis below triple point (4°C), a Cooling device does no longer work to enforce humidity condensation, so the solution in turn is a reverse connected Peltier cell otherwise now a heating device (such as a resistor) in order to reciprocally enforce a dew point in the humidity reservoir. This means a future new sizing of temperature management solution, aside a polarity inverting scheme in the development board (i.e. two driver outputs instead of a single one). Aside implementing an hysteresis algorithm in software in order to let the system produce heat between a DP less equal 0°C and 4°C, and cold above such point.

6.1.3. - Several dew point calculation methods were found. Actually, however, the best and most accurate method found depends entirely only on RH% and ambient temperature readouts and results to be Magnus formula. Below are the 4 most used methods which were evaluated prior to their implementation in the firmware, Table 8 depicts the results for the test cases so, the conclusion leaded to select Magnus formula.

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Dew point calculation interactive formulas and website, available at : http://www.ajdesigner.com/phphumidity/dewpoint_equation_dewpoint_temperature.php

APENDIX A. SHT11_Driver_V20.c

```
/*********************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ****/
/*********************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*********************************************************/
/*** DESCRIPTION: SENSIRION SHT11 SENSOR BASIC DRIVER **/
/*********************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      FEB 12,2016      ****/
/*********************************************************/

#include "SHT11_Driver_V20.h"            /**** Source Header ****/

/************************************************/
/** brief    SHT11 Sensor Warmup Timer         **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SHT11_Setup_Time(void)
{
      Output_LOW(SCK);        /** Bus initial conditions **/
      Output_HIGH(SDATA);
      Delay_mS(WARMUP_TIME);  /** Hardware warmup timer  **/
}

/************************************************/
/** brief    SHT11 Sensor Transmission Start   **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SHT11_XM_Start(void)
{
      Output_HIGH(SDATA);
      Delay_uS(1);
      Output_HIGH(SCK); /*** First SCK Pulse rise    *****/
      Delay_uS(1);
      Output_LOW(SDATA);     /*** Start DATA fall (BEGIN) ****/
      Output_LOW(SCK);  /*** First SCK Pulse fall    *****/
      Delay_uS(1);
      Output_HIGH(SCK); /*** Second SCK Pulse rise ******/
      Delay_uS(1);
      Output_HIGH(SDATA);    /*** Start DATA rise (CLOSE) ****/
      Output_LOW(SCK);  /*** Second SCK Pulse fall ******/
      Delay_uS(1);
}
```

```
/************************************************/
/** brief    Send an 8 Bit word to Sensor bus  **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    SHT_WR_Word: Word to be written   **/
/** return   void                              **/
/************************************************/
void SHT11_Wrd_Send(int8 SHT_WR_word)
{
      int1 Cmd_MSBit;               /* CMD More Sig bit          */
      int8 WRT_Byte=SHT_WR_word;    /* Backup WR Cmmd word  */
      int8 i;                       /* Iteration variable   */

      for(i=0;i<=7;i++)             /* 8 Bit Looper              */
      {
            Cmd_MSBit=BIT_Test(WRT_Byte,7);/** Tst Cmd MSB **/
            if(Cmd_MSBit)
                  Output_HIGH(SDATA);     /**** MSB= 1 ****/
            else
                  Output_LOW(SDATA);            /**** MSB =0 ****/
            SHT11_Clock_Pulse();                /** SCK Pulse ***/

            Rotate_LEFT(&WRT_Byte,1);           /*** Next MSB ***/
      }
      Output_FLOAT(SDATA);                      /** ACK Pulse ***/
      SHT11_Clock_Pulse();
}

/************************************************/
/** brief    Read an 8 Bit word from Sensor bus**/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   SHT11_Read: 8 Bit read word       **/
/************************************************/
int8 SHT11_RDByte(void)
{
      int1 SDATA_Test=0;            /** Probe BIT                 */
      int8 SHT11_Read=0x00;         /** RD Byte                   */
      int8 j=0;                     /** Iteration variable  */

      Output_FLOAT(SDATA);          /** SDATA= Input  *****/
      Delay_uS(1);
      for(j=0;j<=7;j++)             /** 8 Bit Looper        */
      {
            Output_HIGH(SCK);                   /** Clock= Rise **/
            Delay_uS(1);
            SDATA_Test= Input(SDATA);           /** Read SDATA ***/
            Output_LOW(SCK);
            if(SDATA_Test)
                  SHT11_Read=SHT11_Read|RD_HIGH;/** RD BIT=1     **/
            else
                  SHT11_Read=SHT11_Read&RD_LOW; /** RD BIT=0     **/
            if(j!=7)
                  Rotate_LEFT(&SHT11_Read,1);    /** Next BIT    **/
      }
```

```
      Output_LOW(SDATA);                        /** ACK Sequence */
      Delay_uS(1);
      Output_HIGH(SCK);                         /** ACK Pulse    **/

      Delay_uS(2);
      Output_LOW(SCK);
      Delay_uS(1);
      Output_FLOAT(SDATA);                      /** Release SDATA */
      return SHT11_Read;
}

/************************************************/
/** brief    Dummy checksum processor          **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SHT11_Dummy_Chksm(void)
{
      int8 k;
      Output_Float(SDATA);                      /** Release DATA */
      for(k=0;k<=8;k++)
            SHT11_Clock_Pulse();                /** 9 Dummy SCKs */
}                                               /** Include ACK  **/

/************************************************/
/** brief    Issue a bus clock pulse in SCK line**/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SHT11_Clock_Pulse(void)
{
      Output_HIGH(SCK);                         /** Rise edge    **/

      Delay_uS(2);
      Output_LOW(SCK);                          /** Fall edge    **/
      Delay_uS(2);
}

/************************************************/
/** brief    Hold until SDATA line is released **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SHT11_Probe_SDATA_Free(void)
{
      int1 Probe_SDATA=0;
      while(!Probe_SDATA)                       /** Test DATA Release **/
            Probe_SDATA=Input(SDATA);
}
```

```
/************************************************/
/** brief    Await TEMP / RH measurement time  **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SHT11_Wait_Measure(int8 SH_Param)
{
      int8 Sel_resolution;
      int1 Test_SDATA=1;
      switch(SH_Param)
      {
            /***** TEMPERATURE MEASUREMENT TIMER *****/
            case TEMP:
                  Sel_resolution= SHT_Cfg_Wd&0x01;/** Mask Resl Bit  **/
                  if(Sel_Resolution==0x01)
                        Delay_mS(LO_T_MEAS);    /** LOW Res Temp   **/
                  else
                        Delay_mS(HI_T_MEAS);    /** HIGH Res Temp  **/
                  Output_FLOAT(SDATA);          /** Release SDATA  **/
                  while(Test_SDATA)             /** Wait until EOC **/
                         Test_SDATA=Input(SDATA);/** Test SDATA Line */
            break;

            /*** RELATIVE HUMIDITY MEASUREMENT TIMER **/
            default:
                  Sel_resolution= SHT_Cfg_Wd&0x01;/** Mask Resl Bit  **/
                  if(Sel_Resolution==0x01)
                        Delay_mS(LO_RH_MEAS);   /** LOW Res RH       **/
                  else
                        Delay_mS(HI_RH_MEAS);   /** HIGH Res RH    **/
                  Output_FLOAT(SDATA);          /** Release SDATA  **/
                  while(Test_SDATA)             /** Wait until EOC **/
                         Test_SDATA=Input(SDATA);/** Test SDATA Line */
            break;
      }
```

APENDIX B. SHT11_Driver_V20.h

```
/*********************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM ****/
/*********************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*********************************************************/
/*** DESCRIPTION: SENSIRION SHT11 SENSOR DRIVER HEADER */
/*********************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      FEB 12,2016      ****/
/*********************************************************/

/********** HW INTERFACE PINOUT ASSIGNMENTS    ******/
#define SCK             PIN_B4      /* SERIAL CLOCK LINE */
#define SDATA           PIN_B5      /* SERIAL DATA LINE  */

/********** DRIVER CONSTANTS & MACROS ****************/
#define WARMUP_TIME 0x0C      /** Sensor warmup time   */
#define EDGE_TIME 0X01        /** Protocol pulse timer */
#define RD_LOW          0xFE  /** Mask for & low       **/
#define RD_HIGH         0x01  /** Mask for | high     **/
#define LO_RH_MEAS      20    /** 8  Bit RH Meas time **/
#define LO_T_MEAS 80          /** 12 Bit T Meas Time  **/
#define HI_RH_MEAS      80    /** 12 Bit RH Meas time **/
#define HI_T_MEAS 320         /** 14 Bit T Meas Time  **/

/************** FUNCTIONS PROTOTYPES *****************/

void SHT11_Clock_Pulse(void); /** Issue SCK Pulse **/
void SHT11_XM_Start(void);
void SHT11_Wrd_Send(int8 SHT_WR_word);
void SHT11_Wait_Measure(int8 SH_Param);
int8 SHT11_RDByte(void);
void SHT11_Dummy_Chksm(void);
void SHT11_Probe_SDATA_Free(void);
void SHT11_Setup_Time(void);
```

