CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Electrical Engineering
Department of Measurement

Increased Moisture Detection and Early Warning System for Buildings

Systém pro včasnou detekci zvýšené vlhkosti v budovách

Master's thesis

Study program: Cybernetics and Robotics
Study field: Sensors and Instrumentation

Supervisor: Ing. Pavel Mlejnek, Ph.D.

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Pokyny pro vypracování:

Navrhněte a realizujte levný senzorový systém, který umožní monitorování vlhkosti a teploty stavebních konstrukcí (primárně dřevo, beton příp. izolační materiály) v několika kritických místech. Typicky se jedná o místa se zvýšenou možností úniku vodovodních, otopných a odpadních systémů, tedy kuchyně, koupelny, toalety a technické místnosti.

Systém se má skládat z cca 10 samostatných senzorů propojených komunikačním a napájecím kabelem a s napojením na centrální jednotku, která bude data vyhodnocovat. Systém má dlouhodobě monitorovat vlhkost v objektu a díky znalosti umístění senzorů má být možné přibližně určit oblast zvýšené vlhkosti a včas zajistit opravu.

Seznam odborné literatury:

[1] Vrána, J. a kol.: Technická zařízení budov v praxi. Grada Publishing, Praha 2007, ISBN 978-80-247-1588-9

[2] Vaverka, J., Havířová, Z., Jindrák, M. a kol.: Dřevostavby pro bydlení. Grada Publishing, Praha 2008, ISBN 978-80-247-2205-4

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V Praze dne 25. 11. 2013

[1] Platnost zadání je omezena na dobu tří následujících semestrů.

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Abstract

This master's project is focused on construction of system for moisture monitoring in building's structures and early warning in case of an accident.

This system is measures the moisture contained in the construction material. The measuring process is based on resistive method. Simultaneously other physical quantities having effect on moisture reading are measured. These functions are built-in in standalone intelligent sensor communicating via bus with superior system.

This project also includes central unit that processes data from several sensors. The data are stored on the SD card and potential problems in the building are detected from them. Maintenance service is warned in case of potential problem.

Keywords

Monitoring of buildings, moisture, relative humidity, temperature, Modbus RTU, intelligent sensor, sensor system, data acquisition and storing data.

Abstrakt

Tato práce se zabývá návrhem systému pro monitoring vlhkosti v konstrukcích budov a včasného varování v případě nehody.

Tento systém měří vlhkost obsaženou v materiálech rezistivní metodou. Současně jsou měřeny také ostatní veličiny mající vliv na určování vlhkosti. Tyto funkce jsou vestavěné do samostatného inteligentního senzoru komunikujícího s nadřazeným systémem po sběrnici.

Tato práce obsahuje také centrální jednotku schopnou zpracovávat data z několika senzorů. Data jsou ukládána na SD kartu a kontrolována pro vyhledávání možných problémů s vlhkostí v budově. Správce budovy je v případě možného problému upozorněn.

Klíčová slova

Monitoring budov, vlhkost, teplota, Modbus RTU, inteligentní senzor, senzorový systém, sběr a ukládání dat.

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Introduction

Recently, number of newly built wooden buildings in total number of buildings is increasing every year. It's due to the effort to use renewable resources. All of these buildings have to fulfil demanding tests on materials on strength, fire resistance etc. However it appears, that much more common problem than a fire can be leakage of operating liquids. The source of leakage can be water supply pipes, drains, heating system etc. This leakage might be very difficult to reveal, especially if it's small. It can last months or even years to show up any effect of this leakage. At this point the damage is usually fatal because there are wood-decaying fungi and moulds in the wooden structure. Remediation of this damage is very expensive because it includes replacement of some building structures.

Currently there are available commercial devices for wood moisture measurements on the market. However these instruments can take only single reading in accessible locations. The measurements can be done only randomly because presence of human operator is crucial. Moreover, there has to be access to the wooden structure and the task is time-consuming.

The aim of this project is to develop a system for detection of increased moisture in building, composed of several sensors combining moisture and temperature sensing and control unit. The assumption is that the sensors will be built-in during construction at critical points in the building with respect to placement of water supply pipes, drains and heating system or other systems that could cause waterlogging of building. These critical places can be bathrooms, toilets, kitchens, utility rooms etc. Also places situated next to the surrounding terrain are potentially dangerous, because the building may be waterlogged in case of hydro isolation failure. Sensors are mounted on these potentially dangerous places and they are connected via bus to central unit. The central unit collects data from sensors and evaluates them for possible failure.

Development of sensor is from the very beginning focused on compactness, robustness and low-costs, so it will be suitable for mass production.

1 Moisture in wood

1.1 Definitions

Wood is hygroscopic material capable of water exchange with its surroundings. Wood contains water in three forms:

1. **Free water**. Large volume of water in cell lumina is held only by capillary forces without any chemical bound. It's called free water. Free water is a thermodynamic state different from liquid water – energy is needed to overcome the capillary forces. It may contain chemicals changing the drying characteristics of wood.
2. **Bound or hygroscopic water**. Using hydrogen bonds, water is bonded to the wood.
3. **Vapours**. It's water in cell lumina in the form of water vapour. Providing normal temperature and relative humidity, vapours in the wood are negligible.

Absolute moisture content MC_{ABS} or relative moisture content MC_{REL} is most often used as a parameter describing wood moisture:

$$MC_{ABS} = \frac{m_G - m_{OD}}{m_{OD}} \cdot 100 = \frac{m_W}{m_{OD}} \cdot 100\ (\%) \tag{1.1}$$

$$MC_{REL} = \frac{m_G - m_{OD}}{m_G} \cdot 100 = \frac{m_W}{m_G} \cdot 100\ (\%) \tag{1.2}$$

where m_W (kg, g) is water mass contained in wood, m_{OD} (kg, g) is oven dry mass of wood, i.e. of completely dried wood, m_G (kg, g) is tested wet "green" wood mass

Editing (1.1) and (1.2) we can get conversion equations between absolute and relative moisture content:

$$MC_{REL} = \frac{100 \cdot MC_{ABS}}{100 + MC_{ABS}} \tag{1.3}$$

$$MC_{ABS} = \frac{100 \cdot MC_{REL}}{100 - MC_{REL}} \tag{1.4}$$

Relationship between absolute and relative moisture content illustrates Fig. 1.1

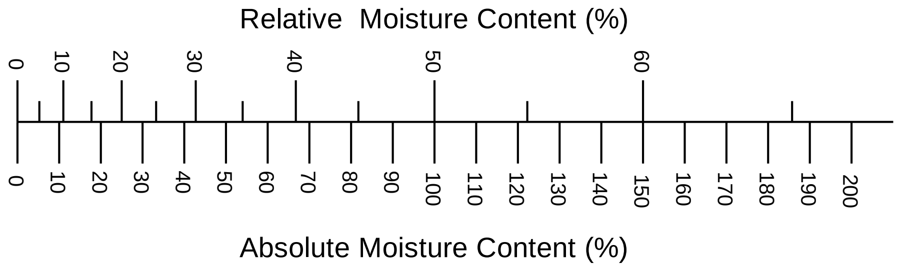


Fig. 1.1 - Relation between absolute and relative moisture content

Because relative moisture content is used rarely, every time when talking about moisture content it's meant absolute moisture content (as well as in this thesis). [1], [4], [6]

1.2 Methods of determining moisture content

1.2.1 Direct methods

Water content is determined directly measuring water mass removed from the wood. These methods are in general applicable only on wood sample and they are destructive, i.e. the moisture level is changed in the sample using these methods.

1.2.1.1 Gravimetric (weight) method

The gravimetric method comes out directly from the definition of moisture content. The weight of wood sample is measured and then the specimen is being dried at temperature 103 ± 2 °C. Every two hours the sample is weight. If the change in weight of two consecutive measurements is lower than 1 %, the sample is considered to be dried (moisture 0 %). The moisture content of the sample before drying process is determined using equation (1.1).

This method is used as reference for its reliability.

1.2.1.2 Distillation method

Using distillation process on the wood sample together with distillation medium (xylene, toluene, etc.) results in drying the wood sample and capturing the water extracted from the sample.

This method of determining wood moisture is faster than the gravimetric method (1.2.1.1).

1.2.2 Indirect methods

Water content is determined indirectly measuring different physical quantities dependent on the moisture content. These methods are applicable on large wood pieces and are non-destructive.

1.2.2.1 Electrophysical method

It is the most widely used method of measuring moisture content. The electrophysical characteristics affected by moisture content are resistivity, capacity, relative permittivity, power loss, dielectric loss and complex permittivity.

The moisture meters can be divided in to two groups:

- **resistive moisture meters** – measures resistance to determine the moisture content
- **dielectric moisture meters** – measures capacitance, permittivity, admittance or phase shift to determine the moisture content

1.2.2.2 Radiometric method

This method is based on absorption of different kind of rays.

1.2.2.3 Acoustic method

This method is based on changes of propagation speed or absorption of sound and ultrasound waves in the wood.

1.2.2.4 Wood shrinkage method

Method of determining average moisture in drying kilns based on wood shrinkage.

1.2.2.5 Weight-loss method

This method is used to determine average moisture content of a wood stack in a drying kiln. It is based on weight loss during drying process.

[2], [4], [6]

1.3 Resistive moisture meters

The function of resistive moisture meters is based on huge impact of electric resistance on moisture content in the wood. The resistance may vary from several kilo-ohms to several tera-ohms depending in the wood moisture and electrode system. The sensing electrodes contact the wood and connect the wood into the electric circuit which measures the resistance. These electrodes can have many shapes. For example penetrating electrodes, which are driven into the wood, surface electrodes which have contact created by external pressure against the wood's surface, etc. Each type of electrodes has its advantage is suitable for different application. The electrodes can be part of the moisture meter or external.

Fig. 1.2 – External penetrating pin electrodes with sliding hammer

(from http://accurate.kiwi/moisture/probe.htm)

The read resistance depend on the length of electrodes, distance between them, diameter etc.

Impact of the moisture on wood resistance can be express in form:

$$R = A \cdot M_R^B \tag{1.5}$$

$$M_R = \left(\frac{A}{R}\right)^{\frac{1}{B}} \tag{1.6}$$

where R (Ω) is the measured resistance in the wood, M_R (%) is the wood moisture read by sensor and A and B are coefficients related to the sensor's dispositions

Several moisture-to-resistance characteristics for different species coming from real data are shown on Fig. 1.3. Using those test data on equation (1.5), the coefficients A and B can be found using some mathematical application (e.g. MATLAB®). Those coefficients are unique for the electrodes system and for wood type.

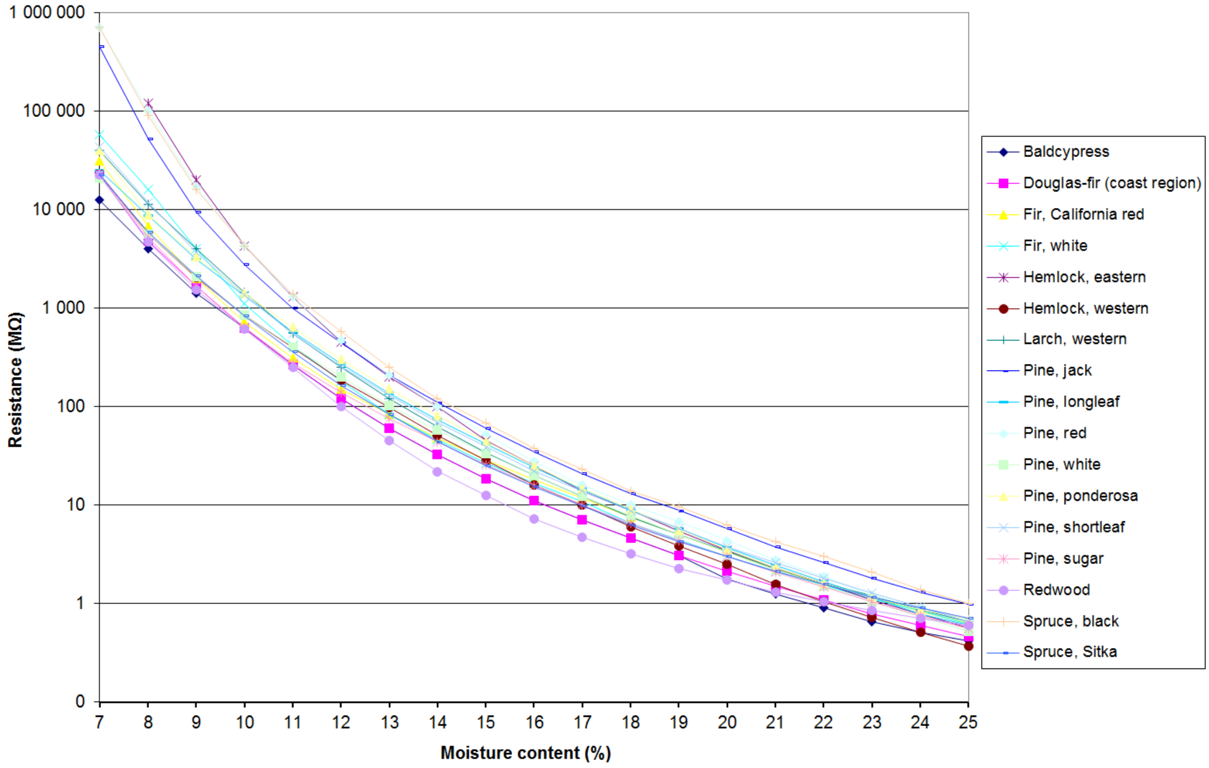


Fig. 1.3 - Resistance to moisture dependence for several wood species

(from http://woodgears.ca/)

1.3.1 Factors affecting moisture reading

The same conditions as there were during calibration process have to be guaranteed when taking moisture reading. Different conditions lead to inexact values. Some condition can be corrected.

1.3.1.1 Temperature

Increasing the temperature while keeping the moisture content constant, the resistance is decreasing. Using moisture meter at ambient temperature different from calibration temperature, the result has to be corrected for temperature.

The equation (1.7) shows empirically established formula for calibration temperature 22.8 °C.

$$M_T = \frac{M_R + 0.567 - 0.026\,\vartheta + 0.000051\,\vartheta^2}{0.881 \cdot (1.0056)^{\vartheta}} \tag{1.7}$$

where M_T (%) is the wood moisture with respect to ambient temperature, M_R (%) is the wood moisture read by sensor and ϑ (°C) is the ambient temperature

The characteristics described by equation (1.7) are shown on Fig. 1.4.