APENDIX C. SPI_Driver_V20.c

```
/*******************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ***/
/*******************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*******************************************************/
/*** DESCRIPTION: SSD1306 OLED-4 WIRE SPI BASIC DRIVER */
/*******************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      FEB 12,2016       ***/
/*******************************************************/

#include "SPI_Driver_V20.h"

/************************************************/
/** brief    SPI RESET Sequence                **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SPI_Reset(void)
{
      Output_LOW(SPI_RES);
      Delay_uS(50);
      Output_HIGH(SPI_RES);
      OLED_CTRL;
      SPI_CS_Enabled;
      SPI_Write(DISPLAY_OFF); /*** DISPLAY OFF ****/
      SPI_CS_Disabled;
}

/************************************************/
/** brief    SPI OLED Initialization Sequence  **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SPI_OLED_Init(void)
{
      SPI_CS_Enabled;
      OLED_CTRL;

      SPI_Write(OLED_CLK_DIV);  /** Clock Divider **/
      SPI_Write(K_CLK_DIV);

      SPI_Write(OLED_MUX_RATIO);/* Multiplx Ratio **/
      SPI_Write(K_MUX_RATIO);

      SPI_Write(OLED_DISP_OFST);/* Display Offset **/
      SPI_Write(K_DISP_OFST);
```

```
        SPI_Write(OLED_STRT_L0);  /** Start Line 0  **/

        SPI_Write(OLED_CH_PUMP);  /** Charge Pump ON */
        SPI_Write(K_CH_PUMP_ON);

        SPI_Write(OLED_ADRS_MOD); /* Addrs= Page Mode*/
        SPI_Write(K_PAGE_MODE);

        SPI_Write(OLED_REMAP_ON);/*** Remap enabled **/

        SPI_Write(COMSCN_NORMAL);/** COM Scan Normal**/

        SPI_Write(OLED_COM_HW);  /** COM HW Cfg= Alt**/
        SPI_Write(K_ALTERNATE);

        SPI_Write(OLED_CONTRAST);/*** Contrast set ***/
        SPI_Write(K_CONTRST_SET);

        SPI_Write(OLED_PRECHARG);/*** Prechrg Period**/
        SPI_Write(K_PRECHRG_PER);

        SPI_Write(OLED_VCOM_DES);/*** VCOM Desel Level*/
        SPI_Write(K_VCOM_DES_LV);

        SPI_Write(OLED_NINVERSE);/*** Inverse OFF   ***/

        SPI_Write(OLED_YESRAM);  /*** Start with RAM***/

        SPI_Write(DISPLAY_ON);   /*** Display ON    ***/

        SPI_CS_Disabled;
}
```

APENDIX D. SPI_Driver_V20.h

```
/*********************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ****/
/*********************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*********************************************************/
/*** DESCRIPTION: SSD1306 OLED BASIC DRIVER HEADER     **/
/*********************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      FEB 12 2016       ****/
/*********************************************************/

/********** HW INTERFACE PINOUT ASSIGNMENTS    ******/
#define SPI_SCLK  PIN_C3      /* SPI Clock Line        */
#define SPI_SDIN  PIN_C5      /* SPI Data IN Line      */
#define SPI_DC          PIN_A5      /* DATA/CONTROL Line */
#define SPI_RES         PIN_A4      /* RESET Signal          */
#define SPI_CS          PIN_A7      /* Chip Select Signal*/

#define OLED_CTRL       Output_LOW(SPI_DC)
#define OLED_DATA       Output_HIGH(SPI_DC)
#define SPI_CS_Enabled  Output_LOW(SPI_CS)
#define SPI_CS_Disabled Output_HIGH(SPI_CS)

/********** OLED DRIVER CONFIG DEFINITIONS *******/

/**** Clock divider *****/
#define OLED_CLK_DIV    0xD5
#define K_CLK_DIV       0x80

/**** Multiplex ratio***/
#define OLED_MUX_RATIO  0xA8
#define K_MUX_RATIO     0x3F

/**** Display Offset ***/
#define OLED_DISP_OFST  0xD3
#define K_DISP_OFST     0x00

/**** Start Line  ******/
#define OLED_STRT_L0    0x40

/**** Charge Pump ******/
#define OLED_CH_PUMP    0x8D
#define K_CH_PUMP_ON    0x14

/**** Address Mode ******/
#define OLED_ADRS_MOD   0x20
#define K_PAGE_MODE     0x02
```

```
/**** Remap mode ********/
#define OLED_REMAP_ON   0xA1


/**** COM Scan dir ******/
#define COMSCN_NORMAL   0xC0

/**** COM HW CONFIG *****/
#define OLED_COM_HW     0xDA
#define K_ALTERNATE     0x12

/**** CONTRAST SETTING **/
#define OLED_CONTRAST   0x81
#define K_CONTRST_SET   0xB0

/**** PRECHARGE PERIOD **/
#define OLED_PRECHARG   0xD9
#define K_PRECHRG_PER   0xF1

/**** VCOM DESELECT LEV */
#define OLED_VCOM_DES   0xDB
#define K_VCOM_DES_LV   0x20

/**** INVERSE MODE ******/
#define OLED_NINVERSE   0xA6

/**** RAM AT STARTUP ****/
#define OLED_YESRAM     0xA4

/** OLED POWER CONTROL **/
#define DISPLAY_ON      0xAF
#define DISPLAY_OFF     0xAE

/********** DRIVER CONSTANTS DEFINITION **********/
#define DSP_OFF         0xAF  /* Display Reset CMD */
#define CTRL            0x00  /* Control command  **/
#define DAT             0x01  /* Data Disp command */
#define Tsetup          0x05  /* Data setup uS time*/
#define Tclk            0x05  /* Tclock           **/
#define RSTTMR          0x20  /* uS SPI RESET Time */

/************** FUNCTIONS PROTOTYPES **************/
void SPI_Reset(void);         /* OLED SPI Modl Rst */
void SPI_OLED_Init(void);     /* OLED Initialize  **/
```

APENDIX E. SHT11_Handler_V20.c

```
/*********************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ****/
/*********************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*********************************************************/
/*** DESCRIPTION: SENSIRION SHT11 SENSOR HANDLER FILE **/
/*********************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      FEB 12,2016       ****/
/*********************************************************/

#include "SHT11_Handler_V20.h"      /** Source Header **/
#include "SHT11_Driver_V20.c"       /** BSW Layer       **/
#include "math.h"                   /** Math std libr **/

int1 desat_active= FALSE;           /** Htr resistor ***/

/************************************************/
/** brief    Sensor saturation handler routine **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SHT11_Saturation_Chk(void)
{
/***************** RH >= UPPER LIMIT ? *************/
      if((DRHTrue[1]>=DEC_SAT_ULIM)&&(DRHTrue[2]>=UNT_SAT_ULIM))
      {
            Output_HIGH(LED_SATURTD);     /** Flag Saturation **/
            if(!desat_active)
            {
                  SHT11_Command(CMD_ACT_DESAT);
                  desat_active=TRUE;
            }
      }
/****************** RH <= LOW LIMIT ? *************/
      else
      {
            if((DRHTrue[1]<=DEC_SAT_LLIM)&&(DRHTrue[2]<=UNT_SAT_LLIM))
            {
                  Output_LOW(LED_SATURTD);      /* Flag Non Saturation */
                  if(desat_active)
                  {
                        SHT11_Command(CMD_DIS_DESAT); /** Turn HTR off */
                        desat_active=FALSE;           /** Clear flag  **/
                  }
            }
      }
}
```

```
/************************************************/
/** brief    SHT11 Sensor Initialization       **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SHT11_Init(void)
{
      SHT11_Setup_Time();
}

/************************************************/
/** brief    SHT11 Sensor configuration loading**/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void SHT11_Config_Load(void)
{
      SHT_Cfg_Wd =  Stat_Cfg_Wd;    /** Load baseline word **/
      SHT_Cfg_Wd |= Stat_Hi_Res;    /* Cfg: Meas Resolution */
      SHT_Cfg_Wd |= Stat_OTP_Reld;  /* Cfg: OTP Cal Reload  */
      SHT_Cfg_Wd &= Stat_Heat_OFF;  /* Cfg: Heater          */
}

/************************************************/
/** brief    SHT11 Sensor Command Processor    **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    SHT_Command: 8 Bit command        **/
/** return   void                              **/
/************************************************/
void SHT11_Command(int8 SHT_Command)
{
      switch(SHT_Command)
      {
            /**** Command: TEMP MEASURE ***/
            case CMD_RD_Temp:
                              SHT11_XM_Start();       /* Start Xmission */
                              SHT11_Wrd_Send(SHT_Tmp_Meas); /* Send Meas
Cmmd */
                              SHT11_Wait_Measure(TEMP);/* Sensor measure
*/
                              SOT_MSB=SHT11_RDByte(); /* Read SOT MSByte*/
                              SOT_LSB=SHT11_RDByte(); /* Read SOT LSByte*/
                              SOT16=SOT_MSB<<8;       /* Compose SOT16 **/
                              SOT16=SOT16|SOT_LSB;
                              SHT11_Dummy_Chksm();    /* Dummy chksum  **/
                              Calc_SOT_2_Float();     /* SOT 2 Float **/
                              Calc_Temp4Disp();       /* Get Displayable*/
                              break;
```

```
            /**** Command: RH% MEASURE ****/
            case CMD_RD_RH:
                                SHT11_XM_Start();       /* Start Xmission */
                                SHT11_Wrd_Send(SHT_RH_Meas);  /* Send Meas
Cmmd */
                                SHT11_Wait_Measure(RH); /* Sensor measure */
                                SORH_MSB=SHT11_RDByte();/* RD SORH MSByte */
                                SORH_LSB=SHT11_RDByte();/* RD SORH LSByte */
                                SORH16= SORH_MSB<<8;    /* Compose SORH16 */
                                SORH16= SORH16|SORH_LSB;
                                SHT11_Dummy_Chksm();    /* Dummy chksum  */

                                Calc_SORH_2_Float();    /* SORH 2 Float  **/
                                Calc_RH4Disp();         /* Get Displayable*/
                                break;

            /**** Command: WRITE STATUS ***/
            case CMD_WR_Status:
                                SHT11_XM_Start();       /* Start Xmission
      */
                                SHT11_Config_Load();/* Ld config params */
                                SHT11_Wrd_Send(SHT_WR_Stat);/* Write STATUS
Cmd */
                                SHT11_Wrd_Send(SHT_Cfg_Wd);/* Write CFG word
      */
                                break;


            /**** Command: READ STATUS ****/
            case CMD_RD_Status:
                                SHT11_XM_Start(); /* Start Xmission       */
                                SHT11_Wrd_Send(SHT_RD_Stat);/* Read STATUS
Cmd   */
                                RD_Status=SHT11_RDByte();/* Execute STATUS
RD*/
                                SHT11_Dummy_Chksm();/* Bypass Checksum   */
                                break;

            /**** Command: ACTIV DESAT ***/
            case CMD_ACT_DESAT:
                                SHT11_XM_Start(); /* Start Xmission       */
                                SHT_Cfg_Wd |=Stat_Heat_ON;  /** Enable
Heater ***/
                                SHT11_Wrd_Send(SHT_WR_Stat);/* Write STATUS
Cmd */
                                SHT11_Wrd_Send(SHT_Cfg_Wd);  /* Write CFG
word  */
                                break;
```

```
                  /**** Command: ACTIV DESAT ***/
            case CMD_DIS_DESAT:
                              SHT11_XM_Start(); /* Start Xmission      */
                              SHT_Cfg_Wd &=Stat_Heat_OFF; /** Disable
Heater **/
                              SHT11_Wrd_Send(SHT_WR_Stat);/* Write STATUS
Cmd */
                              SHT11_Wrd_Send(SHT_Cfg_Wd);   /* Write CFG
word  */
                              break;

            /**** Command: SOFT RESET *****/
            default:          SHT11_XM_Start();
                              SHT11_Wrd_Send(SHT_Soft_RST);
                              Delay_mS(WARMUP_TIME);
                              SHT11_Probe_SDATA_Free();
                              break;
      }
}

/************************************************/
/** brief    SOT (Readout) to Float T°C Convert**/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Calc_SOT_2_Float(void)
{
      float d1f=0;                  /** Float constants **/
      float d2f=0;

      if(SHT_Cfg_Wd & (0x01))       /** LOW Res Constant **/
            d2f=d2L;
      else                          /** HIGH Res Constant**/
            d2f=d2H;
      d1f= d1;
      F_Temp=(d2f*SOT16)+d1f;       /** T°C= d2(SOT)+d1  **/
}

/************************************************/
/** brief    SORH (Readout) to Float RH% Convert**/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Calc_SORH_2_Float(void)
{
      float C1f=0;                        /** Float constants ***/
      float C2f=0;
      float C3f=0;
      float t1f=0;
      float t2f=0;
```

```
      if(SHT_Cfg_Wd & (0x01))       /** LOW Res Constants */
      {
            C2f=C2L;
            C3f=C3L;
            t2f=t2L;
      }
      else                          /** HIGH Res Constants*/
      {
            C2f=C2H;
            C3f=C3H;
            t2f=t2H;
      }
      C1f=C1;                       /*** C1 loading     ***/
      t1f=t1;                       /*** t1 Loading     ***/

      /***** CALCULATION OF LINEARIZED RH% **************/
      f_RH_Lin=(C3f*(pow(SORH16,2)))+(C2f*SORH16)+C1f;

      /******* CALCULATION OF TEMP COMP RH% *************/
      f_RH_True=((F_temp-25)*((t2f*SORH16)+t1))+f_RH_Lin;
}

/************************************************/
/** brief    Get Displayable Temp Digits       **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    Raw SOT Temperature               **/
/** return   void                              **/
/************************************************/
void Calc_Temp4Disp(void)
{
   char Tdigit;                     /** iteration digit     **/
   int16 Tdivisor;                  /** operation divisor*/
   int16 Casttemp;
   char Tdisp_digit;                /** displayable digit*/
   char i;                          /** iteration var **/

   Tdivisor= THRdiv;
   Casttemp= (int16)(f_Temp*100);

   for(i=0;i<5;i++)
      {
      Tdigit = Casttemp/Tdivisor;
      Casttemp-=Tdigit*Tdivisor;
      Tdivisor/=10;
      Tdisp_digit=Tdigit+'0';
      Dtemp[i]=Tdisp_digit;  /* Record Disp digits */
      }
}
```

```
/************************************************/
/** brief    Get Displayable RH Digits         **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Calc_RH4Disp(void)
{
   int16 RHdivisor;          /** operation divisor*/
   int16 CastRH;             /** Cast RH variable */
   char RHdigit;             /** iteration digit **/
   char RHdisp_digit;        /** displayable digit*/
   char i;                   /** iteration var   **/

/************ Linearized RH Calculation *****/
   RHdivisor= RHdiv;
   CastRH=(int16)(f_RH_Lin*100);

   for(i=0;i<5;i++)
      {
      RHdigit = CastRH/RHdivisor;
      CastRH-= RHdigit*RHdivisor;
      RHdivisor/=10;
      RHdisp_digit=RHdigit+'0';
      DRHLin[i]=RHdisp_digit;/* Record Disp digits */
      }

/************* True RH Calculation *********/
   RHDivisor= RHDiv;
   CastRH= (int16)(f_RH_True*100);

   for(i=0;i<5;i++)
      {
      RHdigit = CastRH/RHdivisor;
      CastRH-= RHdigit*RHdivisor;
      RHdivisor/=10;
      RHdisp_digit=RHdigit+'0';
      DRHTrue[i]=RHdisp_digit;/* Record Disp digits */
      }
}
```

```
/************************************************/
/** brief    Calculate DP from Temp & RH%      **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Calc_DewPoint(void)
{
      float logfactor;
      float tempfactor;

      logfactor=  log(f_RH_TruE/100);
      tempfactor= (m*(f_Temp))/(Tn+f_Temp);
      f_Dewpoint= Tn*(tempfactor+logfactor);
      f_Dewpoint= f_Dewpoint/(m-logfactor-tempfactor);
}

/************************************************/
/** brief    Get Displayable Dew Point         **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Calc_DP4Disp(void)
{
      signed int16 DPcast;    /* ftoa variable*/
      int16 DPdivisor;
      int1 DPsign=0;          /** Sign flag **/
      char i;
      char DPdisp_digit;
      char DPdigit;

      DPcast=(signed int16)(f_Dewpoint*100);
      if((DPcast & DPcastmask)== DPcastmask)/* Negative? */
      {
            DPcast=1-DPcast;
            DPsign=1;
      }
      DPdivisor=DPdiv;

      for(i=0;i<5;i++)
      {
      DPdigit = DPcast/DPdivisor;
      DPcast-= DPdigit*DPdivisor;
      DPdivisor/=10;
      DPdisp_digit=DPdigit+'0';
      DDewPt[i]=DPdisp_digit;/* Record Disp digits */
      }
}
```