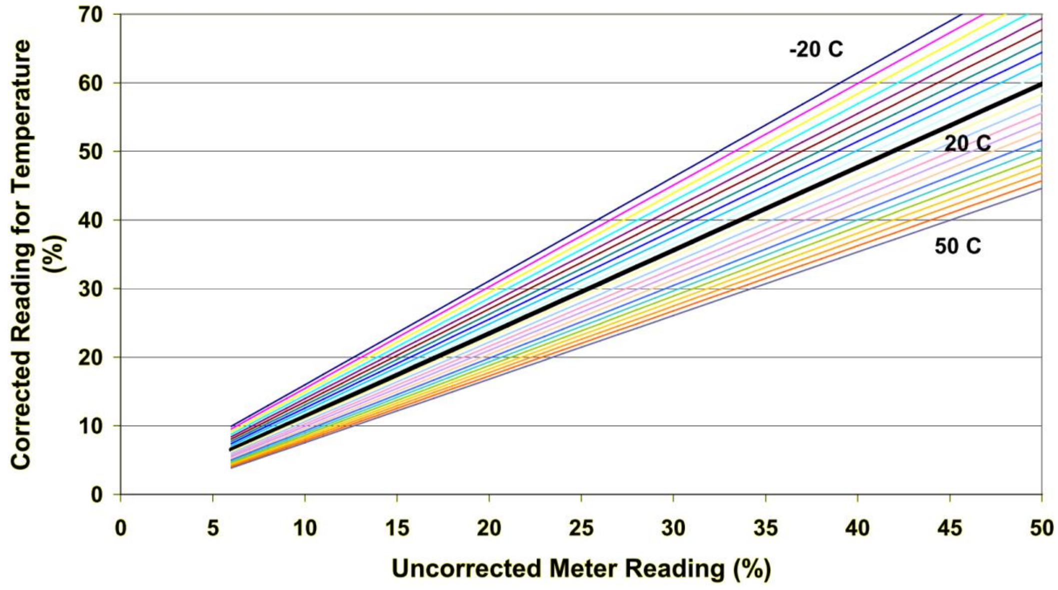


Fig. 1.4 - Temperature correction of moisture

(from [5])

1.3.1.2 Type of wood

Different wood species have different wood structure, density, etc. This fact results in different reading of resistance at the same moisture levels. It is possible to calibrate the moisture meter directly for every type of wood independently (equation (1.5)). More effective is to calibrate the moisture meter only for one type of wood (spruce is used most often) and then correct the value for different type of wood using equation (1.8). The coefficients a and b are independent on moisture meter's electrode configuration. Since those coefficients are same for every moisture meter, they are known and can be used more easily.

$$M_T = a \cdot M + b \tag{1.8}$$

$$M = \frac{M_T - b}{a} \tag{1.9}$$

where M (%) is the actual wood moisture, M_T (%) is the wood moisture corrected for ambient temperature and a and b are coefficients related to the type of wood

The Fig. 1.5 shows the results of correction for wood species according to equation (1.8).

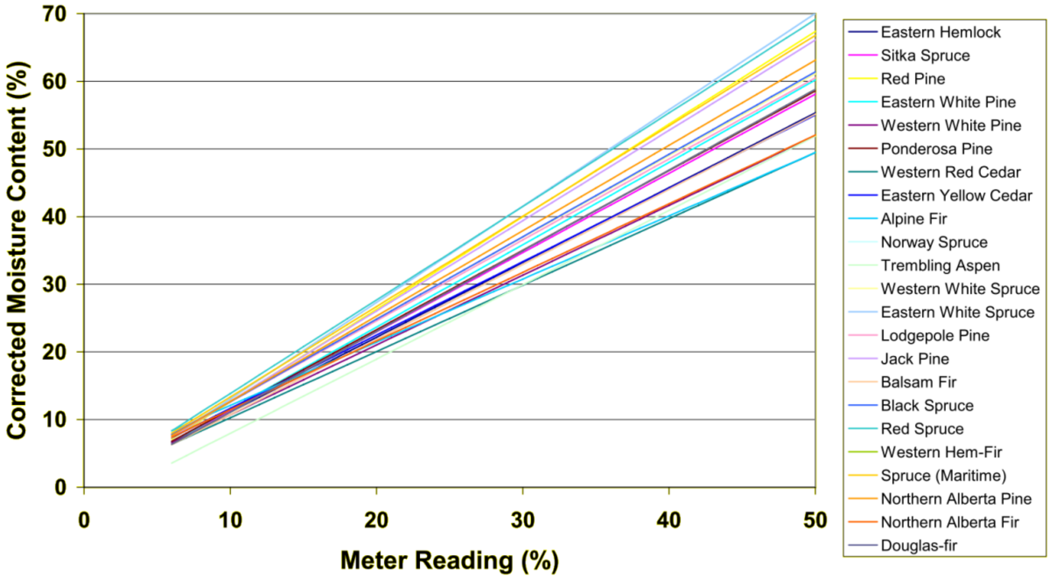


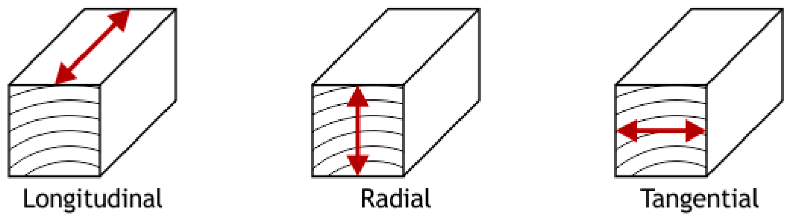
Fig. 1.5 - Species correction of moisture

(from [5])

It should be taken in account that contamination of wood by chemical, especially with ion character affects the moisture reading.

1.3.1.3 Anatomical structure of wood

The wood resistance has anisotropic character. In radial direction the resistance is 2 – 8x higher than in longitudinal direction. In tangential direction the resistance is approx. 10 % higher than in radial direction. The moisture meter can be calibrated for certain orientation of the electrodes. The orientation must respect when reading is taken.



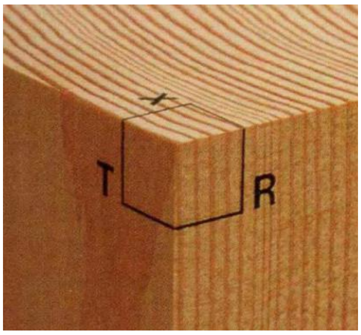


Fig. 1.6 - Wood directions

(from http://blog.lostartpress.com/)

Fig. 1.7 - Wood directions

(from [5])

To longitudinal direction is used more often, because changes in the length of timber with moisture are much smaller than in other directions.

1.3.1.4 Electrodes

Due to wood shrinkage during drying the electrodes may become loosen resulting in higher read resistance.

1.3.1.5 Polarization

The polarization effect rises on the border of electrodes and wood. It greatly depends on flowing current and takes shape mainly at moistures above 15 %.

1.3.1.6 Uneven distribution of moisture

It's obvious the moisture is measured at the placement of the moisture meter in case of moisture uneven distribution along the length of the timber.

In case the moisture is unevenly distributed along the depth of the timber, i.e. the surface has higher moisture content than the core, the situation is more complicated. For simplicity let's assume there is step distribution of moisture in the timber (in real it would be gradient distribution). Thus we are having 2 layers with different moisture content. From electrodes point of view, the layers are parallel resistors. From the theory of parallel connection of resistors in, the overall resistance would be smaller than each of them (equal to the smaller one in case of big difference between the resistors). The read moisture content thus corresponds to the layer with higher moisture content.

[1], [2], [3], [5]

2 Sensor unit

2.1 Principle of sensing moisture

Construction of sensor continuously measuring wood moisture requires usage of one of indirect methods of measuring moisture. Not all methods are suitable for application in low-cost permanently installed bus sensors.

Suitable method (chosen also for this thesis) is based on measuring changes in resistance between two electrodes installed in wood timber approx. 20-30 mm apart. Wood is very good isolation material. The resistance varies from several hundreds of kilo-ohms to several tens of giga-ohms according to moisture content.

Measuring resistance in so high ranges is not easy. Classical methods of measuring voltage and flowing current to determine electric resistance is unusable here. Too high voltage would have to be applied across measuring electrodes to generate measurable current. Better way is converting task of measuring high resistance to measuring time necessary to charge a capacitor through resistor formed by wood resistance. Method comes out from equation describing voltage *v(t)* on capacitor *C* being charged through resistor *R*:

$$v(t) = V\left(1 - e^{-\frac{t}{RC}}\right) \tag{2.1}$$

With knowledge of supply voltage V, time t, voltage on capacitor at this time $v(t)$ and capacitor's size *C*, it's easy to calculate measured value of resistance:

$$R = -\frac{t}{C \cdot \ln\left(1 - \frac{v(t)}{V}\right)} \tag{2.2}$$

Disadvantage of method described is measuring voltage on capacitor itself. Even using very good measuring instrumentation with high input impedance, current flowing to theirs input is too high in comparison with current charging capacitor. This affects charging the capacitor and making measuring almost impossible. Better solution is increasing voltage compare to reference voltage and measure time necessary to reach this threshold. Comparators (OPAMs) have in general very high input impedances.

It's necessary to discharge the capacitor in order to repeat the measuring process. This can be easily done connecting transistor in parallel with the capacitor. When transistor is in open state, capacitor's terminals are short-circuited. This capacitor is discharged and ready for next measurement.

Both ideas mentioned above can be realized using monostable multivibrator circuit (one-shot) integrated in well-known integrated timer circuit 555. This IC is very cheap and for its function needs basically only measuring capacitor. Those properties make this IC suitable for this low-cost application. The IC has built-in voltage divider creating comparing level on value of 2/3 of power supply voltage and built-in transistor handling also discharging capacitor. With suitable input impulse it's possible to start charging capacitor. On the output of IC impulse is generated with duration corresponding to time till comparator switch.

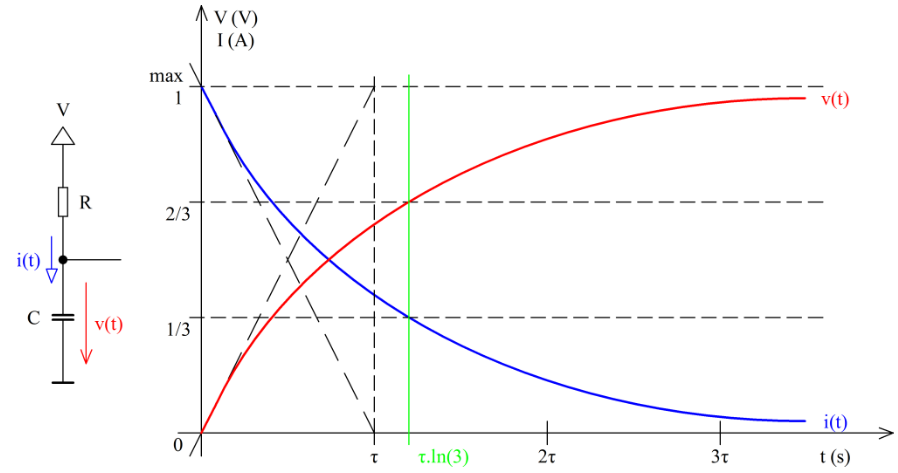


Fig. 2.1 - Charging curves of capacitor

Substituting the threshold level $(2/3\ V)$ instead of $v(t)$ in equation (2.2) it's possible to express new equation for calculating resistance R of measured sample:

$$R = \frac{t}{C \cdot \ln 3} \tag{2.3}$$

It's remarkable, that final relation is independent of power supply voltage V.

If we look into the 555-IC's structure, there are comparator and transistor. The simplified model of the input circuitry is shown on Fig. 2.2. There are parasitic currents I_{TH} and I_{DIS}. The I_{DIS} is reverse saturation current of transistor, i.e. current flowing through closed transistor. The I_{TH} is current flowing into the pin of comparator formed by OPAM. To learn more about this current, we would have to look also into the structure of OPAM, but it's not important for this model. Those parasitic currents are normally negligible and considered to be zeros. For example when charging a capacitor from 5 V power supply through 10 GΩ resistor, the maximal charging current will be 500 pA and will go down. Since we're dealing with very high resistances in case of low moistures (tens of giga-ohms), those currents are not negligible and must be taken in account.

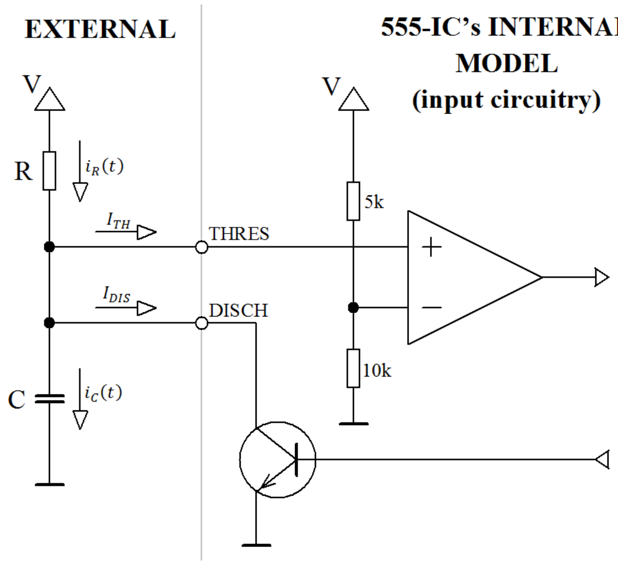


Fig. 2.2 - Model of input circuitry of 555-IC

The charging curves were shown on Fig. 2.1. The currents flowing through resistor and capacitors were equal. If we take in account the parasitic currents, we'll get:

$$i_R(t) = i_C(t) + I_{TH} + I_{DIS} \tag{2.4}$$

The charging of capacitor is terminated when voltage on capacitor reaches the threshold level $2/3\ V$. The remaining part $1/3\ V$ is on resistor. At the threshold level there is steady state:

$$v(t') = \frac{i_R(t')}{R} = \frac{i_C(t') + I_{TH} + I_{DIS}}{R} = \frac{i_C(t')}{R} + \frac{I_{TH} + I_{DIS}}{R} \tag{2.5}$$

That means the remaining $1/3\ V$ on the resistor is now given by sum of drop voltage caused by the parasitic currents and drop voltage caused by capacitor's charging current. Because the parasitic currents are constant, it's obvious that charging current has to become smaller exactly by value of parasitic currents. From charging curve of capacitor Fig. 2.1 it can be seen that, the current will drop to this level at some time t', where $t > t$. Therefore the measurement will finish later resulting in higher measured resistance after conversion (equation (2.3)) than the real resistance is.