APENDIX F. SHT11_Handler_V20.h

```
/*********************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ***/
/*********************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*********************************************************/
/*** DESCRIPTION: SENSIRION SHT11 SENSOR HANDLER HEADER*/
/*********************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      JAN 14,2016       ***/
/*********************************************************/

/************ GLOBAL VARIABLES DEFINITION ************/
int8 SOT_MSB;                       /** Readout Temp MSB */
int8 SOT_LSB;                       /** Readout Temp LSB */
int8 SORH_MSB;                      /** Readout RH MSB  **/
int8 SORH_LSB;                      /** Readout RH LSB  **/
int16 SOT16= 0x0000;                /** Whole SOT RD  **/
int16 SORH16=0x0000;                /** Whole SORH RD **/
int8 RD_Status;                     /** Read STATUS reg **/
int8 SHT_Cfg_Wd;                    /** Composed cfg wrd */
float f_Temp;                       /** Float pt Temp   **/
float f_RH_Lin;                     /** Float Linear RH% */
float f_RH_True;                    /** Float True    RH%*/
float f_Dewpoint;                   /** Float Dew Point **/
char DTemp[5];                      /** Displ Temp Chrs  */
char DRHLin[5];                     /** Displ RH Lin Ch  */
char DRHTrue[5];                    /** Disp Comp RH Chrs*/
char DDewPt[5];                     /** Displayable DewPt*/

/********* PARAMETERS CONVERSION CONSTANTS ***********/
float const d1  = -39.65;           /** Temp Offset     **/
float const d2H = 0.01;             /** High Res T Coeff**/
float const d2L = 0.04;             /** Low Res T Coeff **/
float const C1  = -2.0468;          /** Const RH Offset **/
float const C2H = 0.0367;           /** 1st Deg RH HR C **/
float const C2L = 0.5872;           /** 1st Deg RH LR C **/
float const C3H = -1.5995E-6;       /** 2nd Deg RH HRC  **/
float const C3L   = -4.085E-4;      /** 2nd Deg RH Lo RC */
float const t1  = 0.01;             /** Comp RH factor 1 */
float const t2L = 0.00128;          /** Comp RH factor 2**/
float const t2H = 0.00008;          /** Comp RH factor 2**/
float const m   = 17.62;            /** Dew point m fact */
float const Tn  = 243.12;           /** Dew point Tn fact*/
```

```
/************** CONVERSION MACROS CONSTANTS  **********/
int16 const THRdiv      = 10000;    /** Temp HRres divr **/
int16 const RHdiv = 10000;          /** RH divisor      **/
int16 const DPdiv       = 10000;    /** DP divisor       */
int16 const DPcastmask  = 0x8000;   /** DP ftoa mask     */

/***************** SHT11 COMMAND LIST *****************/
#define CMD_RD_Temp     0x01  /* Temp measurement **/
#define CMD_RD_RH       0x02  /* RH Measurement       **/
#define CMD_WR_Status   0x03  /* Write Status reg     **/
#define CMD_RD_Status   0x04  /* Read Status reg      **/
#define CMD_Soft_RST    0x05  /* Soft RST Command     **/
#define CMD_ACT_DESAT   0x06  /* Enable Desaturat     **/
#define CMD_DIS_DESAT   0x07  /* Disable Desaturt     **/

/************ SHT11 COMMAND WORDS MACROS **************/
#define SHT_Tmp_Meas    0b00000011  /* Measure Temp   **/
#define SHT_RH_Meas     0b00000101  /* Measure RH%    **/
#define SHT_WR_Stat     0b00000110  /* RD Status Reg  **/
#define SHT_RD_Stat     0b00000111  /* WR Status Reg  **/
#define SHT_Soft_RST    0b00011110  /* Soft Reset     **/

/******** SHT11 SATURATION LIMITS SETTINGS  **********/
#define DEC_SAT_ULIM    0x38        /*RH Decs UTL     **/
#define UNT_SAT_ULIM    0x35        /*RH Units UTL    **/
#define DEC_SAT_LLIM    0x35        /*RH Decs LTL     **/
#define UNT_SAT_LLIM    0x39        /*RH Units LTL    **/

/********* SHT11 CONFIG PARAMETERS MACROS  ***********/
#define Stat_Cfg_Wd     0b00000000  /* Stat Baseline  */
#define Stat_Hi_Res     0b00000000  /* Hi Res Mask    */
#define Stat_Low_Res    0b00000001  /* Low Res Mask   */
#define Stat_OTP_Reld   0b00000000  /* Calib Reload   */
#define Stat_OTP_NoReld 0b00000010  /* No Reload      */
#define Stat_Heat_ON    0b00000100  /* Heatr ON Mask */
#define Stat_Heat_OFF   0b11111011  /* Heatr OFF Mask*/

/********* MEASUREMENT PARAMETERS FLAGS **************/
#define TEMP                  0x01  /* TEMP Meas flag*/
#define RH                    0x02  /* RH% Meas flag */
```

```
/*******************************************************/
/************** FUNCTIONS PROTOTYPES *******************/
/*******************************************************/

/****** SENSOR COMMANDS PROCESSOR  *********************/
void SHT11_Command(int8 SHT_Command);

/****** CONVERT TEMP HEX READOUT TO FLOATING POINT ***/
void Calc_SOT_2_Float(void);

/****** CONVERT RH% HEX READUT TO FLOATING POINT *****/
void Calc_SORH_2_Float(void);

/****** CREATE TEMP DISPLAYABLE INT DIGITS ***********/
void Calc_Temp4Disp(void);

/****** CREATE RH% DISPLAYABLE INT DIGITS ************/
void Calc_RH4Disp(void);

/************** CALCULATE DEW POINT  *****************/
void Calc_DewPoint(void);

/**** CREATE DEW POINT DISPLAYABLE INT DIGITS ********/
void Calc_DP4Disp(void);
```

APENDIX G. OLED_Handler_V20.c

```
/*******************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ***/
/*******************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*******************************************************/
/*** DESCRIPTION: SSD1306 OLED HANDLER FILE           **/
/*******************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      FEB 12,2016       ***/
/*******************************************************/

#include "OLED_Chartable_V20.h"
#include "OLED_Handler_V20.h"
#include "SPI_Driver_V20.c"

char OLEDtext[5];                  /** OLED Char buffer **/

/*************************************************/
/** brief    OLED Saturation signals update    **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/*************************************************/
void OLED_Satur_Upd(void)
{
      OLED_Setcursor(ROW6_PAGE,HT_ICON_COL);
      if(desat_active)
      {
            OLED_Chardisp(0x00);    /* active Icon **/
            Output_HIGH(LED_HEATER);
      }
      else
      {
            OLED_Chardisp(0x01);    /* inactive Icon*/
            Output_LOW(LED_HEATER);
      }
      OLED_sat_status();                 /* Update text **/
}

/*************************************************/
/** brief    OLED Forced heat display          **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/*************************************************/
```

```
void OLED_forced_heat(void)
{
      OLED_Setcursor(ROW5_PAGE,SAT_TXT_COL);
      OLED_Chardisp('F');
      OLED_Chardisp('O');
      OLED_Chardisp('R');
      OLED_Chardisp('C');
      OLED_Chardisp('E');
      OLED_Chardisp('D');
      OLED_Chardisp(' ');
      OLED_Chardisp('H');
      OLED_Chardisp('T');
}

/************************************************/
/** brief    OLED Saturation Text updating     **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void OLED_sat_status(void)
{
      OLED_Setcursor(ROW5_PAGE,SAT_TXT_COL);
      if(desat_active)
      {
            OLED_Chardisp('S');
            OLED_Chardisp('A');
            OLED_Chardisp('T');
            OLED_Chardisp('U');
            OLED_Chardisp('R');
            OLED_Chardisp('A');
            OLED_Chardisp('T');
            OLED_Chardisp('E');
            OLED_Chardisp('D');
      }
      else
      {
            OLED_Chardisp('N');
            OLED_Chardisp('O');
            OLED_Chardisp('N');
            OLED_Chardisp(' ');
            OLED_Chardisp('S');
            OLED_Chardisp('A');
            OLED_Chardisp('T');
            OLED_Chardisp(' ');
            OLED_Chardisp(' ');
      }
}
```

```
/************************************************/
/** brief    OLED Splash screen display        **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void OLED_Splashscr(void)
{
      Skeletonscr_Row1();     /** First Skeleton row **/
      Skeletonscr_Row2();     /** Second Skeleton row**/
      Skeletonscr_Row3();     /** Third Skeleton row **/
      Skeletonscr_Row4();     /** Fourth Skeleton row**/
      Skeletonscr_Row5();     /** Fifth Skeleton row **/
      Skeletonscr_Row6();     /** Sixth Skeleton row **/
}

/************************************************/
/** brief    OLED Skeleton Display 1st row     **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Skeletonscr_Row1(void)
{
      OLED_Setcursor(ROW1_PAGE,ROW1_COL);/* First row */
      OLED_Chardisp('*');
      OLED_Chardisp(' ');
      OLED_Chardisp('C');
      OLED_Chardisp('O');
      OLED_Chardisp('2');
      OLED_Chardisp(' ');
      OLED_Chardisp('S');
      OLED_Chardisp('Y');
      OLED_Chardisp('N');
      OLED_Chardisp('T');
      OLED_Chardisp('H');
      OLED_Chardisp(' ');
      OLED_Chardisp('S');
      OLED_Chardisp('Y');
      OLED_Chardisp('S');
      OLED_Chardisp('T');
      OLED_Chardisp('E');
      OLED_Chardisp('M');
      OLED_Chardisp(' ');
      OLED_Chardisp('V');
      OLED_Chardisp('1');
      OLED_Chardisp('.');
      OLED_Chardisp('0');
      OLED_Chardisp(' ');
      OLED_Chardisp('*');
}
```

```
/************************************************/
/** brief    OLED Skeleton Display 2nd row     **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Skeletonscr_Row2(void)
{
      char i;
      OLED_Setcursor(ROW2_PAGE,ROW2_COL);/* Second Row */
      for(i=0;i<=25;i++)
      {
            OLED_Chardisp('*');
      }
}

/************************************************/
/** brief    OLED Skeleton Display 3rd row     **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Skeletonscr_Row3(void)
{
      OLED_Setcursor(ROW3_PAGE,ROW3_COL);/* Third Row */
      OLED_Chardisp('*');
      OLED_Chardisp('*');
      OLED_Chardisp(' ');
      OLED_Chardisp('M');
      OLED_Chardisp('T');
      OLED_Chardisp('G');
      OLED_Chardisp('E');
      OLED_Chardisp('.');
      OLED_Chardisp('I');
      OLED_Chardisp('T');
      OLED_Chardisp('E');
      OLED_Chardisp('S');
      OLED_Chardisp('O');
      OLED_Chardisp(' ');
      OLED_Chardisp('E');
      OLED_Chardisp('S');
      OLED_Chardisp('E');
      OLED_Chardisp('.');
      OLED_Chardisp('2');
      OLED_Chardisp('0');
      OLED_Chardisp('1');
      OLED_Chardisp('6');
      OLED_Chardisp(' ');
      OLED_Chardisp('*');
      OLED_Chardisp('*');
}
```

```
/************************************************/
/** brief    OLED Skeleton Display 4th row     **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Skeletonscr_Row4(void)
{
      OLED_Setcursor(ROW4_PAGE,ROW4_COL);/* Fourth Row */
      OLED_Chardisp('T');                /* Temp messg */
      OLED_Chardisp('e');
      OLED_Chardisp('m');
      OLED_Chardisp('p');
      OLED_Chardisp(' ');
      OLED_Chardisp('0');
      OLED_Chardisp('0');
      OLED_Chardisp('0');
      OLED_Chardisp('.');
      OLED_Chardisp('0');
      OLED_Chardisp('0');
      OLED_Chardisp('°');
      OLED_Chardisp('C');
      OLED_Chardisp(' ');
      OLED_Chardisp(' ');
      OLED_Chardisp('R');                /* RH Message */
      OLED_Chardisp('H');
      OLED_Chardisp(' ');
      OLED_Chardisp('0');
      OLED_Chardisp('0');
      OLED_Chardisp('.');
      OLED_Chardisp('0');
      OLED_Chardisp('0');
      OLED_Chardisp(' ');
      OLED_Chardisp('%');
}

/************************************************/
/** brief    OLED Skeleton Display 5th row     **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Skeletonscr_Row5(void)
{
      OLED_Setcursor(ROW5_PAGE,ROW5_COL);/* Fifth Row */
      OLED_Chardisp('D');                    /* Dew Pt msg*/
      OLED_Chardisp('E');
      OLED_Chardisp('W');
      OLED_Chardisp(' ');
      OLED_Chardisp('P');
      OLED_Chardisp('t');
      OLED_Chardisp(' ');
      OLED_Chardisp('0');
      OLED_Chardisp('0');
```

```
      OLED_Chardisp('.');
      OLED_Chardisp('0');
      OLED_Chardisp('0');
      OLED_Chardisp('°');
      OLED_Chardisp('C');;
      OLED_Chardisp(' ');
      OLED_Chardisp('N');
      OLED_Chardisp('O');
      OLED_Chardisp('N');
      OLED_Chardisp(' ');
      OLED_Chardisp('S');
      OLED_Chardisp('A');
      OLED_Chardisp('T');
}

/************************************************/
/** brief    OLED Skeleton Display 6th row     **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void Skeletonscr_Row6(void)
{
      OLED_Setcursor(ROW6_PAGE,ROW6_COL);/* Sixth Row */
      OLED_Chardisp('g');     /* Gas intake*/
      OLED_Chardisp('i');
      OLED_Chardisp(' ');
      OLED_Chardisp(0x00);    /** Active **/
      OLED_Chardisp(' ');
      OLED_Chardisp(' ');
      OLED_Chardisp('c');     /* Cold source*/
      OLED_Chardisp('o');
      OLED_Chardisp('o');
      OLED_Chardisp('l');
      OLED_Chardisp(' ');
      OLED_Chardisp(0x01);    /**Inactive **/
      OLED_Chardisp(' ');
      OLED_Chardisp(' ');
      OLED_Chardisp('h');     /* Desat heater*/
      OLED_Chardisp('t');
      OLED_Chardisp('r');
      OLED_Chardisp(' ');
      OLED_Chardisp(0x01);    /** Inactive **/
}

/************************************************/
/** brief    OLED Temperature refresh routine  **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
```

```
void OLED_Temp_Upd(void)
{
      OLED_Setcursor(ROW4_PAGE,T_COL_HUND);
      ASC_2_OLED(DTemp[0]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW4_PAGE,T_COL_DECS);
      ASC_2_OLED(DTemp[1]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW4_PAGE,T_COL_UNITS);
      ASC_2_OLED(DTemp[2]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW4_PAGE,T_COL_TENTH);
      ASC_2_OLED(DTemp[3]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW4_PAGE,T_COL_CENTS);
      ASC_2_OLED(DTemp[4]);
      OLED_Writechar(OLEDtext);
}

/************************************************/
/** brief    OLED RH refresh routine           **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void OLED_RH_Upd(void)
{
      OLED_Setcursor(ROW4_PAGE,H_COL_DECS);
      ASC_2_OLED(DRHTrue[1]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW4_PAGE,H_COL_UNITS);
      ASC_2_OLED(DRHTrue[2]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW4_PAGE,H_COL_TENTH);
      ASC_2_OLED(DRHTrue[3]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW4_PAGE,H_COL_CENTS);
      ASC_2_OLED(DRHTrue[4]);
      OLED_Writechar(OLEDtext);
}

/************************************************/
/** brief    OLED Dew Point refresh routine    **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
```

```
void OLED_DP_Upd(void)
{
      OLED_Setcursor(ROW5_PAGE,W_COL_DECS);
      ASC_2_OLED(DDewPt[1]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW5_PAGE,W_COL_UNITS);
      ASC_2_OLED(DDewPt[2]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW5_PAGE,W_COL_TENTH);
      ASC_2_OLED(DDewPt[3]);
      OLED_Writechar(OLEDtext);
      OLED_Setcursor(ROW5_PAGE,W_COL_CENTS);
      ASC_2_OLED(DDewPt[4]);
      OLED_Writechar(OLEDtext);
}

/************************************************/
/** brief    OLED Display a single character   **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    ASCII Character                   **/
/** return   none                              **/
/************************************************/
void OLED_Chardisp(char ASCchar)
{
      ASC_2_OLED(ASCchar);
      OLED_Writechar(OLEDtext);
}

/************************************************/
/** brief    ASCII Number to OLED Char convert **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    ASCII Byte                        **/
/** return   OLED graphic char in OLEDtext var **/
/************************************************/
void ASC_2_OLED(char ASCparam)
{
      switch(ASCparam)
      {
            case '0':         OLEDtext[0]=ch_ZERO[0];
                              OLEDtext[1]=ch_ZERO[1];
                              OLEDtext[2]=ch_ZERO[2];
                              OLEDtext[3]=ch_ZERO[3];
                              OLEDtext[4]=ch_ZERO[4];
                              break;
            case '1':         OLEDtext[0]=ch_ONE[0];
                              OLEDtext[1]=ch_ONE[1];
                              OLEDtext[2]=ch_ONE[2];
                              OLEDtext[3]=ch_ONE[3];
                              OLEDtext[4]=ch_ONE[4];
                              break;
```

```
case '2':         OLEDtext[0]=ch_TWO[0];
                  OLEDtext[1]=ch_TWO[1];
                  OLEDtext[2]=ch_TWO[2];
                  OLEDtext[3]=ch_TWO[3];
                  OLEDtext[4]=ch_TWO[4];
                  break;
case '3':         OLEDtext[0]=ch_THREE[0];
                  OLEDtext[1]=ch_THREE[1];
                  OLEDtext[2]=ch_THREE[2];
                  OLEDtext[3]=ch_THREE[3];
                  OLEDtext[4]=ch_THREE[4];
                  break;
case '4':         OLEDtext[0]=ch_FOUR[0];
                  OLEDtext[1]=ch_FOUR[1];
                  OLEDtext[2]=ch_FOUR[2];
                  OLEDtext[3]=ch_FOUR[3];
                  OLEDtext[4]=ch_FOUR[4];
                  break;
case '5':         OLEDtext[0]=ch_FIVE[0];
                  OLEDtext[1]=ch_FIVE[1];
                  OLEDtext[2]=ch_FIVE[2];
                  OLEDtext[3]=ch_FIVE[3];
                  OLEDtext[4]=ch_FIVE[4];
                  break;
case '6':         OLEDtext[0]=ch_SIX[0];
                  OLEDtext[1]=ch_SIX[1];
                  OLEDtext[2]=ch_SIX[2];
                  OLEDtext[3]=ch_SIX[3];
                  OLEDtext[4]=ch_SIX[4];
                  break;
case '7':         OLEDtext[0]=ch_SEVEN[0];
                  OLEDtext[1]=ch_SEVEN[1];
                  OLEDtext[2]=ch_SEVEN[2];
                  OLEDtext[3]=ch_SEVEN[3];
                  OLEDtext[4]=ch_SEVEN[4];
                  break;
case '8':         OLEDtext[0]=ch_EIGHT[0];
                  OLEDtext[1]=ch_EIGHT[1];
                  OLEDtext[2]=ch_EIGHT[2];
                  OLEDtext[3]=ch_EIGHT[3];
                  OLEDtext[4]=ch_EIGHT[4];
                  break;
case '9':         OLEDtext[0]=ch_NINE[0];
                  OLEDtext[1]=ch_NINE[1];
                  OLEDtext[2]=ch_NINE[2];
                  OLEDtext[3]=ch_NINE[3];
                  OLEDtext[4]=ch_NINE[4];
                  break;
case 0x00:        OLEDtext[0]=ch_ACTIVE[0];
                  OLEDtext[1]=ch_ACTIVE[1];
                  OLEDtext[2]=ch_ACTIVE[2];
                  OLEDtext[3]=ch_ACTIVE[3];
                  OLEDtext[4]=ch_ACTIVE[4];
                  break;
```

```
case 0x01:        OLEDtext[0]=ch_INACTIVE[0];
                  OLEDtext[1]=ch_INACTIVE[1];
                  OLEDtext[2]=ch_INACTIVE[2];
                  OLEDtext[3]=ch_INACTIVE[3];
                  OLEDtext[4]=ch_INACTIVE[4];
                  break;
case ' ':         OLEDtext[0]=ch_SPACE[0];
                  OLEDtext[1]=ch_SPACE[1];
                  OLEDtext[2]=ch_SPACE[2];
                  OLEDtext[3]=ch_SPACE[3];
                  OLEDtext[4]=ch_SPACE[4];
                  break;
case '%':         OLEDtext[0]=ch_PERCENT[0];
                  OLEDtext[1]=ch_PERCENT[1];
                  OLEDtext[2]=ch_PERCENT[2];
                  OLEDtext[3]=ch_PERCENT[3];
                  OLEDtext[4]=ch_PERCENT[4];
                  break;
case '°':         OLEDtext[0]=ch_DEGREE[0];
                  OLEDtext[1]=ch_DEGREE[1];
                  OLEDtext[2]=ch_DEGREE[2];
                  OLEDtext[3]=ch_DEGREE[3];
                  OLEDtext[4]=ch_DEGREE[4];
                  break;
case '.':         OLEDtext[0]=ch_PERIOD[0];
                  OLEDtext[1]=ch_PERIOD[1];
                  OLEDtext[2]=ch_PERIOD[2];
                  OLEDtext[3]=ch_PERIOD[3];
                  OLEDtext[4]=ch_PERIOD[4];
                  break;
case 'A':         OLEDtext[0]=ch_A[0];
                  OLEDtext[1]=ch_A[1];
                  OLEDtext[2]=ch_A[2];
                  OLEDtext[3]=ch_A[3];
                  OLEDtext[4]=ch_A[4];
                  break;
case 'C':         OLEDtext[0]=ch_C[0];
                  OLEDtext[1]=ch_C[1];
                  OLEDtext[2]=ch_C[2];
                  OLEDtext[3]=ch_C[3];
                  OLEDtext[4]=ch_C[4];
                  break;
case 'D':         OLEDtext[0]=ch_D[0];
                  OLEDtext[1]=ch_D[1];
                  OLEDtext[2]=ch_D[2];
                  OLEDtext[3]=ch_D[3];
                  OLEDtext[4]=ch_D[4];
                  break;
case 'E':         OLEDtext[0]=ch_E[0];
                  OLEDtext[1]=ch_E[1];
                  OLEDtext[2]=ch_E[2];
                  OLEDtext[3]=ch_E[3];
                  OLEDtext[4]=ch_E[4];
                  break;
```

```
case 'F':         OLEDtext[0]=ch_F[0];
                  OLEDtext[1]=ch_F[1];
                  OLEDtext[2]=ch_F[2];
                  OLEDtext[3]=ch_F[3];
                  OLEDtext[4]=ch_F[4];
                  break;
case 'G':         OLEDtext[0]=ch_G[0];
                  OLEDtext[1]=ch_G[1];
                  OLEDtext[2]=ch_G[2];
                  OLEDtext[3]=ch_G[3];
                  OLEDtext[4]=ch_G[4];
                  break;
case 'H':         OLEDtext[0]=ch_H[0];
                  OLEDtext[1]=ch_H[1];
                  OLEDtext[2]=ch_H[2];
                  OLEDtext[3]=ch_H[3];
                  OLEDtext[4]=ch_H[4];
                  break;
case 'I':         OLEDtext[0]=ch_I[0];
                  OLEDtext[1]=ch_I[1];
                  OLEDtext[2]=ch_I[2];
                  OLEDtext[3]=ch_I[3];
                  OLEDtext[4]=ch_I[4];
                  break;
case 'M':         OLEDtext[0]=ch_M[0];
                  OLEDtext[1]=ch_M[1];
                  OLEDtext[2]=ch_M[2];
                  OLEDtext[3]=ch_M[3];
                  OLEDtext[4]=ch_M[4];
                  break;
case 'N':         OLEDtext[0]=ch_N[0];
                  OLEDtext[1]=ch_N[1];
                  OLEDtext[2]=ch_N[2];
                  OLEDtext[3]=ch_N[3];
                  OLEDtext[4]=ch_N[4];
                  break;
case 'O':         OLEDtext[0]=ch_O[0];
                  OLEDtext[1]=ch_O[1];
                  OLEDtext[2]=ch_O[2];
                  OLEDtext[3]=ch_O[3];
                  OLEDtext[4]=ch_O[4];
                  break;
case 'P':         OLEDtext[0]=ch_P[0];
                  OLEDtext[1]=ch_P[1];
                  OLEDtext[2]=ch_P[2];
                  OLEDtext[3]=ch_P[3];
                  OLEDtext[4]=ch_P[4];
                  break;
case 'R':         OLEDtext[0]=ch_R[0];
                  OLEDtext[1]=ch_R[1];
                  OLEDtext[2]=ch_R[2];
                  OLEDtext[3]=ch_R[3];
                  OLEDtext[4]=ch_R[4];
                  break;
```

```
case 'S':         OLEDtext[0]=ch_S[0];
                  OLEDtext[1]=ch_S[1];
                  OLEDtext[2]=ch_S[2];
                  OLEDtext[3]=ch_S[3];
                  OLEDtext[4]=ch_S[4];
                  break;
case 'T':         OLEDtext[0]=ch_T[0];
                  OLEDtext[1]=ch_T[1];
                  OLEDtext[2]=ch_T[2];
                  OLEDtext[3]=ch_T[3];
                  OLEDtext[4]=ch_T[4];
                  break;
case 'U':         OLEDtext[0]=ch_U[0];
                  OLEDtext[1]=ch_U[1];
                  OLEDtext[2]=ch_U[2];
                  OLEDtext[3]=ch_U[3];
                  OLEDtext[4]=ch_U[4];
                  break;
case 'V':         OLEDtext[0]=ch_V[0];
                  OLEDtext[1]=ch_V[1];
                  OLEDtext[2]=ch_V[2];
                  OLEDtext[3]=ch_V[3];
                  OLEDtext[4]=ch_V[4];
                  break;
case 'W':         OLEDtext[0]=ch_W[0];
                  OLEDtext[1]=ch_W[1];
                  OLEDtext[2]=ch_W[2];
                  OLEDtext[3]=ch_W[3];
                  OLEDtext[4]=ch_W[4];
                  break;
case 'Y':         OLEDtext[0]=ch_Y[0];
                  OLEDtext[1]=ch_Y[1];
                  OLEDtext[2]=ch_Y[2];
                  OLEDtext[3]=ch_Y[3];
                  OLEDtext[4]=ch_Y[4];
                  break;
case 'c':         OLEDtext[0]=chm_c[0];
                  OLEDtext[1]=chm_c[1];
                  OLEDtext[2]=chm_c[2];
                  OLEDtext[3]=chm_c[3];
                  OLEDtext[4]=chm_c[4];
                  break;
case 'e':         OLEDtext[0]=chm_e[0];
                  OLEDtext[1]=chm_e[1];
                  OLEDtext[2]=chm_e[2];
                  OLEDtext[3]=chm_e[3];
                  OLEDtext[4]=chm_e[4];
                  break;
case 'g':         OLEDtext[0]=chm_g[0];
                  OLEDtext[1]=chm_g[1];
                  OLEDtext[2]=chm_g[2];
                  OLEDtext[3]=chm_g[3];
                  OLEDtext[4]=chm_g[4];
                  break;
```

```
case 'h':         OLEDtext[0]=chm_h[0];
                  OLEDtext[1]=chm_h[1];
                  OLEDtext[2]=chm_h[2];
                  OLEDtext[3]=chm_h[3];
                  OLEDtext[4]=chm_h[4];
                  break;
case 'i':         OLEDtext[0]=chm_i[0];
                  OLEDtext[1]=chm_i[1];
                  OLEDtext[2]=chm_i[2];
                  OLEDtext[3]=chm_i[3];
                  OLEDtext[4]=chm_i[4];
                  break;
case 'l':         OLEDtext[0]=chm_l[0];
                  OLEDtext[1]=chm_l[1];
                  OLEDtext[2]=chm_l[2];
                  OLEDtext[3]=chm_l[3];
                  OLEDtext[4]=chm_l[4];
                  break;
case 'm':         OLEDtext[0]=chm_m[0];
                  OLEDtext[1]=chm_m[1];
                  OLEDtext[2]=chm_m[2];
                  OLEDtext[3]=chm_m[3];
                  OLEDtext[4]=chm_m[4];
                  break;
case 'o':         OLEDtext[0]=chm_o[0];
                  OLEDtext[1]=chm_o[1];
                  OLEDtext[2]=chm_o[2];
                  OLEDtext[3]=chm_o[3];
                  OLEDtext[4]=chm_o[4];
                  break;
case 'p':         OLEDtext[0]=chm_p[0];
                  OLEDtext[1]=chm_p[1];
                  OLEDtext[2]=chm_p[2];
                  OLEDtext[3]=chm_p[3];
                  OLEDtext[4]=chm_p[4];
                  break;
case 'r':         OLEDtext[0]=chm_r[0];
                  OLEDtext[1]=chm_r[1];
                  OLEDtext[2]=chm_r[2];
                  OLEDtext[3]=chm_r[3];
                  OLEDtext[4]=chm_r[4];
                  break;
case 't':         OLEDtext[0]=chm_t[0];
                  OLEDtext[1]=chm_t[1];
                  OLEDtext[2]=chm_t[2];
                  OLEDtext[3]=chm_t[3];
                  OLEDtext[4]=chm_t[4];
                  break;
default     :     OLEDtext[0]=ch_ASTERISK[0];
                  OLEDtext[1]=ch_ASTERISK[1];
                  OLEDtext[2]=ch_ASTERISK[2];
                  OLEDtext[3]=ch_ASTERISK[3];
                  OLEDtext[4]=ch_ASTERISK[4];
                  break;
```

```
      }
      return;
}

/************************************************/
/** brief    OLED Write a DATA character       **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    5 row composite character         **/
/** return   void                              **/
/************************************************/
void OLED_Writechar(char datachar[])
{
      SPI_CS_Enabled;
      OLED_DATA;
      SPI_write(datachar[0]); /** Leftmost column **/
      SPI_write(datachar[1]);
      SPI_write(datachar[2]);
      SPI_write(datachar[3]);
      SPI_write(datachar[4]); /** Rightmost column */
      SPI_CS_Disabled;
}

/************************************************/
/** brief    OLED Place cursor @ Page& Col     **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    Page Number                       **/
/** return   void                              **/
/************************************************/
void OLED_Setcursor(char pagenumber,char colnumber)
{
      char lowcolumn;
      char hicolumn;
      pagenumber=pagenumber&0x07;
      lowcolumn=colnumber&0x0F;
      hicolumn=colnumber;
      hicolumn=hicolumn>>4;
      hicolumn=(hicolumn&0x07)|0x10;
      SPI_CS_Enabled;
      OLED_CTRL;
      SPI_Write(0xB0+pagenumber);
      SPI_Write(lowcolumn);
      SPI_Write(hicolumn);
      SPI_CS_Disabled;
}

/************************************************/
/** brief    OLED RAM/SCRN Clearing            **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
```

```
void OLED_Clr_Scrn(void)
{
      char i;
      char j;
      char col_low;
      char col_hi;

      SPI_CS_Enabled;
      for(i=0;i<=7;i++)
      {
            OLED_CTRL;
            SPI_Write(0xB0+i);      /** Page Iterator **/

            for(j=0;j<=127;j++) /** Column Iterator*/
            {
                  OLED_CTRL;        /* Control command */
                  col_low=j&0x0F;   /*** SEG Select ****/
                  SPI_Write(col_low); /* Lower nibble*/
                  col_hi=j;
                  col_hi=col_hi>>4;
                  col_hi=(col_hi&0x07)|0x10;
                  SPI_Write(col_hi);  /* Higher nibb */
                  OLED_DATA;        /** Data command ***/
                  SPI_Write(0x00);/** Zero fillers ***/
            }
      }
      SPI_CS_Disabled;
}

/************************************************/
/** brief    OLED SPI bus Initialization       **/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
void OLED_Startup(void)
{
      SPI_Reset();            /*** Reset OLED SPI ***/
      SPI_OLED_Init();  /*** Initialize OLED **/
}
```