Different and maybe easier to understand point of view to this problem is, that parasitic currents are creating constant part of voltage drop on the resistor. The voltage V', the capacitor is being charged from, is lower by this drop.

$$V' = V - (I_{TH} + I_{DIS})R \tag{2.6}$$

The equation (2.3) can't no longer be used, because it was derived for the threshold level 2/3 V and capacitor's charging voltage V. The equation (2.2) can be rearranged into form:

$$t = -RC \ln\left(1 - \frac{v(t)}{V}\right) = RC \ln\left(\frac{V}{V - v(t)}\right) \tag{2.7}$$

Applying steady state to equation (2.7):

$$t' = RC \ln\left(\frac{V'}{V' - v(t')}\right) = RC \ln\left(\frac{V - (I_{TH} + I_{DIS})R}{\frac{1}{3}V - (I_{TH} + I_{DIS})R}\right) \tag{2.8}$$

$$R = \frac{t'}{C \ln\left(\frac{V - (I_{TH} + I_{DIS})R}{\frac{1}{3}V - (I_{TH} + I_{DIS})R}\right)} \tag{2.9}$$

Unfortunately the equation (2.9) doesn't give easily visible conclusion. Common sense says if the capacitor is being charged from smaller voltage source (V', equation (2.6)) to the same threshold voltage ($2/3\ V$), it will last longer ($t' > t$).

Not only that the parasitic currents are creating errors when resistance readings are taken, they can make the reading impossible. In case the voltage drop on resistor caused by parasitic currents is even bigger than $1/3\ V$, the measurement is never finished, because the capacitor will never be charged to level exceeding the threshold $2/3\ V$.

There are several manufacturers fabricating 555-ICs. The selection was focused on parasitic currents. Texas Instruments TLC555C was chosen for its best datasheet parameters and also for its best performance during test.

	I_{TH} (pA)	I_{DIS} (pA)
Typical	10	100
Maximal	75	500

Tab. 2.1 - Parasitic currents of TLC555C

With 5 V supply voltage, the maximal possible measurable resistance would be approx. 15 GΩ when typical values are considered and approx. 3 GΩ when maximal values are considered.

It turned out it's possible to measure resistances even higher than 50 GΩ. It has to be taken in account that measured values might be affected by errors. [18]

2.2 Prototype

The prototype was designed after verifying the sensing principle on the breadboard.

The requirements on the sensor were small size, low costs and self-enumeration.

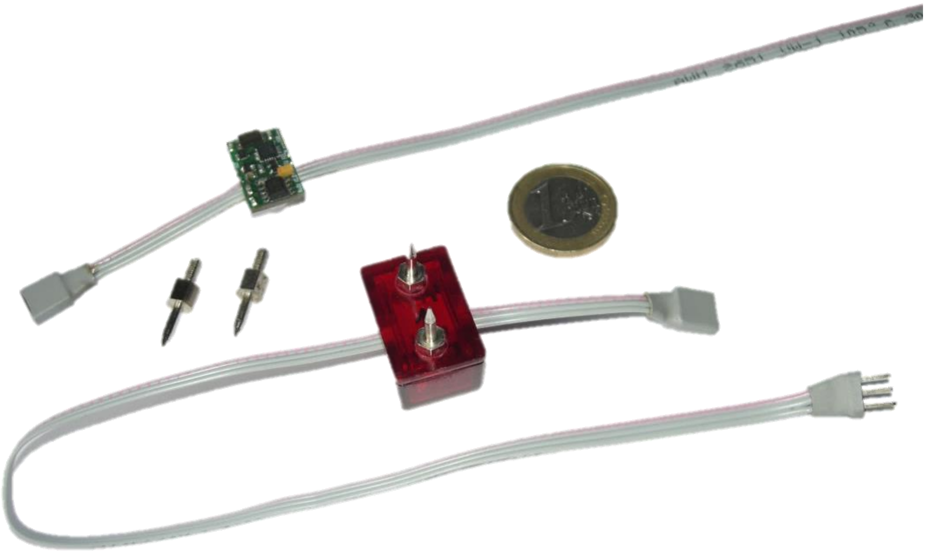


Fig. 2.3 - Photo of the prototype of sensor

2.2.1 Hardware

The design of circuit is attached in appendices (Appendix 2).

2.2.1.1 Enclosure

The designing process of sensor has started by searching suitable enclosure. The enclosure (Fig. 2.4) has outer dimensions 26.8 x 17.4 x 14.5 mm (length x width x height). The enclosure's material is ABS and it's available in dark black or translucent red variant. Main part and its cap holds together just by tight fit of those two parts.

Fig. 2.4 - Prototype's enclosure

(from http://www.tme.cz/)

2.2.1.2 Microcontroller

Heart of the sensor unit is 8 bit microcontroller Microchip PIC16F1508 (U1). From features used in this application, this microcontroller have program memory (4096 words), data memory (256 bytes), enhanced UART module (EUSART), 10b ADC, gated timer and other timers and counters. The MCU has small package (QFN20, 4 x 4 mm)

Although the microcontroller has built in RC oscillator capable of running on several frequencies, external 12 MHz crystal (XTAL1) is used. This ensures more stable clock for the microcontroller through various temperatures and over years.

There is programming ICSP connector (X4). Its presence enables changing firmware in already soldered microcontroller. In fact it’s not connector at all, but only a row of pads with pitch 1.27 mm. The centres of the pads are located on the edge of PCB, so the pads are cut in half by board outline during milling process. Programming is done pressing connector against those pads and running programming process. This method saves lot of place on the PCB. [7]

2.2.1.3 Wood resistance measurement

The measuring principle was described in 2.1.

The timer TLC555C (U2) is working in monostable multivibrator circuit. There are two brass nuts M2.5, 15 mm apart soldered on the PCB (X2, X3) for connecting two sensing electrodes in timber. This solution was used due to fact these electrodes (Fig. 2.5) are available on the market as accessories for handheld moisture meters and it makes this sensor unit cheaper. The electrode’s diameter is 2 mm and its active sensing length is 10 mm. It is made from stainless steel, but detailed specifications of its properties are unknown. Sensing capacitor is film dielectric for stability through varies temperatures an over years. Its capacitance was chosen to be as big as possible, but offering sufficient acquisition time. In this setup it will take approximately 60 s to charge the 1.2 nF capacitor on 2/3 power supply voltage threshold through 45 GΩ resistance.

Fig. 2.5 - Prototype's electrode

(from http://www.voltcraft.cz/)

There are signals RST for resetting the monostable multivibrator and putting it to the idle state and TRIG for starting the charging process. The signal OUT is gating the MCU's timer. Because the gating pin shares function with programming pin, there is separating resistor (R3) inserted between OUT and MCLR signals.

2.2.1.4 Temperature sensing

The microcontroller has built in Temperature Indicator Module. It is based on inverse dependence of diode's forward voltage and temperature while constant forward current is fed through the diode. This dependency is described by Shockley equation:

$$I = I_S \cdot \left(e^{\frac{q\,V_T}{n\,k\,T}} - 1\right) \tag{2.10}$$

where I is the current, I_S is the reverse saturation current, q is the magnitude of an electron charge, V_T is the voltage across the diode, n is a junction constant, k is Boltzmann's constant, T is temperature in Kelvin

Each diode has temperature coefficient −1.32 mV/°C. The module is using 2 or 4 (selectable) diodes in series to maximize the temperature impact on the diode's forward voltage (−5.24 mV/°C using 4 diodes in series). The voltage has to be converted using built in ADC (1 LSB ≈ 4.88 mV).

Achievable resolution of this measuring method would be good with external amplifier. Unfortunately the MCU doesn't provide this option. Without external amplifier using just built in ADC, the resolution is poor, just about 1 °C ideally (no additional errors are counted, e.g. quantization noise). Moreover offset of the forward voltage can vary a lot from microcontroller's part to part. The differences can be even 10 – 20 °C between microcontrollers from the same lot and even up to 70 °C between microcontrollers from various lots. The slope (voltage dependence on temperature) is consistent part to part, but can differ with different power supply voltage. Therefore at least single-point calibration would be necessary in order to remove the huge offset, but of course two-point calibration would be better to calibrate also the slope. [7]

Nevertheless, the built in Temperature Indicator Module is dedicated only as temperature indicator, not precise temperature sensor. External temperature sensor has to be used to measure the temperature in the moisture sensor.

The temperature sensor was chosen with respect to price. Microchip MCP9700A (U3) is a low-power analogue thermometer converting temperature to analogue voltage, which is optimized for use with ADCs. Its measuring range is from −40 to +150 °C with accuracy within range 0 – 70 °C of ±1 °C typically, ±2 °C maximally and within range −40 – +125 °C of ±1 °C typically, −2 °C, +4 °C maximally. The sensor's sensitivity is 10 mV/°C. [12]

The output of the sensor is the analogue voltage, so use of ADC is required. Using built-in ADC in MCU (1 LSB ≈ 4.88 mV) it is giving resolution better than 0.5 °C. Using additional statistical method, resolution is improved up to 0.05 °C.

One of the pins of the temperature sensor is directly connected to the electrodes. This ensures heat transfer between the timber and the sensor itself, so the sensor measures temperature in the wood.

2.2.1.5 Communication bus

The physical layer of communication bus is inspired by LIN bus. LIN is a simply low-cost bus developed for used in automotive systems. The bus communicates just over one wire bidirectionally. The topology should be bus, but it's not critical. There are low demands on application conditions – basically just MCU with UART module and LIN driver is required. The bus uses 12 V signalling and communicates on low speed, typically 19200 bit/s. The whole bus system was design to be tolerant to oscillator's deviations.

The bus can connect up to 16 devices using master-slave access method, which is deterministic thus there are no collisions. The exception may be collision when event polling procedure initiated by master. The collision is detected and each case is solved individually.

The model of LIN bus driver is shown on Fig. 2.6. There are two states on the bus – recessive (logical 1) and dominant (logical 0). The bus driver is open-collector type and it has weak pull-up resistor. There is stronger pull-up in the master unit. During recessive state the transistor is closed, therefore the bus line is pulled high. When transistor is opened, the bus line is shorted to the ground.[18 [19]

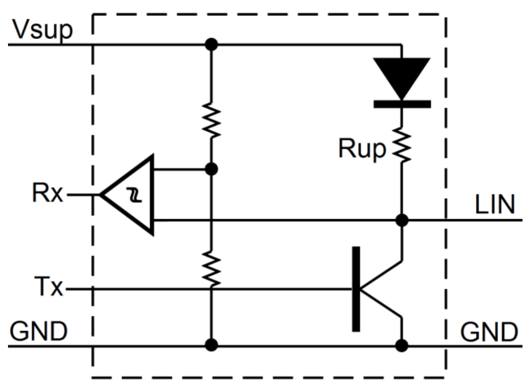


Fig. 2.6 - LIN driver principle of work

(from [23])

The bus used in the developed sensor uses 5 V signalling, because whole sensor is supplied by 5 V power supply and just 2400 bit/s speed is used for higher robustness. The LIN bus uses static slave addresses, which has to be unique and known in the system. In my case, there was a special demand on the bus system, that it shall be self-enumerating. That means there are no static slave addresses and the addresses are assigned dynamically by master during initiation of the bus (enumeration process). The addresses are assigned in the order of the slaves on the bus. This enables localization of sensor on the bus and no manual address setup is needed.

To implement this auto-enumeration process, the bus needed some changes. The bus can no longer be just one long wire connecting every sensor. The bus is split in each sensor and analogue multiplexer (U4) is inserted between those two ends of lines. This enables to connect unenumerated sensors to the master unit one-by-one. While the sensor is not enumerated, rest of the bus line is unconnected. When the enumeration of the sensor is done, another sensor is connected to the bus system and thus to the master unit.

The voltage levels on the transmitting pin of the MCU has to be inverted (in the meaning of standard UART frame). Pulling up the bus line is done by pull resistor (R2). 10 kΩ value is weak enough, because there is already stronger pull up in the master unit (approx. 1 kΩ). Pulling down is done by transistor (Q1).

2.2.1.6 General

The analogue switch (U4) operates in range from 1.65 V to 5.5 V, the MCU (U1) and the temperature sensor (U3) operate in range from 2.3 V to 5.5 V and the timer (U2) operates in range from 2 V to 15 V. Therefore the sensor should be capable to work in range from 2.3 V to 5.5 V. Even though resistance measuring is independent on supply voltage, using as high as possible supply voltage is recommended. This will inhibit leakage currents to affect measuring process. It was tested that supply voltage in range from 4.5 V to 5.5 V works well. There is no voltage regulator used, so it should be ensured supply voltage is stabilized and without noise. The power consumption is 2 mA.

For connection to superior system, 3-wire cable is needed – 2 powering wires and 1 communicating wire. The communication wire has to be split in order to create bus system, therefore 4-way connector is needed. Easy installation is assured using 3-way ribbon cable together with 4-way IDC connector.

Installation process is done in several steps:

- position of sensor is marked on the timber
- 2 holes for electrodes are predrilled (diameter 1 mm, 15 mm apart)
- position of sensor is marked on the cable
- communication wire (outer wire) of ribbon cable is cut in half
- cable is installed to the connector making sure communication wire is installed properly
- connector's housing is pressed making conductive connection of cable and connector
- cap of enclosure is slid on electrodes and sensor is installed on the timber
- main part of enclosure is installed

The PCB has dimensions 21 x 12 mm to fit into the enclosure. There are main connector (X1) and two nuts for the electrodes (X2, X3) placed on one side of the PCB. All other components are placed on the other side. There is programming connector (X4) on the side of PCB. The PCB is 2-layer. The PCB design and bill of material are attached in the appendices (Appendix 7, Appendix 8).

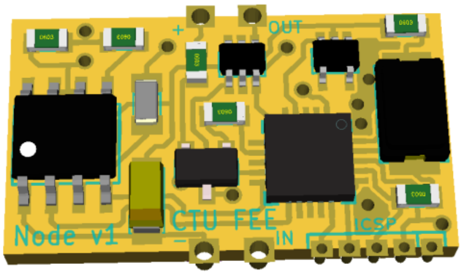


Fig. 2.7 - 3D visualization of sensor's prototype PCB

2.2.2 Firmware

The measurement tasks run continuously, i.e. once the measurement of temperature and resistance is done, new acquisition is started. All measured values are smoothed using moving average function with windows width 8 samples.

2.2.2.1 Resistance

According to 2.1, the resistance measurement is converted to the time measurement. For this purpose the MCU is equipped by gated timer. That means the timer counts the clock signal only if there is active state on the gating input pin.

The result of measurement is number of clock's periods over the length of gating impulse in the capture register. Multiplying the number of clock's ticks by clock's period, the time is obtained. Using formula (2.3), the time is converted to the resistance.

The measuring time is limited to 45 s. In case this period is exceeded, the value is considered to be as maximal measurable, i.e. approx. 40 GΩ. The resolution is 2 kΩ. The resistance value is in kΩ and is stored in 32 bit register.