APENDIX H. OLED_Handler_V20.h

```
/*********************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ***/
/*********************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*********************************************************/
/*** DESCRIPTION: SSD1306 OLED HANDLER HEADER         **/
/*********************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      FEB 12,2016       ***/
/*********************************************************/

/********** HANDLER CONSTANTS DEFINITION *********/
#define ROW1_PAGE 0x07  /** Row 1 Page set      **/
#define ROW2_PAGE 0x06  /** Row 2 Page set      **/
#define ROW3_PAGE 0x05  /** Row 3 Page set      **/
#define ROW4_PAGE 0x03  /** Row 4 Page set      **/
#define ROW5_PAGE 0x01  /** Row 5 Page set      **/
#define ROW6_PAGE 0x00  /** Row 6 Page set      **/

#define ROW1_COL  0x00  /** Column 1 Setting */
#define ROW2_COL  0x00  /** Column 2 Setting */
#define ROW3_COL  0x00  /** Column 3 Setting */
#define ROW4_COL  0x00  /** Column 4 Setting */
#define ROW5_COL  0x00  /** Column 5 Setting */
#define ROW6_COL  0x00  /** Column 6 Setting */

#define T_COL_HUND      0x19  /** Temp Hundreds col*/
#define T_COL_DECS      0x1E  /** Temp Decens colmn*/
#define T_COL_UNITS     0x23  /** Temp Units column*/
#define T_COL_TENTH     0x2D  /** Temp Tenths colmn*/
#define T_COL_CENTS     0x32  /** Temp Cents column*/

#define H_COL_DECS      0x5A  /** RH Decens column */
#define H_COL_UNITS     0x5F  /** RH Units column  */
#define H_COL_TENTH     0x69  /** RH Tenths column */
#define H_COL_CENTS     0x6E  /** RH Cents column  */

#define W_COL_DECS      0x23  /** DP Decens column */
#define W_COL_UNITS     0x28  /** DP Units column  */
#define W_COL_TENTH     0x32  /** DP Tenths column */
#define W_COL_CENTS     0x37  /** DP Cents column  */

#define HT_ICON_COL     0x5A  /** Heater Icon colmn*/
#define SAT_TXT_COL     0x4B  /** Satur status col */
```

```
/************** FUNCTIONS PROTOTYPES **************/
void OLED_Clr_Scrn(void);
void OLED_Setcursor(char pagenumber,char colnumber);
void OLED_Writechar(char datachar[]);
void Skeletonscr_Row1(void);  /** First Skeleton row **/
void Skeletonscr_Row2(void);  /** Second Skeleton row**/
void Skeletonscr_Row3(void);  /** Third Skeleton row **/
void Skeletonscr_Row4(void);  /** Fourth Skeleton row**/
void Skeletonscr_Row5(void);  /** Fifth Skeleton row **/
void Skeletonscr_Row6(void);  /** Sixth Skeleton row **/
void OLED_Chardisp(char ASCchar); /** Display ASCII char*/
void OLED_sat_status(void);        /** Update satur signal */
void ASC_2_OLED(char ASCparam);    /** ASCII 2 OLED Convert*/
```

APENDIX I. OLED_Chartable_V20.h

```
/*********************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ****/
/*********************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*********************************************************/
/*** DESCRIPTION: SSD1306 OLED CHARACTER GEN TABLE     **/
/*********************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      FEB 12,2016       ****/
/*********************************************************/

#ORG 0x3600,0x36FF     /** Place table at very end of HEX */

/************* NUMERIC CHARACTERS *****************/
char const ch_ZERO[5]=  {0x7E,0x85,0xC1,0x7E,0x00}; // 0
char const ch_ONE[5]=   {0x00,0x81,0xFF,0x01,0x00}; // 1
char const ch_TWO[5]=   {0x47,0x89,0x91,0xA1,0x41}; // 2
char const ch_THREE[5]= {0x00,0x82,0x91,0xB1,0xCE}; // 3
char const ch_FOUR[5]=  {0x18,0x28,0x48,0xFF,0x00}; // 4
char const ch_FIVE[5]=  {0x00,0xF1,0x91,0x91,0x8E}; // 5
char const ch_SIX[5]=   {0x00,0x7E,0x91,0x91,0x4E}; // 6
char const ch_SEVEN[5]= {0x80,0x8F,0xB0,0xC0,0x00}; // 7
char const ch_EIGHT[5]= {0x00,0x6E,0x91,0x91,0x6E}; // 8
char const ch_NINE[5]=  {0x62,0x91,0x91,0x7E,0x00}; // 9

/************* SPECIAL CHARACTERS ******************/
char const ch_SPACE  [5]= {0x00,0x00,0x00,0x00,0x00}; //{SPACE}
char const ch_PERCENT[5]= {0x62,0x94,0x6E,0x19,0x26}; // %
char const ch_DEGREE[5]=  {0x60,0x90,0x90,0x60,0x00}; // º
char const ch_ASTERISK[5]={0x54,0x38,0x38,0x54,0x00}; // *
char const ch_PERIOD[5]=  {0x00,0x03,0x03,0x00,0x00}; // .
char const ch_ACTIVE[5]=  {0x1F,0x1F,0x1F,0x1F,0x1F}; //
char const ch_INACTIVE[5]={0x1F,0x11,0x11,0x11,0x1F}; // o

/******** UPPERCASE ALPHABETIC CHARACTERS **********/
char const ch_A[5]= {0x3F,0xC8,0xC8,0x3F,0x00}; // A
char const ch_C[5]= {0x7E,0x81,0x81,0x42,0x00}; // C
char const ch_D[5]= {0xFF,0x81,0x81,0x7E,0x00}; // D
char const ch_E[5]= {0xFF,0x91,0x81,0x81,0x00}; // E
char const ch_F[5]= {0xFF,0x90,0x90,0x80,0x00}; // F
char const ch_G[5]= {0x7E,0x81,0x89,0x4E,0x00}; // G
char const ch_H[5]= {0xFF,0x10,0x10,0xFF,0x00}; // H
char const ch_I[5]= {0x00,0x81,0xFF,0x81,0x00}; // I
char const ch_M[5]= {0xFF,0x40,0x20,0x40,0xFF}; // M
char const ch_N[5]= {0xFF,0x30,0x18,0xFF,0x00}; // N
char const ch_O[5]= {0x7E,0x81,0x81,0x7E,0x00}; // O
char const ch_P[5]= {0xFF,0x88,0x88,0x70,0x00}; // P
char const ch_R[5]= {0xFF,0x88,0x8C,0x73,0x00}; // R
char const ch_S[5]= {0x72,0x91,0x91,0x4E,0x00}; // S
char const ch_T[5]= {0x80,0x80,0xFF,0x80,0x80}; // T
char const ch_U[5]= {0x7E,0x01,0x01,0x7E,0x00}; // U
char const ch_V[5]= {0xE0,0x1C,0x03,0x1C,0xE0}; // V
```

```
char const ch_W[5]= {0xFC,0x03,0x0C,0x03,0xFC}; // W
char const ch_Y[5]= {0xC0,0x20,0x1F,0x20,0xC0}; // Y
//char const ch_B[5]= {0x00,0x00,0x00,0x00,0x00}; // B
//char const ch_J[5]= {0x00,0x00,0x00,0x00,0x00}; // J
//char const ch_K[5]= {0x00,0x00,0x00,0x00,0x00}; // K
//char const ch_L[5]= {0x00,0x00,0x00,0x00,0x00}; // L
//char const ch_Q[5]= {0x00,0x00,0x00,0x00,0x00}; // Q
//char const ch_X[5]= {0x00,0x00,0x00,0x00,0x00}; // X
//char const ch_Z[5]= {0x00,0x00,0x00,0x00,0x00}; // Z

/******** LOWERCASE ALPHABETIC CHARACTERS **********/
char const chm_c[5]= {0x1E,0x21,0x21,0x12,0x00}; // c
char const chm_e[5]= {0x1E,0x29,0x29,0x1A,0x00}; // e
char const chm_g[5]= {0x3E,0x41,0x49,0x2E,0x00}; // g
char const chm_h[5]= {0x7F,0x10,0x10,0x0F,0x00}; // h
char const chm_i[5]= {0x01,0x5F,0x01,0x00,0x00}; // i
char const chm_l[5]= {0x00,0x3F,0x01,0x00,0x00}; // l
char const chm_m[5]= {0x1F,0x20,0x1F,0x20,0x1F}; // m
char const chm_o[5]= {0x1E,0x21,0x21,0x1E,0x00}; // o
char const chm_p[5]= {0x00,0x3F,0x24,0x24,0x18}; // p
char const chm_r[5]= {0x3F,0x10,0x20,0x10,0x00}; // r
char const chm_t[5]= {0x10,0x7E,0x11,0x02,0x00}; // t
//char const chm_a[5]=  {0x00,0x00,0x00,0x00,0x00}; // a
//char const chm_b[5]=  {0x00,0x00,0x00,0x00,0x00}; // b
//char const chm_d[5]=  {0x00,0x00,0x00,0x00,0x00}; // d
//char const chm_f[5]=  {0x08,0x3F,0x48,0x48,0x20}; // f
//char const chm_j[5]=  {0x00,0x00,0x00,0x00,0x00}; // j
//char const chm_k[5]=  {0x00,0x00,0x00,0x00,0x00}; // k
//char const chm_n[5]=  {0x00,0x00,0x00,0x00,0x00}; // n
//char const chm_q[5]=  {0x00,0x00,0x00,0x00,0x00}; // q
//char const chm_s[5]=  {0x00,0x00,0x00,0x00,0x00}; // s
//char const chm_u[5]=  {0x00,0x00,0x00,0x00,0x00}; // u
//char const chm_v[5]=  {0x00,0x00,0x00,0x00,0x00}; // v
//char const chm_w[5]=  {0x00,0x00,0x00,0x00,0x00}; // w
//char const chm_x[5]=  {0x00,0x00,0x00,0x00,0x00}; // x
//char const chm_y[5]=  {0x00,0x00,0x00,0x00,0x00}; // y
//char const chm_z[5]=  {0x00,0x00,0x00,0x00,0x00}; // z
```