2.2.2.2 Temperature

The temperature is sampled by MCU's internal ADC.

The temperature is in °C and is stored in 16 bit register with two fixed decimal places.

2.2.2.3 Communication

Every frame on the bus line consists of synchronization (4 bytes 0x55), address (1 byte), data (N bytes) and checksum (1 byte). The communication is master-slave and sensor answers only if it is addressed.

After powering up, the sensor is in unenumerated state. It has address 0 and disconnected the bus switch. First the address has to be changed. The master sends command, where new address is contained in the data field. From now the sensor has its unique address and is considered to be enumerated. The bus switch is turned on to enable the enumeration process of another sensor on the bus. If there is no other sensor to be enumerated, the master doesn't get the response from new generated address changing command. Enumeration process is finished sending broadcast (address 0) command telling the sensors to proceed to the operational state.

In the operational state if sensor is addressed, it answers with values of temperature and resistance. The values have to be split into bytes and are sent most significant byte first.

2.3 Final version

Final version was developed based on experience obtained from the prototype and from new demands coming from market research.

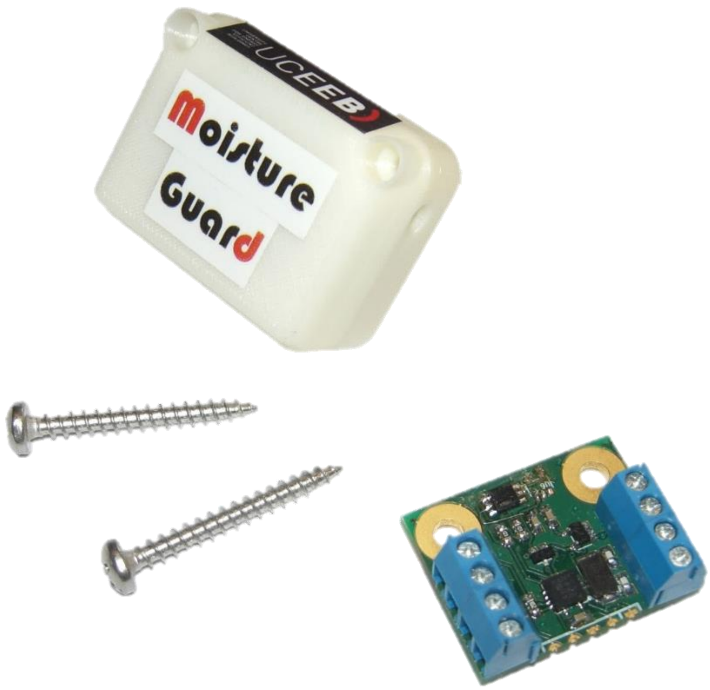


Fig. 2.8 - Photo of the sensor unit

2.3.1 Hardware

The design of circuit is attached in appendices (Appendix 3).

2.3.1.1 Microcontroller

Microcontroller was changed in the final version. Microchip PIC16F1825 for the same price as Microchip PIC16F1508 offers two times bigger program memory (8192 words), four times bigger data memory (1024 bytes) and in addition it has EEPROM memory (256 bytes). It has lower pin count (12 I/Os), so the package can be smaller (QFN16, 3 x 3 mm).

In this version ADC won't be used any more, I2C feature will be used instead. [7[8]

2.3.1.2 Wood resistance measurement

In the prototype, one of the electrodes was connected to the supply voltage, which may lead to the wood polarization effect (1.3.1.5). In this version the electrode is connected to the output of MCU and thus can be driven high, low and also into high impedance state. The 1 kΩ resistor (R3) was inserted in order to limit the current in case of electrode's shortcut. This value is negligible against the measured value.

The electrodes became loosen due to wood shrinkage during drying processes. This is huge problem, because contact of the electrodes with wood is crucial to proper measure the wood resistance. New system of mounting sensor and sensing resistance in the timber had to be used. Wood screws ensure good mounting of sensor and also very good contact of the electrodes with wood. The screws have to have anti rust finish to last over years. Used wood screws are made from stainless steel. The length *l* is 30 mm (the active length is therefore approx. 20 mm) and the diameter d_1 is 3.5 mm. The screw has dome head with diameter d_2 7 mm. It is Pozidrive (PZ2) screw drive type. In the PCB there are holes with tight fit for those screws (approx. 0.2 mm larger in the diameter) with pad around it.

Fig. 2.9 - Electrode (wood screw)
(from http://www.nastatecku.cz/)

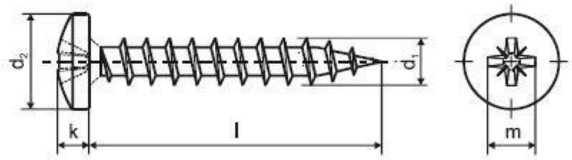


Fig. 2.10 - Electrode's (wood screw's) dimensions
(from http://www.briol.cz/)

2.3.1.3 Temperature sensing

It turned out that the temperature sensor MCP9700A used in prototype has insufficient accuracy. Considerable impact for precision had also ADC built in MCU. Therefore digital sensor Microchip MCP9800 (U6) was chosen, which eliminates other errors in acquisition chain.

Typical accuracy of this sensor is ±0.5 °C at +25 °C and maximal accuracy is ±3 °C within whole operating range from −55 to +125 °C. However this range is unusable for this application, the usable range from −10 to +85 ° has accuracy ±1 °C. [13]

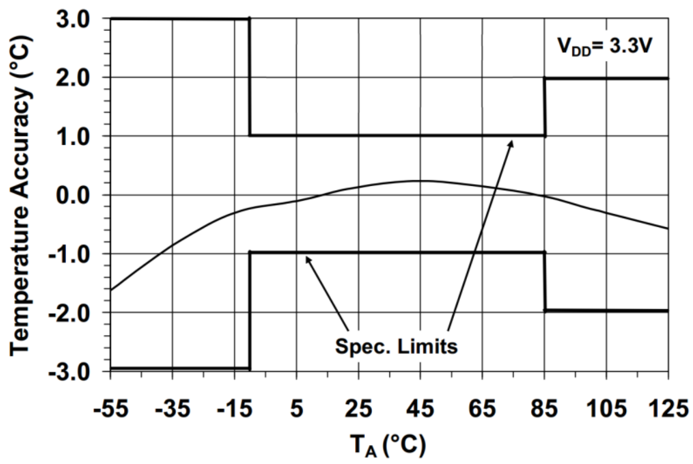


Fig. 2.11 - Maximum accuracy of temperature for MCP9800 sensor

(from [13])

2.3.1.4 Relative humidity sensing

New demand on the sensor was to have optional capability to measure also relative humidity of air. For those purposes fully integrated sensors Sensirion SHT20, SHT21 or SHT25 (U5) were chosen. Those sensors are interchangeable, because they have same package and pinout. The only difference between them is the accuracy tolerance, which is redeemed by its price. The cheapest one is SHT20 while the best is SHT25. Those sensors are equipped by I^2C bus.

Mostly the middle version of this sensor will be used. The parameters of SHT21 humidity sensor can be seen in Tab. 2.2. The maximal accuracy tolerance for this sensor is determined by the Fig. 2.12.

RELATIVE HUMIDITY	SHT20	SHT21	SHT25
Resolution	0.04 %RH		
Accuracy tolerance (typical)	±3 %RH	±2 %RH	±1.8 %RH
Accuracy tolerance (maximal)	?	see. Fig. 2.12	?
Repeatability	±0.1 %RH		
Hysteresis	±1 %RH		
Nonlinearity	<0.1 %RH		
Operating range	0 – 100 %RH		

Tab. 2.2 - Relative humidity parameters of Sensorion's sensors

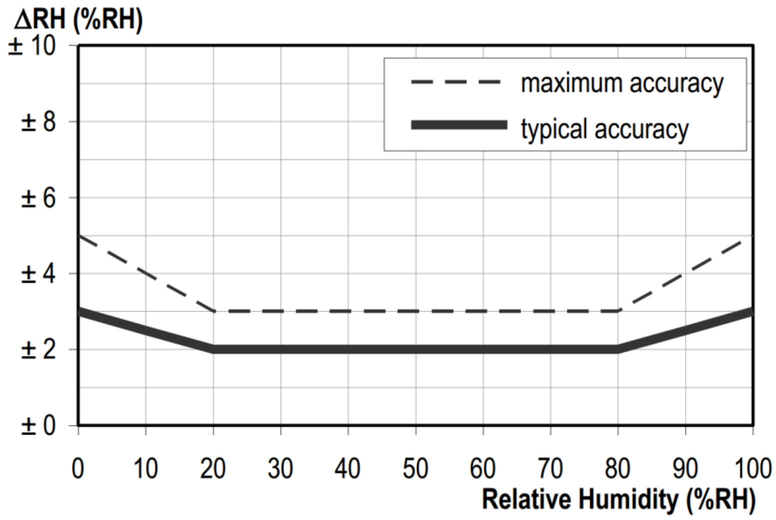


Fig. 2.12 - Typical and maximal tolerance of relative humidity for SHT21 sensor

(from [17])

These sensors have also built in temperature sensor. This makes this combined sensor more useful. The parameters of SHT21 temperature sensor can be seen in Tab. 2.3. The maximal accuracy tolerance for this sensor is determined by the Fig. 2.13.

TEMPERATURE	SHT20	SHT21	SHT25
Resolution		0.01 °C	
Accuracy tolerance (typical)	±0.3 °C	±0.3 °C	±0.2 °C
Accuracy tolerance (maximal)	?	see. Fig. 2.13	?
Repeatability		±0.1 °C	
Operating range		−40 – +125 °C	

Tab. 2.3 - Temperature parameters of Sensorion's sensors

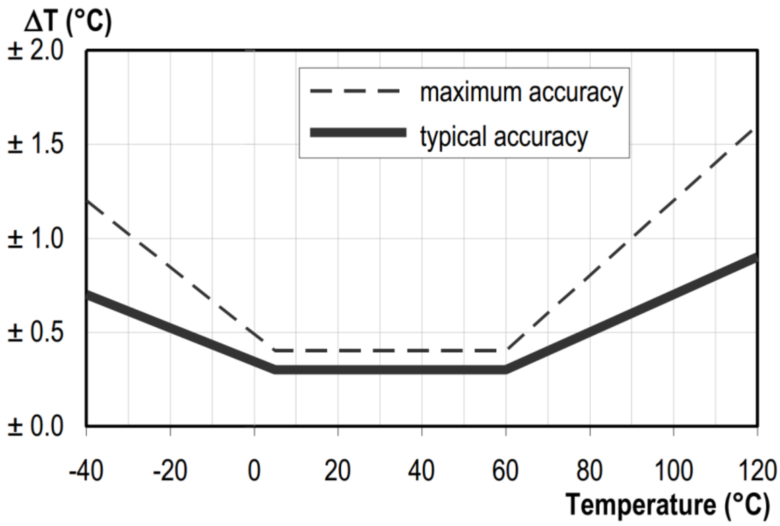


Fig. 2.13 - Typical and maximal tolerance of temperature for SHT21 sensor

(from [17])

If humidity sensor is assembled, dedicated temperature sensor (2.3.1.3) can be omitted. [16[17]

2.3.1.5 Communication bus

Even though the custom bus (2.2.1.5) used in prototype was working well, commonly used bus is better choice. Different communication buses can offer better robustness, therefore communication on longer distances or with higher speeds is possible.

As one of commonly used buses was chosen RS-485 (EIA/TIA-485) bus. This bus uses differential line to communicate in half-duplex mode. It uses line driver which is taking care of differential signalling. The disadvantage is already mentioned necessity of bus line driver, which makes the PCB design slightly larger and increases the costs. RS-485 needs 2 wires for communication instead of 1 wire and self-enumerating won't be possible anymore.

To use benefits of robustness of RS-485, cable with twisted pairs should be used. For cable 1200 m long the communication speed can be up to 100 kbit/s. Communication speed of 35 Mbit/s might be used, when distance is not exceeding than 10 m. RS-485 can handle up to 32 devices on bus. Termination resistors 120 Ω should be used on both sides of the bus.

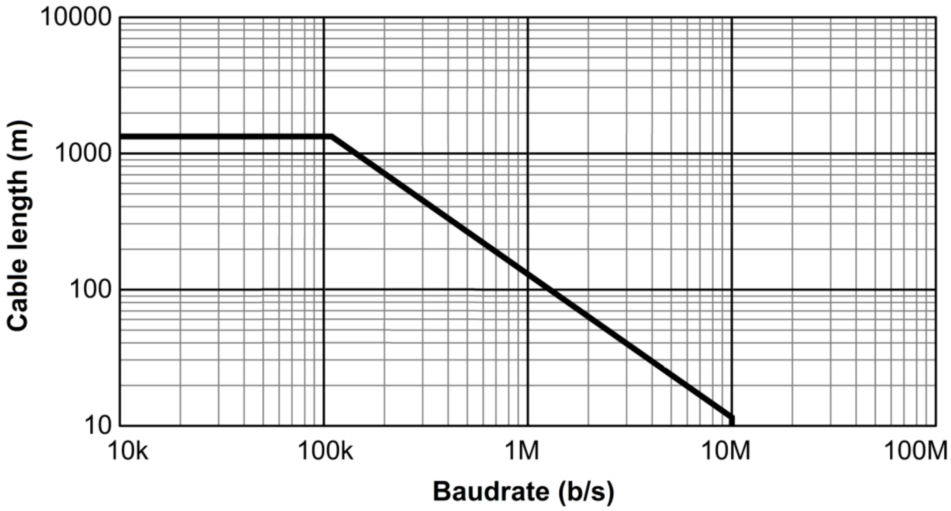


Fig. 2.14 - RS-485: speed vs. distance

(from http://e2e.ti.com/)

It will be possible to connect the sensor directly to PLC without any gateway. Also the properties (distances, speeds, reliability etc.) are known, because there are many articles about this bus.

There is RS-485 driver Texas Instrument SN65HVD72 used with resistors (R5, R6) and TVS diode (D3) as protection against overvoltage, bursts etc. on signal lines. [19]

2.3.1.6 General

There was a demand on sensor to be capable to work from 5 V power supply. In addition wide input voltage range should be supported. Ultra low-dropout voltage regulator Texas Instruments LP2985-4.5 (U3) was used to get as high as possible stabilized voltage for powering the components. The output voltage is 4.5 V giving the regulator up to 0.5 V dropout voltage as a regulating reserve. In this setup, the regulator should reject any disturbances on the power line. Rated maximal input voltage of the regulator is 16 V which is also the maximal input voltage of the sensor. The sensors current consumption is 3 mA. [20]

The humidity sensor (U5) requires power supply voltage to be in range from 2.1 V to 3.6 V and the RS-485 driver (U2) requires supply voltage in range from 3 V to 3.6 V. Even though the temperature sensor (U6) can work in range from 2.7 V to 6 V, it has to use same supply voltage as humidity sensor. It's because of connecting it to the same I^2C communicating bus, whose 2 lines have to be pulled up (R1, R2). Another voltage regulator could be used, but simpler and cheaper solution is to drop the voltage on diodes. The 2 diodes in series (D2) will have dropout voltage around 1.3 V (0.65 V each) at rated supply currents. This will provide 3.2 V for powering the components.

The sensor needs 4 wires to be connected to the superior system – 2 powering wires and 2 communication wires. For easy installation screw terminal block shall be used and for easier construction of bus structure, this terminal block should be doubled.

2.3.1.7 PCB and enclosure

The PCB was designed so it has the smallest possible dimensions. Basically the size is determined by the interface connectors (X1 and X2) and holes for the electrodes (X3). The components are placed on both sides of 2-layer PCB, which dimensions are 29 x 23 mm. The PCB design and bill of material are attached in the appendices (Appendix 7, Appendix 9).

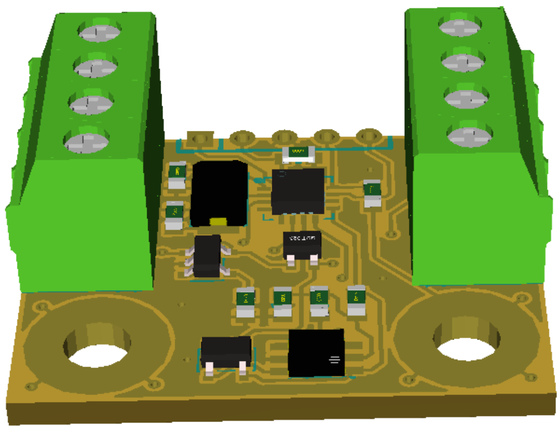


Fig. 2.15 - 3D visualization of final sensor's PCB

Special care has to be taken in account when soldering the SHT21 sensor (U5). This sensor has hole to enable air humidity enter the chip. It's not possible to use cleaning chemicals to remove residues after soldering. It is recommended to solder all components except the sensor, clean the PCB and then solder the sensor itself.

Custom enclosure was designed for final version of sensor unit and was printed on 3D printer. The enclosure has dimensions 42 x 31 x 18 mm. It is made out of ABS-M30 material, the printing process takes about 1.5 hours.

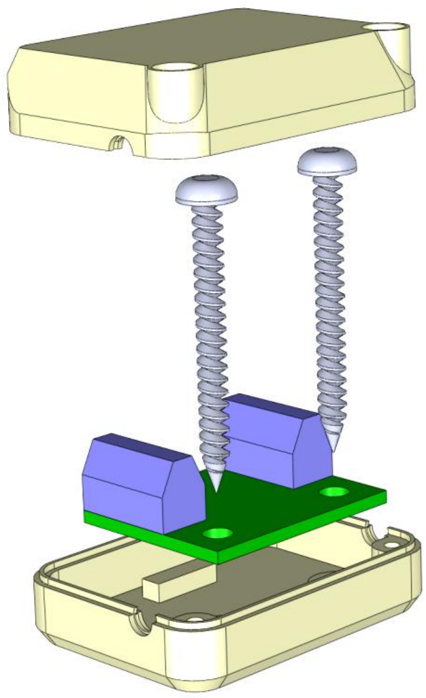


Fig. 2.16 - 3D visualization of final sensor's enclosure

2.3.2 Firmware

The sensor implements setting of many parameters including the calibration coefficients, bus communication settings, etc. These parameters are stored in non-volatile memory in the MCU.

The measurement tasks are triggered with selectable period. All measured values are smoothed using moving average function with selectable windows width from 0 to 32 samples independently on each measured value.

2.3.2.1 Resistance and moisture

The measuring process is same as in prototype (2.2.2.1).

The measuring time is limited to 45 s. In case this period is exceeded, the value is considered to be as maximal measurable, i.e. approx. 50 GΩ. The resolution is 2 kΩ. The resistance value is in kΩ and is stored in 32 bit register. The value can be calibrated on scale and offset using equation (2.11).

$$y = kx + q \tag{2.11}$$

where y is the calibrated value, x is the measured value, k is the scale factor and q is the offset

The measure resistance is converted to the moisture content (formula (1.6)). Then the temperature correction takes place (formula (1.7)) and finally the wood species correction is done (formula (1.9)).

The moisture value in % is stored in 16 bit register with two fixed decimal places.

2.3.2.2 Temperature and relative humidity

The temperature and humidity are read out via I^2C bus.

The temperature in °C and the relative humidity in % are stored in 16 bit register with two fixed decimal places. Values can be calibrated on scale and offset using equation (2.11).

2.3.2.3 Communication

The Modbus RTU protocol (4.1) is implemented.

The address space is divided into several parts representing the registers defined by Modbus standard:

Address	Length	Content	Notes
0x2000	5 words	Information about sensor	Writable only if section is unlocked (code 0xE302)
0x3000	32 words	User's text description	
0x4000	5 words	Measured values	Read only
0x5000	15 words	Calibration data	
0x8000	3 words	Configuration of sensor	Writable only if section is unlocked (code 0x0001), takes effect after reset

Tab. 2.4 - Address space of sensor

There are some sections, which are protected for writing. Wrong settings of configuration section can cause that the master unit might not be able to communicate with sensor anymore, so the user has to confirm the operation by special code. The information section shouldn't be accessed by user at all. Writable rights are needed only during manufacturing, when sensor's identificators are assigned. These sections are in default locked for writing and are read-only. Trying to write these sections at locked state results in error message the section does not exist. Using configuration function (0) with unlocking code results in unlocking section. The section becomes writable, but only for the next command. After that is automatically locked.

Address	Content
0x2000	Type of sensor
0x2001	Serial number
0x2002	Hardware version
0x2003	Firmware version
0x2004	Sensor's chip code

Tab. 2.5 - Address space of sensor - information section

There is space of 64 bytes for user-defined text description, e.g. location of the sensor. Each address location contains two characters.

The temperature, humidity and moisture are stored with two fixed decimal points. The resistance is split into two registers.

Address	Content
0x4000	Temperature
0x4001	Humidity
0x4002	Moisture
0x4003	Resistance
0x4004	

Tab. 2.6 - Address space of sensor - Measured values section

The scale coefficients are stored with three fixed decimal points, the offset coefficients have two fixed decimal points. Coefficients A, B, a and b correspond to equation (1.6) and (1.9). They are all stored with three fixed decimal points.

Address	Content
0x5000	Sampling rate
0x5001	Temperature – scale
0x5002	Temperature – offset
0x5003	Temperature – averaging window
0x5004	Humidity – scale
0x5005	Humidity – offset
0x5006	Humidity – averaging window
0x5007	Moisture – A
0x5008	Moisture – exponent of A
0x5009	Moisture – B
0x500A	Moisture – a
0x500B	Moisture – b
0x500C	Resistance – scale
0x500D	Resistance – offset
0x500E	Resistance – averaging window

Tab. 2.7 - Address space of sensor - Calibration section

The communication speed are 1200 Bd, 2400 Bd, 4800 Bd, 9600 Bd, 19200 Bd, 38400 Bd and 57600 Bd. The parameter describing the speed is an index from 0 to 6, where 0 is the slowest and 6 is the highest communication speed. The parameter describing parity is 0 (no parity, 2 stop bits), 1 (odd parity) or 2 (even parity).

Address	Content
0x8000	Sensor's address
0x8001	Communication speed
0x8002	Communication parity

Tab. 2.8 - Address space of sensor - Configuration section

3 Control unit

3.1 Prototype 1

This prototype was built just in order to test the prototype of sensors, thus it will be described just briefly. Its function is to store data from connected sensors to its internal memory. The data can be then transferred to the PC.

The design of circuit is attached in appendices (Appendix 4).

3.1.1 Hardware

MCU Microchip PIC18F25K22 (U1) was chosen for its availability in home stocks. It has many features, but just two UART modules and 32 kByte of non-volatile memory are used. There are both program and data stored in the non-volatile memory.

The sensor's bus interface is connected to the UART module of MCU. The sensor's bus interface is built in compliance with 2.2.1.5. The second UART of MCU is brought out in order UART to USB convertor could be connected.

There is red LED (D1) signalling the device is not measuring.

The system is powered directly from 5 V power supply. There is no linear regulator, so the power supply should be stable and noise free. Laboratory power supply was used.

The prototype was assembled on breadboard. [9]

3.1.2 Firmware

The control unit can be controlled using the aforementioned UART to USB converter, which appears as virtual COM port in PC. The device communicates with speed 57600 Bd, 8 data bits, no parity with any terminal program. All sent data are only printable data except of CR and LF characters for a new line.

Sending character 'i' or 'I' to the device returns information, which guides the user through all functions of device. Controlling the device using this system of guidance is very intuitive.

Command	Name	Description
i / I	Information	Printing the list of available commands.
s / S	Start/Stop	Starting or stopping the acquisition.
r / R	Read	Read out the content of memory.
e / E	Erase	Erasing the memory.
p / P	Period	Logging period setup.
d / D	Debug	Entering or leaving special mode, in which the communication over sensor’s bus is also printed to the terminal window.

Tab. 3.1 - Control unit prototype's commands

After starting the acquisition, user is asked to put up to 14 character long text describing the measurement (e.g. date and time of acquisition start).

The control unit enumerates connected sensors and periodically reads out the data. The data are stored in non-volatile FLASH memory which is built in in the MCU. The memory has capacity to store data from 4 sensors with 15 minutes read out period for approximately 9 days. In case the memory is filled, the acquisition is terminated and user is warned by the LED.

3.2 Prototype 2

This prototype was built also only for testing purposes of the prototype of sensors, thus it will be described just briefly. Basically this unit creates a gateway between the sensors and superior system. The superior system is PLC SDS MACRO, which is connected to the internet and there is application on the server collecting all the data and storing them to the database. [9]

The design of circuit is attached in appendices (Appendix 5).

3.2.1 Hardware

There is only one demand on microcontroller – two UART modules. MCU Microchip PIC18F25K22 (U1) was chosen for its availability in home stocks.

There is RS-485 driver (U2) connected to the first UART module of MCU. The sensor's bus interface is connected to the second UART module of MCU. The sensor's bus interface is built in compliance with 2.2.1.5.

The system is powered from 24 V power supply. There is linear regulator (U3) providing 5 V for its own operation and for operation of the sensors.

The prototype was assembled on breadboard.

3.2.2 Firmware

The control unit enumerates the connected sensors after powering up. Then it periodically reads out their measured values and keeps those values in its memory.

The simplified version of Modbus RTU protocol (4.1) is implemented. Only read functions are implemented, anything else is not necessary for desired functionality. Superior system can read out information about amount of sensors on the bus and theirs values.

3.3 Final version

The final version doesn't come out from the prototype versions much, because it is designed to use with final versions of sensors and work as standalone device. The requirement on the master unit were: to be capable to work with 10 sensors with intuitive showing their status, be configurable over the USB, storing data on commonly used SD card, has alarm and enables connecting to home security system.

The design of circuit is attached in appendices (Appendix 6) and more photos of the control unit can be seen also in appendices (Appendix 13).

Fig. 3.1 - Photo of the final version of control unit

3.3.1 Hardware

3.3.1.1 Power supply

The unit requires external power supply with 5.5 x 2.1 mm barrel jack. There is Graetz bridge (D2) on the input line, so both AC and DC power adapter can be used without any care of polarity.The device can run from 9 V to 32 V DC or from 6 V to 24 V AC. The device has low power consumption, power supply with rated current 300 mA is sufficient. The actual consumption depends on amount of sensors attached and the state, e.g. alarm on.

There is TVS diode (D6) on the input protecting the device against high voltage on the input or bursts on the input. High voltage at the input cases opening the TVS diode and blowing the fuse (F1) and disconnecting the rest of the device from power supply.

There are linear voltage regulators (U4, U6) giving voltage 5 V and 3.3 V for powering the components.

3.3.1.2 Microcontroller

The microcontroller was chosen with respect to peripherals needed in this application. Those are USB module for communication with PC, SPI bus for interfacing SD card, I^2C bus for interfacing the RTCC and UART module for RS-485 bus. Also other I/Os are necessary and obviously enough large program and data memory to enable to implement all necessary functions.

Chosen 8 bit microcontroller Microchip PIC18F46J50 has USB module, two MSSPs configurable to work either in SPI or I^2C mode, two EUSART modules and many other peripherals, i.e. timers/counters, ADC, RTCC etc. The MCU is in TQFP44 package and have 44 pins, so it has sufficient amount of I/Os. There are 64 kBytes of FLASH program memory and 3776 Bytes of SRAM data memory.

Microcontroller from PIC18 family was chosen for its low price and many similarities with PIC16 family used in sensor unit.

The MCU is clocked using external 12 MHz crystal. It is possible to derive clock 48 MHz using internal system of frequency dividers and PLL. The 48 MHz is necessary for USB to work in accordance with USB 2.0 specifications.

The MCU can be programme in the same way as the sensor unit – via ICSP connector. For debugging purposes and maybe future use, there is UART connector.

Even though the MCU is powered by 3.3 V (3.6 V rated maximal power voltage), some of the pins are up to 5.5 V tolerant. This makes easy connection between MCU and components working with 5 V power. [10]

3.3.1.3 Communication

Same communication with sensor's bus (2.3.1.5) must be used in order to communicate with them. Same components were used to minimise amount of different components to be order when building the devices.

There is bus driver Texas Instruments SN65HVD72 (U2), protecting TVS diode (D8) and protecting resistors (R8, R9).

The RS-485 communication bus should be terminated at the beginning and at the end. It's expected the control unit to be the very first device on the bus. Therefore termination resistor 120 Ω (R12) is used. Unlike the slave's implementation (sensor), the master's implementation (control unit) has to define the idle voltage on bus lines. This is done via pull-up and pull-down resistors (R10, R11).

3.3.1.4 Micro SD card

In order to interface the SD card, SPI bus is used. The card is powered from 3.3 V. The pull-up resistor R34 is required, while R27, R28 and R35 are optional and on the PCB they are not assembled.

Fig. 3.2 - Micro SD card

(from http://cmkcellphones.com/)

The slot for the micro SD card is equipped with contact detecting presence of card in the slot.

3.3.1.5 USB

It is required the USB implementation meets the specification of USB 2.0 protocol. Three sizes of USB connectors are available. Mini version is suitable for devices like this one.