APENDIX J. CO2_Synth_Tasks_V20.c

```
/*******************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ****/
/*******************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*******************************************************/
/*** DESCRIPTION: RTOS SCHEDULER TASKS C FILE        ****/
/*******************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      JAN 14,2016       ****/
/*******************************************************/

int1 heatbutton_press=FALSE; /* Flag: Forced ht button press **/
int1 forcedheating= FALSE;   /* Flag: Forced ht status flag  **/

/************************************************/
/** brief    TASK 425 mS: Forced heater handler**/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
#task(Rate=425ms,Max=425mS)
void CO2_RTOS_425mS_Task()
{
      if(!input(BUTTON_HEAT))                          /* Button press*/
      {
            if(!heatbutton_press)                      /* Prev release*/
            {
                  heatbutton_press=TRUE;               /* Prev active */
                  if(!input(LED_MANHEAT))              /* Heater =OFF */
                  {
                        Output_HIGH(LED_MANHEAT);      /*** Heat= ON **/
                        SHT11_Command(CMD_ACT_DESAT);
                        OLED_Setcursor(ROW6_PAGE,HT_ICON_COL);
                        OLED_Chardisp(0x00);
                        OLED_forced_heat();
                        Output_HIGH(LED_HEATER);
                        forcedheating=TRUE;
                  }
                  else                                 /* Heater= ON  */
                  {
                        Output_LOW(LED_MANHEAT);       /*** Heat= OFF**/
                        SHT11_Command(CMD_DIS_DESAT);
                        OLED_Setcursor(ROW6_PAGE,HT_ICON_COL);
                        OLED_Chardisp(0x01);
                        Output_LOW(LED_HEATER);
                        forcedheating=FALSE;
                  }
            }
            else                                 /* Still pressed*/
            {}                                   /* No action    */
      }
```

```
      else
            heatbutton_press=FALSE;                  /* Yes released */

}

/************************************************/
/** brief    TASK1700mS: Periodic sense/process**/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/************************************************/
#task(Rate=1700ms,Max=425mS)
void CO2_RTOS_1700mS_Task( )
{
      Output_HIGH(LED_PROCESS);     /** Process start flag */
      SHT11_Command(CMD_RD_Temp);   /* Read Temp °C        */
      SHT11_Command(CMD_RD_RH);     /* Read RH%            */
      Calc_DewPoint();              /* Calculate Dew Point */
      Calc_DP4Disp();               /* Calculate displ DP  */
      OLED_Temp_Upd();              /* OLED Refresh Temp   */
      OLED_RH_Upd();                /* OLED Refresh RH%    */
      OLED_DP_Upd();                /* OLED Refresh DP     */
      if(!forcedheating)
      {
            SHT11_Saturation_Chk(); /** Check sensor satur */
            OLED_Satur_Upd();       /* OLED Sat icon update*/
      }
      Output_LOW(LED_PROCESS);      /** Process End flag   */
}
```