Fig. 3.3 - USB2.0 logos

(from http://www.displaybank.com/)

Fig. 3.4 - Standardized USB 2.0 connectors

(from http://www.usbcables.com/)

Because the MCU has physical layer of USB already implemented, no further components are needed. Voltage from USB host is connected through voltage divider (R26, R27) to MCU's input pin enabling sensing whether USB is physically connected.

3.3.1.6 Controlling interface

There is 10-LED-segment two coloured bargraph and also one two coloured LED. Their purpose is to provide simply information about status of whole system. [22]

The IC SCT2167 (U3) works as 8-channel current source for driving the LEDs. The current is adjustable by resistor (R2). The IC has serial interface, thus channel switching can be done via SPI bus. [21]

Switchable current sources connected to cathodes of LEDs together with switching transistors connected to anodes of LEDs create multiplex system of driving the LEDs using minimal amount of MCU's pins.

To make simple setups of the system, two buttons (labelled as 'A' and 'B') are implemented. The pull-ups are built in MCU and capacitors (C3, C6) are creating debouncing filter.

3.3.1.7 Alarm

The buffer (SP1) is used to inform user about possible problem. The buzzer's rated sound intensity is 85 dB at 2.4 kHz. The buzzer does not have built in generator thus it has to be driven by external signal.

The relay (RE1) is used for interconnection this system with home security system. The relay's contacts are rated for switching voltage up to 240 V AC and current up to 10 A. The relay has both NO and NC contacts.

3.3.1.8 Real-Time Calendar/Clock

To keep information about time and date during power cuts, there is built-in RTCC in the MCU. However using this MCU's function requires powering the MCU during the power cut, which creates bigger requirements for backup power source. Therefore dedicated IC Microchip MCP7940N (U5) with low power consumption was used. The IC is clocked by 32.768 kHz crystal (XTAL2).

There has to be a backup power source to power the IC during power cuts. Often used backup source is li-ion battery or the supercapacitor.

It's expected that power cut won't last more than couple of days. Thus 5 days (120 hours) backup time should be sufficient. The backup time is determined from capacitor's capacity, initial voltage of charged capacitor, minimal voltage of discharging capacitor when the RTCC can still operate and current consumption.

The capacitor will be charged from 5 V, but there is drop approx. 0.6 V on diode (D7). The diode prevents all other components except the RTCC to be powered from the capacitor. The drop voltage could be minimized to approx. 0.3 V using Schottky diode. In general the Schottky diodes have larger reverse leakage current which would lead to discharging of capacitor. The maximal voltage thus will be 4.4 V. The minimal voltage is 1.3 V, when the RTCC ensures the time keeping functionality. Specifying the RTCC's current consumption is complicated, because it depends on actual backup voltage (Fig. 3.5).

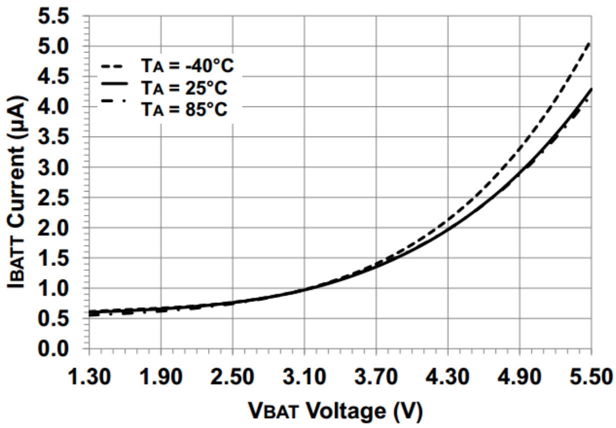


Fig. 3.5 - MCP7940N-RTCC's current vs. backup voltage

(from [14])

The RTCC has rated typical current consumption 925 nA at 3 V. This gives us internal resistance of RTCC R_{RTCC} approx. 3.24 MΩ. For basic estimations, let's make simplification this internal resistance is constant through various supply voltages.

The voltage on capacitor is time is described as:

$$v(t) = V \cdot e^{-\frac{t}{RC}} \tag{3.1}$$

Rewriting the equation (3.1) in terms of used quantities we'll get:

$$V_{MIN} = V_{MAX} \cdot e^{-\frac{t}{R_{RTCC} \cdot C}} \tag{3.2}$$

where V_{MIN} (V) is minimal operating voltage of RTCC, V_{MAX} (V) is maximal voltage of capacitor, R_{RTCC} (Ω) is internal resistance of RTCC, t (s) is desired backup time, C (F) is capacitor's capacitance

Editing the equation (3.2) we will get expression for capacitance:

$$C = \frac{t}{R_{RTCC}} \cdot \ln \frac{V_{MAX}}{V_{MIN}} \tag{3.3}$$

The equation (3.3) is giving required capacity of capacitor approx. 163 mF. The closest larger value is 220 mF. With this larger capacitor and using same simplifications, the backup time will be 162 hours, which is almost 7 days.

Supercapacitors are sensitive devices and must be charged by small current. The resistor (R13) is limiting the maximal charging current to approx. 44 mA. The capacitor will charge in about 24 minutes from fully discharged state. [14]

3.3.1.9 PCB and enclosure

The control unit is supposed to be installed in distribution board, so the enclosure should be mountable to the DIN rail. The amount and size of all connectors determined the size of the enclosure to be 3-module size (52.5 mm width). The chosen enclosure CP-Z-107 has dimensions 90 x 65 x 52.5 mm. The enclosure is made from ABS material.

Fig. 3.6 - Control unit's enclosure

(from http://www.tme.cz/)

The labels on the enclosure were designed and printed on self-adhesive paper and laminated. They are attached in appendices (Appendix 12) in full scale.

The PCB design consists of 2 boards. The smaller board has dimensions 40 x 46.5 mm. There are LEDs, buttons, USB connector and slot for micro SD card on smaller board. The larger board has dimensions 86 x 46.5 mm. There are connectors on the top and bottom of the board using prepared holes in enclosure, the MCU and all other components, which are not necessary to be placed on the smaller board. Connection between those two boards is done with 45 mm long pin headers. The amount of connecting pins was minimized to 20 connections. Therefore there are two 10-pin headers on each side. The PCB designs and bill of material are attached in the appendices (Appendix 10, Appendix 11).

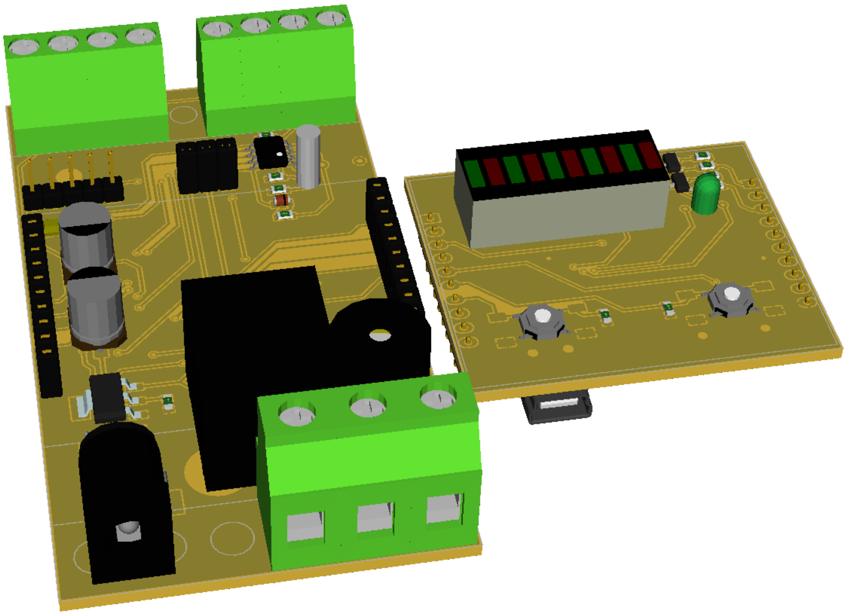


Fig. 3.7 - 3D visualization of final version sensor's PCB

There are connectors (X1, X6) combining communication bus together with power supply voltage for connecting the sensor units. The communication connector is doubled to make the bus installation easier if bus structure cannot be used. One of those connectors can be omitted. This connector can be used also for connecting other devices to the control unit, e.g. other sensors, RS-485 to Ethernet converter etc.

3.3.2 Firmware

After powering up, the control unit performs test of the LEDs and piezo buffer.

Than the control unit performs periodical tasks: reading out the sensor's values, checking them for possible problem, showing sensor's statuses, logging data on memory card. In the meantime, it can serve the commands coming from the USB from superior PC application.

3.3.2.1 Communication

The Modbus RTU protocol (4.1, 0) was implemented. After powering up, the control unit scans the bus and stores the addresses of found sensors in the table. The values from sensors are read out periodically with configurable period and temporary stored in the device.

3.3.2.2 View and alarms

Immediately after the values are read from the sensors, the moisture from each sensor is checked against configurable thresholds and the status is showed on the bargraph.

Each sensor in the system has its own LED in the bargraph. The LEDs are occupied consecutively from the left and the order is determined by the sensor's address. Each LED has 3 colours options: green, orange and red. The green colour means the value is under the first threshold, i.e. there is no problem with moisture. The orange colour means the value is between the first and the second thresholds, i.e. there is slightly higher moisture than normally. The red colour means the value exceeded the second threshold, i.e. there is problem with moisture.

The particular LEDs of bargraph are showing the actual state, i.e. the last read value. There is also a LED common for all sensors. It has the same colours with same meaning. The only difference is that the LED remembers the worst state, i.e. if there was a problem but it isn't anymore, the LED stays red.

Together with the exceeding the second threshold value, the alarm is triggered. That means the relay goes on and piezo starts intermittently beeping. The alarm is persistent in same way as the LED – once it's triggered, it lasts. The alarm can be disabled (relay off, mute piezo) pressing and holding the 'A' button. The whole system can be reset to its working state both disconnecting from the power supply or pressing and holding the 'B' button.

3.3.2.3 SD card

There is Chan's FatFs library used, so the device works with FAT systems (FAT12, FAT16, FAT32). That means no raw data are stored on the card, but they are arranged in the file system, that PCs can work with. [16]

If SD card is detected in the slot, it is automatically mounted and new file is created. The filename is "LOGxxx.CSV", where 'xxx' is automatically increased number. The data are stored to this file with configurable period. The file is opened for writing and then it's closed, thus the file doesn't remains opened and the card can be removed at any time. The advantage of CSV file is that it can be easily read by any spreadsheet application.

Each record in the file consists of timestamp, sensor address, temperature value, relative humidity value, moisture value and resistance value. The values are comma separated and each record in terminated by CR and LF characters.

```
timestamp,sensor,temperature,humidity,moisture,resistance
15,004,22.75,-327.67,17.10,29.839
15,007,21.87,34.79,16.67,40.316
30,004,22.68,-327.67,16.90,33.501
30,007,21.95,34.52,16.97,33.875
45,004,22.75,-327.67,17.11,29.673
45,007,21.96,33.69,16.66,40.238
60,004,22.75,-327.67,17.06,30.589
60,007,22.00,34.79,16.62,41.120
```

Fig. 3.8 - Part of the file stored on the SD card

3.3.2.4 USB

The USB is implemented via Microchip's framework. The device full fills the specifications of USB 2.0 and CDC class. That means after connecting to the system, it appears as virtual COM port. For the Windows based systems, drivers may be needed, on the Linux systems no drivers are needed. [15]

Implementation of CDC class means, that there is opportunity of easy communication through any terminal application and also easy accessibility for user's applications from any programming environment.

The device receives commands represented by a character sent from the terminal window. For example for printing the data from sensors to the terminal window, user has to send command 'o'. The data are represented in the same way as are stored on the SD card (3.3.2.3).

4 General

4.1 Modbus RTU protocol

Modbus RTU and Modbus ASCII are versions of Modbus communication protocol for asynchronous serial communication over a variety of media (RS-232, RS-422, RS-485, fiber, radio etc.). The communication is master-slave. There is only one master on the bus and up to 247 slave devices.

In Modbus RTU raw data bytes are sent while in Modbus ASCII just printable characters are sent. Using same communication speed, Modbus RTU has twice higher throughput as Modbus ASCII, because in ASCII mode each data byte has to be split into 2 characters. Therefore Modbus RTU is implemented in devices used more often and Modbus ASCII as used as optional communication protocol.

Fig. 4.1 - Modbus logo

taken from http://www.modbus.org/

Modbus RTU prefers RS-485 bus using setup 9600 Bd or 19200 Bd, 8 data bits (Modbus ASCII 7 data bits), even parity. This setup is not strict and other can be used. Possible communication speeds are in range from 1200 Bd to 115200 Bd.

Each sent data byte has standard UART format (word) – start bit, 8 data bits (Modbus ASCII 7 data bits), parity bit and stop bit. This means for transferring 1 data byte, 11 bits (Modbus ASCII 10 data bits) are needed. The parity can be even, odd or none. If no parity is used, the parity bit is replaced by additional stop bit so the length of frame is kept fixed on 11 bits (Modbus ASCII 10 data bits).

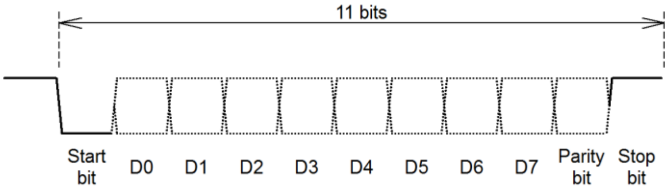


Fig. 4.2 - Modbus RTU word

(from [24])

Modbus RTU message is consisting of series of consecutive words (maximal delay between words cannot be longer than 1.5 times the time duration of word). Messages are divided by time spaces, which have to be at least 3.5 times the time duration of word. The maximal length of Modbus message is 256 bytes.

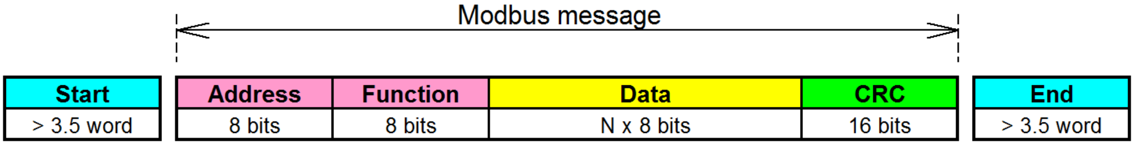


Fig. 4.3 - Modbus RTU message

(from [24])

The address space consists of 256 different addresses. Device address has to be unique on the bus. The units can be address in unicast mode or in broadcast mode. In unicast mode, particular slave device is address, the device answers. In broadcast mode, all slave devices are address, the devices doesn't answer.

Address	Meaning
0	Broadcast
1 - 247	Individual slave address
248 - 255	Reserved

Tab. 4.1 - Modbus addresses

Modbus protocol defines 3 classes of function codes:

- Public function codes – validated by MODBUS.org community, unique
- User-defined function codes – possible implementation of not specified functions
- Reserved function codes – not available for public use

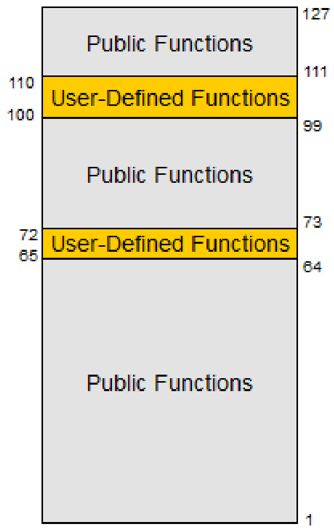


Fig. 4.4 - Modbus function code space

(from [25])

If not states otherwise, Modbus works with 16 bit variables. Each variable has to be split into 2 bytes in order to be transferred. They are sent high order byte first.

For error detection there is 16 bit CRC generated by $x^{16} + x^{15} + x^2 + 1$ polynomial. The CRC is counted from all data bytes in the message except the CRC bytes itself. The CRC is always sent low order byte first.

4.1.1 Errors

When sending message to the slave device, four scenarios can occur:

- Slave receives the request and is able to process it normally, normal response is sent back.
- Slave doesn't receive the request due to error in communication, no response is sent.
- Slave receives the request, but detects a communication error (parity, CRC), no response is sent.
- Slave receives the request without any communication error, but it's not able to process it, exception response is sent back.

The exception response has error code instead of function code. The error code is formed setting the highest bit in received function code. Passed parameter is exception code.

Field	Size	Possible values
Device address	1 B	1 to 247
Error code	1 B	0x80 | received function code
Exception code	1 B	01, 02, 03 or 04
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.2 - Modbus exception response

Exception code	Name	Meaning
01	Illegal function	Unsupported function code was received. It could be cause also by state of slave such uninitialized device.
02	Illegal data address	Trying to access non existing register space. The error is sent even if just some part of accessed register space does not exist.
03	Illegal data value	A value contained in the query data field is invalid in the meaning of data consistency (correct length etc.). It is not a range checking on values passed to the device.
04	Slave device failure	An unrecoverable error has occurred while attempting to perform the requested action.

Tab. 4.3 - Modbus exception codes

4.1.2 Functions

There are many function codes supported by Modbus protocol. Not all of them are necessary for device function, thus don't have to be implemented. In Tab. 4.4 there are used functions in this project. In this project there is no difference between input registers and holding registers as Modbus specifies that. Please notice, there are 3 standard functions and 2 user-defined functions.

Function code	Function name
03, 04	Read registers
06	Write single register
16	Write multiple registers
101	Reset
102	Configuration

Tab. 4.4 - Implemented Modbus functions

4.1.2.1 Read registers function

This function is used to read the content of registers. The inputs are the address of first register and amount of registers to be read.

Field	Size	Possible values
Device address	1 B	0 to 247
Function code	1 B	03 or 04
Starting address	2 B	0x0000 to 0xFFFF
Quantity of registers	2 B	1 to 125
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.5 - Modbus read register function - request

Field	Size	Possible values
Device address	1 B	1 to 247
Function code	1 B	03 or 04
Byte count	1 B	2x N
Register value(s)	N x 2 B	0x0000 to 0xFFFF
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.6 - Modbus read register function - response

4.1.2.2 Write single register function

This function is used to write single register. The inputs are register's address and value to be written.

Field	Size	Possible values
Device address	1 B	0 to 247
Function code	1 B	06
Register address	2 B	0x0000 to 0xFFFF
Register value	2 B	0x0000 to 0xFFFF
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.7 - Modbus write single register function - request

Field	Size	Possible values
Device address	1 B	1 to 247
Function code	1 B	06
Register address	2 B	0x0000 to 0xFFFF
Register value	2 B	0x0000 to 0xFFFF
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.8 - Modbus write single register function - response

4.1.2.3 Write multiple registers function

This function is used to write multiple registers. The inputs are address of the first register, amount of registers to be written and consecutive values to be written.

Field	Size	Possible values
Device address	1 B	0 to 247
Function code	1 B	0x10
Starting address	2 B	0x0000 to 0xFFFF
Quantity of registers	2 B	1 to 123
Registers value(s)	N x 2 B	N x (0x0000 to 0xFFFF)
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.9 - Modbus write multiple registers function - request

Field	Size	Possible values
Device address	1 B	1 to 247
Function code	1 B	0x10
Starting address	1 B	0x0000 to 0xFFFF
Quantity of registers	2 B	1 to 123
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.10 - Modbus write multiple registers function - response

4.1.2.4 Reset function

This function is used to reset the device. There are no input parameters.

Field	Size	Possible values
Device address	1 B	0 to 247
Function code	1 B	101
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.11 - Modbus reset function - request

Field	Size	Possible values
Device address	1 B	1 to 247
Function code	1 B	101
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.12 - Modbus reset function - response

4.1.2.5 Configuration function

This function is used to setup some nonstandard features like accessing the bootloader, unlocking protected registers etc.

Field	Size	Possible values
Device address	1 B	0 to 247
Function code	1 B	102
Sub-function code	2 B	0x0000, 0xE302
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.13 - Modbus configuration function - request

Field	Size	Possible values
Device address	1 B	1 to 247
Function code	1 B	102
Sub-function code	2 B	0x0000 or 0xE302
CRC	2 B	0x0000 to 0xFFFF

Tab. 4.14 - Modbus configuration function - response

[24], [25]

5 Testing and results

Two setups were created for verifying the measuring concept, reliability and robustness over a long time period and over different environment conditions. Base on the results of test, the sensors were also calibrated.

5.1 Experiment 1

For the first experiment, 85 x 85 x 750 mm spruce timber was taken. Its initial moisture content was unknown, but it was dry enough. Four prototypes of sensor were driven into the timber and connected to the prototype 1 of control unit. Close to the sensors a hole was drilled as a reservoir for moisturizing liquid (water).

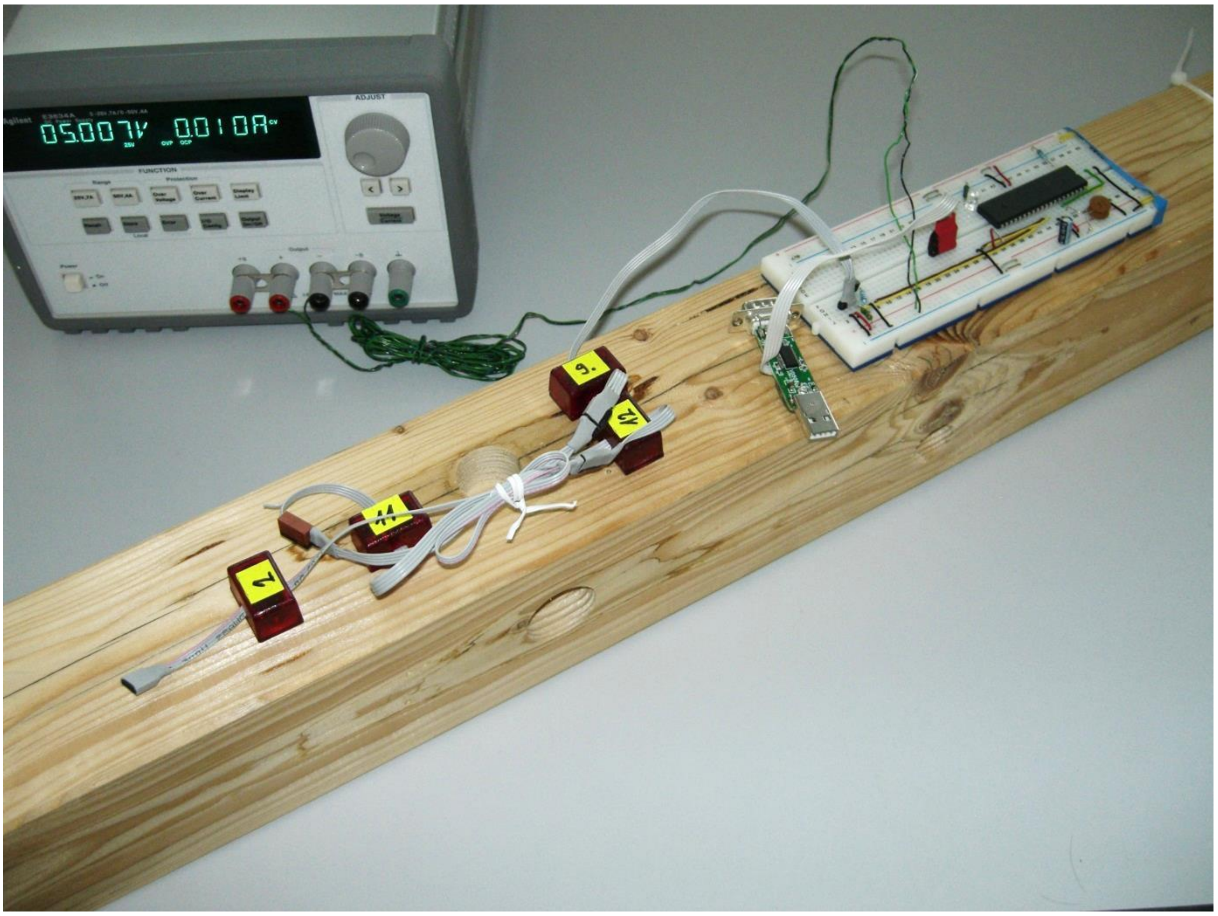


Fig. 5.1 - Setup of experiment 1

This experiment verified the measuring concept used in the sensor units. It also brought the very first experience of measuring resistance in the wood. Different orientation of the electrodes, effect of the moisturizing on the resistance, temperature effect on the readings, etc. were tested in this setup.

The experiment was running for more than a half of year and gave lot of samples. The one month period is shown in the graph attached in appendices (Appendix 14). The data from whole experiment can be found on attached CD (Appendix 1).

5.2 Experiment 2

For the second experiment, two separated chambers of size approx. 210 x 300 x 300 mm were created. In each chamber, there is container at the bottom of chamber with holes and fan in the lid. There are different saline solutions creating defined air relative humidity in the chambers. The fan creates convection in the chamber keeping the relative humidity in the chamber constant across whole space. The relative humidity depends on type of saline solution. There is grid over the container, on which wood samples are lie.

Saline solution	Relative humidity
$K_2\,CO_3$	43,2 %
K Cl	85,0 %
$K_2\,SO_4$	97,6 %

Tab. 5.1 - Saline solutions and relative humidity above the saturated solution

There is 100 x 100 x 100 mm spruce wood sample in each of chamber. Three prototype sensors are driven into each wooden sample and additionally 2 electrodes of Katres system are driven also. There is the experiment setup showed in Fig. 5.2. There are actually three chambers, but just two are used. In the chamber on the right (referenced as “chamber A”), there was $K_2\,SO_4$ saline solution. In the chamber in the middle (referenced as “chamber B”), there was K Cl saline solution. On the outer side of the box, there is Katres system mounted in the middle (green PCB), next to it on the right there is breadboard with prototype 2 of control unit (3.2) with some other electronic parts for controlling the Katres system and PLC SDS MACRO under it.

The Katres system is 8-channel system for measuring moisture during drying process in drying kilns. The system is based on resistive measurement of moisture with switching polarity of flowing current to eliminate the polarization effect. The output is current loop 0 – 20 mA that corresponds to 0 – 100 % moisture content. The system is calibrated for spruce wood at 20 °C.

Given a relative humidity at certain temperature, the wood moisture settles at moisture equilibrium. It requires some time to reach this equilibrium.

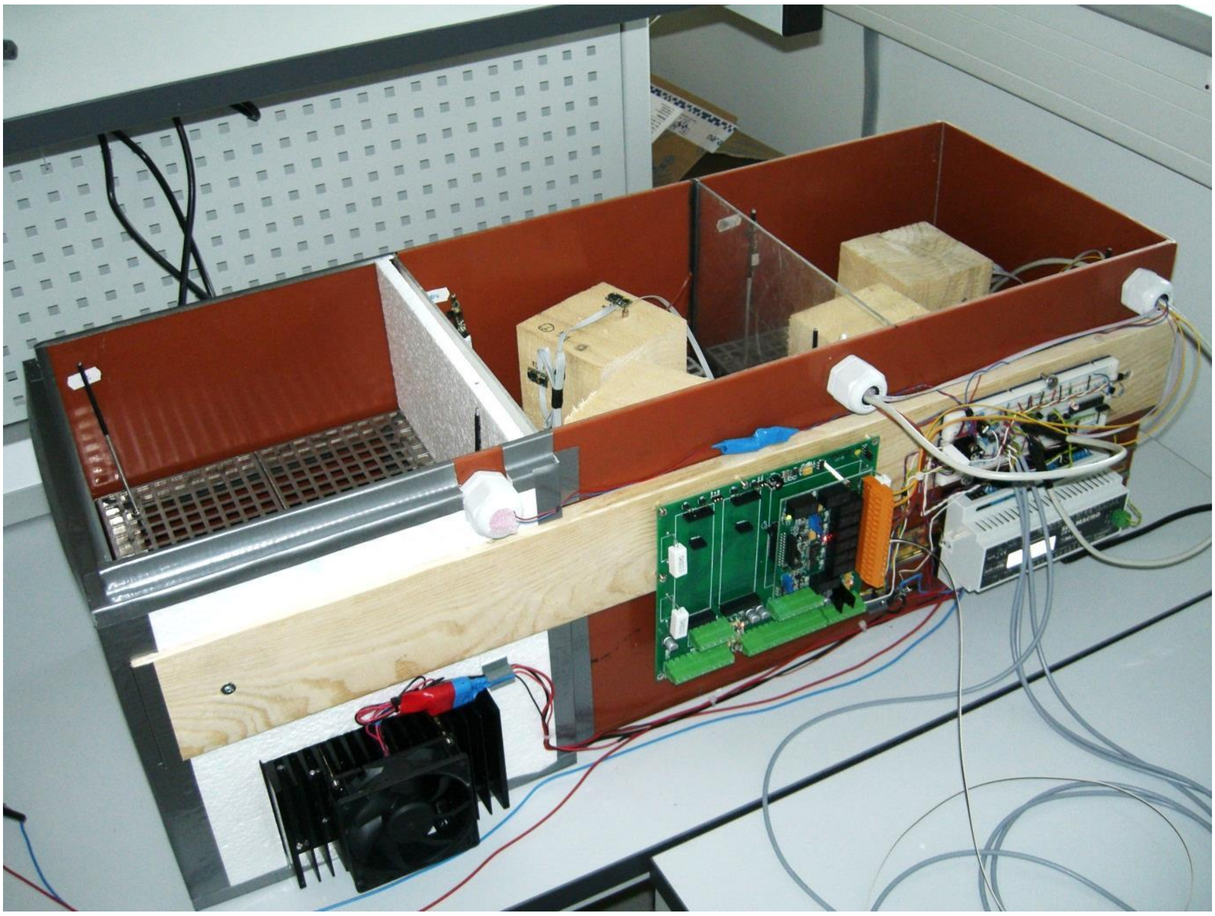


Fig. 5.2 - Setup of experiment 2

The experiment was running for 2 months. It turned out that the Katres system affects readings of the sensors. Nevertheless the data were filtered and can be used without any problem.