APENDIX K. CO2_Synth_V20.h

```
/*********************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ****/
/*********************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*********************************************************/
/*** DESCRIPTION: MAIN APPLICATION HEADER FILE       ****/
/*********************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      JAN 14,2016       ****/
/*********************************************************/

/***************** APPLICATION CPU FUSES ***************/

#fuses INTRC_IO               /*** OSC = Intosc I/O        ****/
#fuses NOPLLEN                /*** PLL = Unused, direct OSC **/
#fuses NOHFOFST               /*** HFINTOSC = Fast startup ***/
#fuses NOPUT                  /*** Power up Timer= Disabled **/
#fuses NOIESO                 /*** I/E Switchover= Disabled **/
#fuses NOFCMEN                /*** Failsafe monitor= Disabled*/

#fuses NOBROWNOUT             /*** Brownout= Disabled      ***/
#fuses BORV22                 /*** Brownout level = 2.2VDC ***/

#fuses NOWDT                  /*** Watchdog timer = Disabled */
#fuses WDT4096                /*** WDT postscaler = 1/4096 ***/

#fuses MCLR                   /*** MCLR= Enabled           ****/
#fuses NOPBADEN               /*** PORTB<5:0> RST digital   ***/
#fuses CCP2C1                 /*** CCP2 I/O = C1 Muxed      ***/
#fuses CCP2D2                 /*** ECCP2 Out = RD2 Muxed    ***/
#fuses CCP3B5                 /*** CCP3 I/O = B5 Muxed      ***/
#fuses TIMER3C0               /*** Timer3 CKI= RC0 Muxed    ***/

#fuses STVREN                 /*** Stack OVF/UNDF will RST ***/

#fuses DEBUG                  /*** Debug support= Unused   ****/
#fuses NOLVP                  /*** Single supply ICSP disable*/
#fuses NOXINST                /*** Instruction set = Legacy **/

#fuses NOPROTECT              /*** Code protected Block0...3 */
#fuses CPB                    /*** Boot block= Code Protected*/
#fuses CPD                    /*** Data EEPROM= Code Protect */
#fuses WRT                    /*** Block0...Block3 WR protect*/
#fuses WRTC                   /*** Config registers= Protect */
#fuses WRTB                   /*** Boot block= Write protect */
#fuses WRTD                   /*** Data EEPROM= Write Protect*/
#fuses EBTR                   /*** B0...B3 Table read protect*/
#fuses EBTRB                  /*** Boot blk = Tbl read protct*/
/*********************************************************/
```

```
/********* APPLICATION PREPROCESSOR DIRECTIVES *********/
#use Delay(clock=4000000)                       /*** Main osc **/
#use RTOS(Timer=0,minor_cycle=425mS)     /*** RTOS Dir **/
#use SPI (MASTER,FORCE_HW)                      /** SPI Config**/
/*******************************************************/

/*********** APPLICATION MACROS & DEFINES **************/
#define LED_PROCESS     PIN_D0            /** Sensing on-going  **/
#define LED_GASINTK     PIN_D1            /** Gas Intake telltale*/
#define LED_COOLING     PIN_D2            /** Cooling ON telltale*/
#define LED_SATURTD     PIN_D3            /** SHT11 sat telltale */
#define LED_HEATER      PIN_D4            /** Desat process ON  **/
#define LED_MANHEAT     PIN_D5            /** Manual forced HTR **/
#define BUTTON_HEAT PIN_B0          /** Forced heat Button */
#define CLR             0x00        /** Macro for bit clr **/
#define HEAT_BUTTON 0X01            /** Mask PORTB Pullups**/
/*******************************************************/

/********** APPLICATION FUNCTIONS PROTOTYPES ***********/
void System_Init(void);
void OLED_Splashscr(void);
void Clr_LEDS(void);
/*******************************************************/
```

APENDIX L. CO2_Synth_V20.c

```
/*******************************************************/
/*** ITESO. EMBEDDED SYSTEMS SPECIALIZATION PROGRAM  ***/
/*******************************************************/
/*** THESIS PROJECT: CO2 TO CaCO3 Synthesis system  ****/
/*******************************************************/
/*** DESCRIPTION: MAIN APPLICATION C FILE            ***/
/*******************************************************/
/*** ING. MANUEL TÉLLEZ-GIRÓN      FEB 12,2016      ***/
/*******************************************************/

/***************** INCLUDE FILES ***********************/
#include "18LF46K22.h"              /*** Device Header  ****/
#include "CO2_Synth_V20.h"          /*** Main app header ***/
#include "SHT11_Handler_V20.c"      /*** SHT11 sensor handr*/
#include "OLED_Handler_V20.c"       /*** OLED Disp handler */
#include "CO2_Synth_Tasks_V20.c"    /*** RTOS Tasks     ****/
/*******************************************************/

/****************** MAIN PROGRAM LOOP *****************/
void main()
{
      System_Init();                      /** Sensor warmup time */
      SHT11_Init();                       /** Sensor initialize **/
      OLED_Startup();                     /** OLED Initialization*/
      OLED_Clr_Scrn();                   /** Clear OLED screen **/
      OLED_Splashscr();                  /** Build OLED mainscr**/

      SHT11_Command(CMD_Soft_RST);       /** Issue a Soft RST  **/
      SHT11_Command(CMD_WR_Status);      /** Configure interface*/
      Output_D(CLR);                     /** Clears all LEDs    */
      RTOS_Run();                        /*** RTOS Dispatcher ***/
}
/*************************************************/
/** brief    CO2 Synth Application Initialization*/
/** author   Ing. Manuel Téllez-Girón          **/
/** param    void                              **/
/** return   void                              **/
/*************************************************/
void System_Init(void)
{
      Setup_ADC_ports(NO_ANALOGS);
      Setup_Comparator(NC_NC_NC_NC);
      Setup_SPI(SPI_MASTER|SPI_SCK_IDLE_HIGH|SPI_XMIT_L_TO_H|SPI_CLK_DIV_
16);
      Setup_CCP1(CCP_OFF);
      Output_LOW(SPI_SCLK);
      Output_HIGH(SPI_RES);
      Output_LOW(SPI_SDIN);
      Output_HIGH(SPI_CS);
      Port_B_Pullups(HEAT_BUTTON);
}
```

APENDIX M: Dew Point Calculation methods

DP0: Method 1 (Magnus Formula):

$$T_d(RH,T) = T_n \cdot \frac{\ln\left(\frac{RH}{100\%}\right) + \frac{m \cdot T}{T_n + T}}{m - \ln\left(\frac{RH}{100\%}\right) - \frac{m \cdot T}{T_n + T}}$$

m = 17.62
T_N= 243.12

DP1: Method 2:

$$Pr = \sqrt[8]{\frac{H}{100}} \cdot (110 + T) - 110$$

DP1-bis: Method 2 bis:

$$Pr = \sqrt[8]{\frac{H}{100}} \cdot (112 + 0.9 \cdot T) + (0.1 \cdot T) - 112$$

DP2:

$$\gamma(T, RH) = \ln\left(\frac{RH}{100}\right) + \frac{bT}{c + T};$$
$$T_{dp} = \frac{c\gamma(T, RH)}{b - \gamma(T, RH)};$$

b = 18.68
c = 257.14

DP3:

$$T_{dp} \approx T - \frac{100 - RH}{5};$$

Table 10. Dew point calculation errors compared against master plot

			CALCULATIONS					ERROR VS PLOT				
T	%RH	PLOT	DP0	DP1	DP1-BIS	DP2	DP3	DP0	DP1	DP1-B	DP2	DP3
10°	20%	-11	-11.98	-11.87	-12.05	-11.95	-6.00	0.98	0.87	1.05	0.95	5.00
	50%	0	0.04	0.04	-0.04	0.08	0.00	0.04	0.04	0.04	0.08	0.00
	80%	7	6.71	6.70	6.67	6.73	6.00	0.29	0.30	0.33	0.27	1.00
25°	20%	1	0.46	0.40	0.49	0.63	9.00	0.54	0.60	0.51	0.37	8.00
	50%	14	13.85	13.80	13.84	13.96	15.00	0.15	0.20	0.16	0.04	1.00
	80%	22	21.31	21.29	21.30	21.35	21.00	0.69	0.71	0.70	0.65	1.00
50°	20%	18	20.92	20.84	21.39	21.34	34.00	2.92	2.84	3.39	3.34	16.00
	50%	32	36.73	36.72	36.97	36.96	40.00	4.73	4.72	4.97	4.96	8.00
	80%	39	45.59	45.60	45.68	45.68	46.00	6.59	6.60	6.68	6.68	7.00

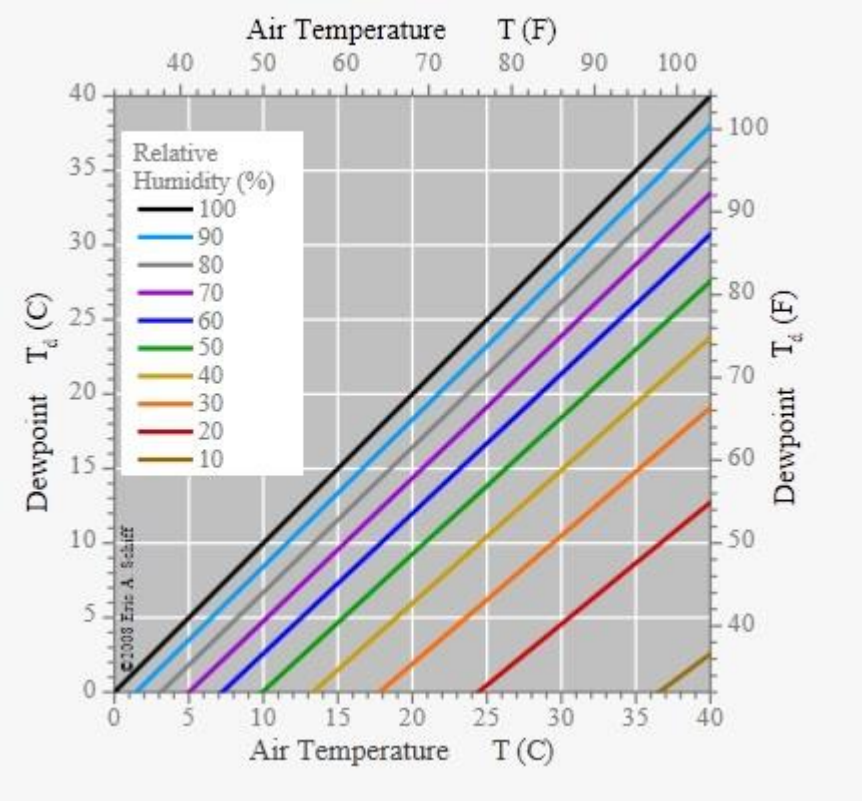

Figure 29. Dew point master plot