The experiment gave the resistance measured by the sensors and corresponding moisture measured by Katres system. Since we know the form of relation between resistance and moisture, the coefficients of the equation (1.5) was found using fitting feature of MATLAB®.

The processed data are attached in appendices (Appendix 15, Appendix 16). The raw and processed data, MATLAB® scripts, etc. can be found on attached CD (Appendix 1).

Thanks to this experiment calibration of the sensor prototype could be done.

5.3 Experiment 3

The prototype sensors were tested and calibrated in the experiment 1 (5.1) and experiment 2 (5.2). In order to verify function of final version of sensors and the control unit, new experiment was setup. This experiment serves also as a demo panel presenting the results of this project. There are control unit and two sensors mounted on spruce timber 60 x 45 x 550 mm. One of the sensors doesn't have enclosure to see what is inside.

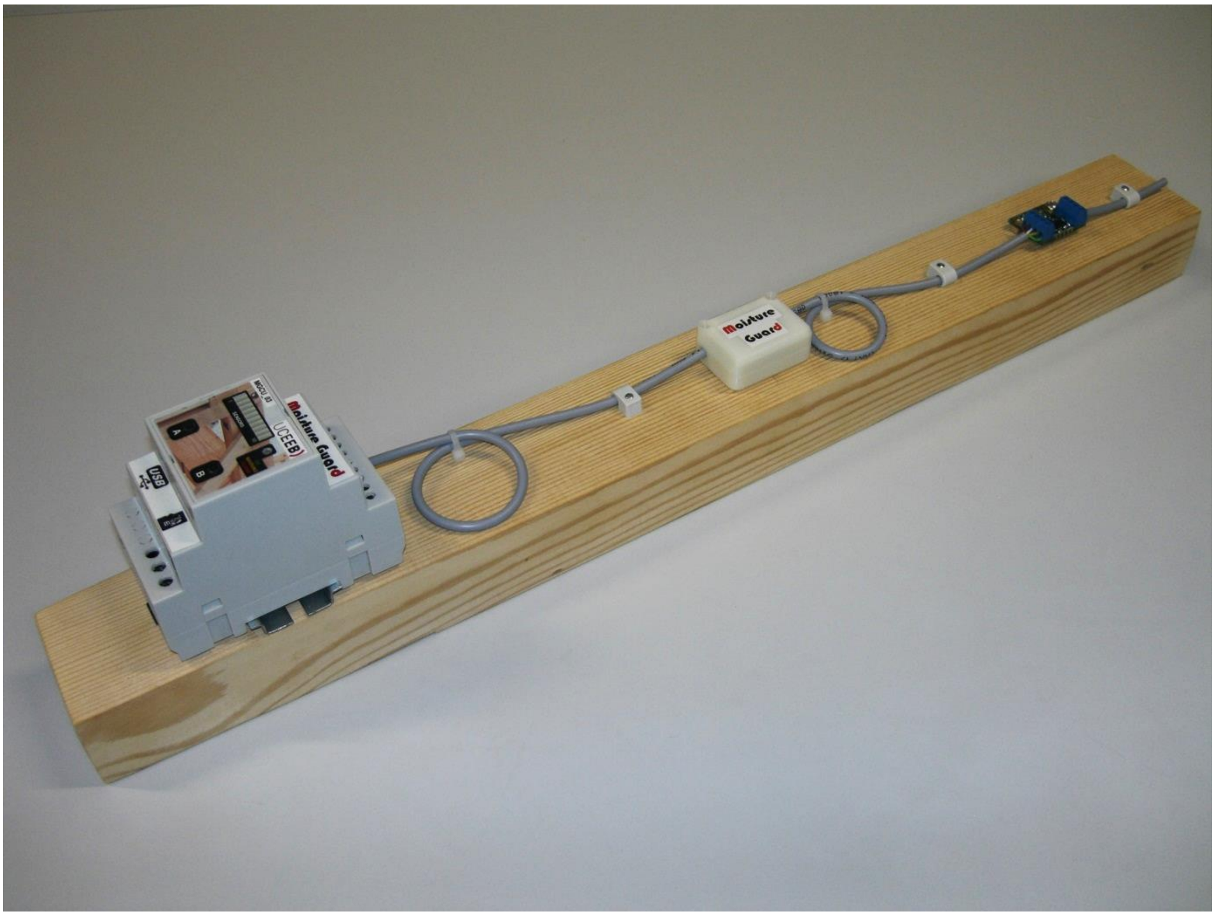


Fig. 5.3 - Setup of experiment 3, demo panel

Before installation of the sensors, the timber had moisture content around 17-18 %. After sensors have been installed, it was transferred to the room, where it was drying for 100 hours. During this time, data were logged onto a SD card by control unit.

In this experiment calibration coefficients from experiment 2 (5.2) were used. Since final version of sensor differs from prototype in electrode system, the coefficients are improper and lead to deviation between real and measured values. However this deviation is small and does not affect the trend of moisture change in time.

The moisture dependency on time is attached in appendices (Appendix 17). Other quantities as ambient temperature, relative humidity and raw resistance can be seen on attached CD (Appendix 1).

5.4 Costs

When calculating manufacturing costs, the amount of units to be produced is necessary. The price of electronic components goes down rapidly with increasing amount. The same is valid for PCBs. The costs of film matrices are not included. The estimated costs are without VAT and includes only material (components, PCBs etc.).

5.4.1 Prototype of sensor

This sensor unit will probably never be produced. Considering 100 sensors to be produced, the price per sensor would be around 100 CZK.

5.4.2 Final version of sensor

This sensor will be probably produced in larger series, let's say from 100 to 1000 units. Considering 100 units to be produced, the price would be around 230 CZK for version without relative humidity sensing and 300 CZK for version with relative humidity sensing. There is not included the machine time for fabrication the custom enclosure of the sensor.

5.4.3 Control unit

It's not expected the control unit will be produced in big series. So considering 10 units to be produced, the cost would be around 500 CZK per unit.

6 Possible future upgrades

6.1 Sensor unit

The sensor unit is almost ready to be launched onto the market. It’s necessary to run some test through different environmental conditions to ensure its reliability. Also the sensor has to be calibrated, because the calibration was done only for the prototype sensors. The calibration should be done for various wood species at different temperatures.

Because this project was focused only on measuring moisture in the wood, some other materials as concrete etc. should be tested and calibrated as well. It’s highly probable that with calibration other materials will work without any change in hardware design or in firmware.

There is one feature that can be implemented in the sensor - bootloader. With this feature it would be possible to change firmware even in the sensors which are already mounted in the buildings.

6.2 Control unit

Besides the sensor, the control unit is not ready to be launched onto the market yet. Currently it works mainly as demonstration device. There is no need to change the hardware design of the device, just firmware has to be upgraded.

Even though there is RTCC module, it’s not used now. The time elapsed since powering up is used as a timestamp which is not ideal. Using threshold value to trigger the alarm is also not the best solution. In the future moisture gradient should be used to trigger the alarm. The control unit should be configurable over the USB much more than it is implemented now. Also user friendly PC application should be created for those purposes.

And last but not least it would be good to implement the bootloader also in the control unit.

Conclusion

Aim of this work was to develop a complete system of increased moisture detection and an early warning system for building. This system was given the name “Moisture Guard”.

In this project I was dealing with problems of measuring the moisture in the building structures, especially in the wood, its calibration and processing. I have built an independent combined sensor measuring the moisture, temperature and relative humidity. Even though, the sensors are designed for detection only, with good calibration they can also serve as a measuring device with good accuracy. I have also built a control unit, which together with sensors forms a complex system.

As it is pointed in the previous chapter, the system is not completely ready to be launched onto the market and further work needs to be done to finish it. I am sure this system will find its place on market. Several companies building wooden buildings have already showed their interest. Currently the utility model is pending on approving.

References

[1] **MAKOVÍNY, Ivan.** Meranie vlhkosti dreva. Zvolen: MATCENTRUM, 1995. *Slovak.* ISBN 80-967315-0-5.

[2] **James W. L.** Electric Moisture Meters for Wood. United States Department of Agriculture, Forest Service, Forest Products Laboratory, General Technical Report FPL-GTR-6, 1988. [online] *http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr06.pdf*

[3] **Duff J. E.** A Probe for Accurate Determination of Moisture Content of Wood Products in Use. U.S. Forrest Service Research Note FPL-0142, 1966. [online] *http://www.fpl.fs.fed.us/documnts/fplrn/fplrn0142.pdf*

[4] Wood Handbook: Wood as an Engineering Material. U.S. Forrest Service, General Technical Report FPL-GTR-190, 2010. [online] *http://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr190.pdf*

[5] **Onysko D., Schumacher Ch., Garrahan P.** Field Measurements of Moisture in Building Materials and Assemblies: Pitfalls and Error Assessment. DMO Associates, Building Science Corporation, FPInnovations, Forintek Division, 2008. [online] *http://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BEST/BEST1_M2-5.pdf*

[6] **ŠLEZINGEROVÁ, Jarmila; HORÁČEK, Petr; GANDELOVÁ, Libuše.** Nauka o dřevě. Brno: Mendelova zemědělská a lesnická univerzita v Brně, 1998. *Czech.* ISBN 80-7157-194-6.

[7] **Microchip Technology Inc.** PIC18(L)F1508/9 Data Sheet: 20-Pin Flash, 8-Bit Microcontrollers with nanoWatt XLP Technology. [online] 2011. *http://www.microchip.com/*

[8] **Microchip Technology Inc.** PIC16(L)F1825/9: 14/20-Pin Flash Microcontrollers with XLP Technology. [online] 2014. *http://www.microchip.com/*

[9] **Microchip Technology Inc.** PIC18(L)F2X/4XK22 Data Sheet: 28/40/44-Pin, Low-Power, High-Performance Microcontrollers with nanoWatt XLP Technology. [online] 2012. *http://www.microchip.com/*

[10] **Microchip Technology Inc.** PIC18F46J50 Family Data Sheet: 28/44-Pin, Low-Power, High-Performance USB Microcontrollers with nanoWatt XLP™ Technology. [online] 2009. *http://www.microchip.com/*

[11] **Microchip Technology Inc.** MPLAB® XC8 C Compiler: User's Guide. [online] 2013. *http://www.microchip.com/*

[12] **Microchip Technology Inc.** MCP9700/9700A, MCP9701/9701A: Low-Power Linear Active Thermistor™ ICs. [online] 2009. *http://www.microchip.com/*

[13] **Microchip Technology Inc.** MCP9800/1/2/3: 2-Wire High-Accuracy Temperature Sensor. [online] 2010. *http://www.microchip.com/*

[14] **Microchip Technology Inc.** MCP7940N: Battery-Backed I^2C™ Real-Time Clock/Calendar with SRAM. [online] 2010. *http://www.microchip.com/*

[15] **Microchip Technology Inc.** Microchip USB Device Firmware Framework User's Guide. [online] 2008. *http://www.microchip.com/*

[16] **Chan.** FatFs Generic FAT File System Module. [online] 2014. *http://elm-chan.org/fsw/ff/00index_e.html/*

[17] **Sensirion.** Datasheet SHT21: Humidity and Temperature Sensor IC. [online] 2014. *http://www.sensirion.com/*

[18] **Texas Instruments.** TLC555: LinCMOS™ TIMER. [online] 2005. *http://www.ti.com/*

[19] **Texas Instruments.** SN65HVD72, SN65HVD75, SN65HVD78: 3.3V-Supply RS-485 with IEC ESD Protection. [online] 2013. *http://www.ti.com/*

[20] **Texas Instruments.** LP2985-N: LP2985-N Micropower 150-mA Low-Noise Ultra Low-Dropout Regulator in SOT-23 and DSBGA Packages Designed for Use With Very Low ESR Output Capacitors. [online] 2014. *http://www.ti.com/*

[21] **StarChips Technology.** SCT2167: 8-bit Serial-In/Parallel-Out Constant Current Driver. [online] 2012. *http://www.starchips.com.tw/*

[22] **Kingbright Electronic Co., Ltd.** 10 SEGMENT BAR GRAPH ARRAY: DC10EGWA, High Efficiency Red and Green. [online] 2010. *http://www.kingbrightusa.com/*

[23] **LIN Consortium.** LIN: Specification Package. [online] Revision 2.2A, 2010. *http://www.cs-group.de/fileadmin/media/Documents/LIN_Specification_Package_2.2A.pdf*

[24] **Modbus Organization.** MODBUS over serial line specification and implementation guide. [online] V1.02, 2006. *http://www.modbus.org/*

[25] **Modbus Organization.** MODBUS APPLICATION PROTOCOL SPECIFICATION. [online] V1.1b3, 2010. *http://www.modbus.org/*

List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AC	Alternating Current
ADC	Analog-to-Digital Convertor
ASCII	American Standard Code for Information Interchange
CDC	Communication Device Class
COM	COMmunication port
CRC	Cyclic Redundancy Code
CSV	Comma-Separated Values
DC	Direct Current
EEPROM	Electrically Erasable Programmable Read-Only Memory
EUSART	Enhanced Universal Synchronous Asynchronous Receiver Transmitter
FAT	File Allocation Table
I2C	Inter-Integrated Circuit
IC	Integrated Circuit
ICSP	In-Circuit Serial Programming
IDC	Insulation Displacement Contact
LED	Light Emitting Diode
LIN	Local Interconnect Network
LSB	Least Significant Bit
MCU	MicroController Unit
MMC	MultiMedia Card
NC	Normaly Closed
NO	Normaly Opened
OPAM	OPerational Amplifier
PC	Personal Computer
PCB	Printed Circuit Board
PLC	Programmable Logic Controller
PLL	Phase Locked Loop
PWM	Pulse Width Modulation
RTCC	Realt-Time Calendar/Clock
RTU	Remote Terminal Unit
SD	Secure Digital
SPI	Serial Peripherial Interface
TVS	Transient-Voltage-Supression
UART	Universal Asynchronous Receiver Transmitter
USB	Universal Serial Bus
VAT	Value Added Tax

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