AN5449

Application note

Temperature sensors: guidelines for system integration

Introduction

The purpose of this application note is to introduce guidelines for system and hardware integration of a temperature sensor in the designs of final applications.

This document also provides details regarding reference designs of applications with temperature sensors for mobile phones, oil baths, and smart nuts.

This document does not modify the content of the official datasheet. Please refer to the datasheet for parameter specifications.

1 System integration

The design for integrating a temperature sensor in an application context is strictly dependent on the final objective. The three main purposes of using a temperature sensor covered in this application note are as follows:

- To measure the temperature of an electronic board or some specific electronic components
- To measure the temperature in the application embodiment (application enclosure)
- To measure the environmental temperature

In this document we will refer to the objective mentioned above as the *thermal target*. We will also include with this term the requested sensor specifications of accuracy and response time.

Thermal targets are important since they impose different and specific design guidelines related to the specific application scenario. For instance, common design elements to be considered are the positioning of the temperature sensor, positioning of the control board in the application context, the mechanical and industrial design of the application itself, and likely many other specific factors (e.g. use of protective membranes).

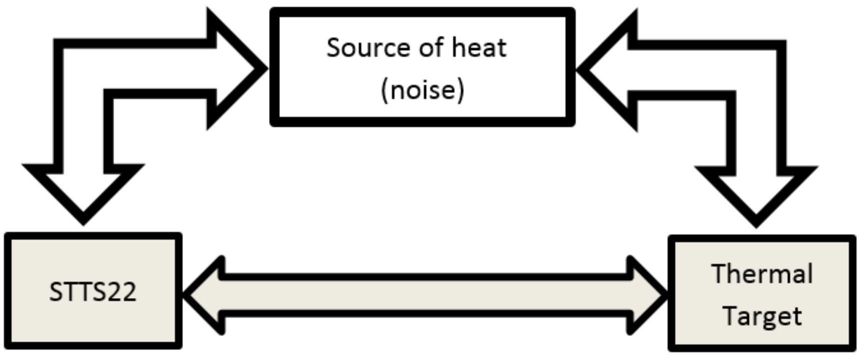
All these system and applicative elements need to be taken carefully into account if the final objective is to have an optimized product design for generating a highly accurate measurement of temperature, for instance ±0.1ºC.

We can consider a typical applicative scenario of temperature measurement as formed by three main elements:

- The temperature sensor
- The object to be measured (thermal target)
- The noise factors that can affect the measurement accuracy and response time.

In general, an optimal design has the objective to achieve perfect thermal coupling between the temperature sensor (STTS22 in Figure 1) and the object to be measured by minimizing the thermal resistance between the two, and by maximizing the thermal resistance between the aforementioned objects and the other sources of heat that can be considered as external noise factors (Figure 1).

Figure 1. Applicative scenario of temperature measurement



This document details guidelines and recommendations for:

(a) handling appropriately, the temperature sensor until its integration in the final application;

(b) testing the temperature sensor and its performance;

(c) achieving the specified thermal target.

The following sections introduce background information for supporting these guidelines.

2 Heat propagation theory

A brief introduction to thermal transfer theory is essential to understand the different issues that could arise with incorrect mounting procedures.

Heat can be transferred in 3 ways:

- Conduction
- Convection
- Radiation

2.1 Heat conduction

Heat is generated in every material by microscopic collision between particles, conduction is the mechanism for which these collisions propagate to where the particles are less agitated, making the temperature rise with a gradient along the material.

When one area on the PCB is hotter, typically due to components that generate heat, the temperature tends to spread along the entire board, following the equation that describes the rate of heat transfer over time:

$$H = -kA\left(\frac{dT}{\mathrm{dx}}\right)$$

Fourier’s law of heat conduction can be simplified to:

$$H = \frac{Q}{t} = kA\frac{(T_2 - T_1)}{\mathrm{L}}$$

Where

H is the energy conducted in time [J/s]

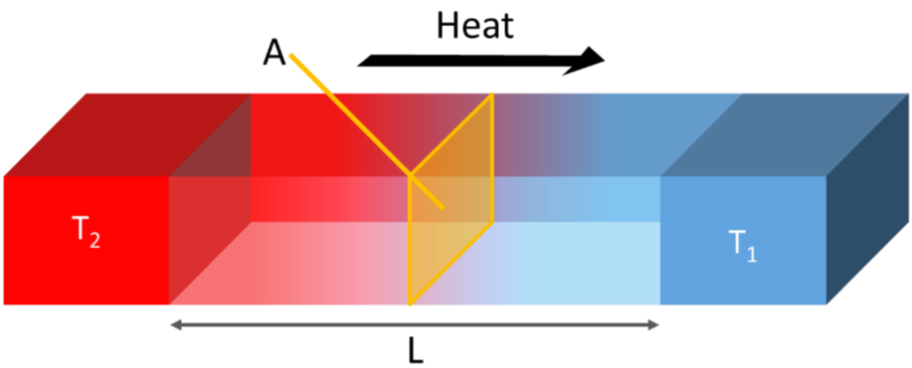
K is the thermal conductivity of the material [W/(m*K)]

A is the area of contact [m²]

T_2 is the temperature of the hotter part and T_1 is the temperature of the colder one [°K]

L is the length of the material [m]

Figure 2. **Heat transfer diagram**



Conduction inside material that is not thermally stationary follows this equation. It is linearly dependent on the dimension of the board, being A = t*w the cross section and L the distance between the 2 points in which the temperature is different.

It is also dependent on the thermal conductivity coefficient k, that depends on the material. Useful values for k are shown in the following table: copper is a good thermal conductor while FR4 and air are good thermal insulators.

Table 1. Thermal conductivity of different materials

Material	Thermal conductivity coefficient [W/(m*K)]
Air	0.0275
Solder mask	0.245
FR4	0.25
Lead	34.7
Gold	314
Copper	385
Diamond	~1000

2.2 Heat convection

In liquid and gasses the movement of molecules propagates heat with the flow of the fluid. Convection flows are generated because of this mechanism: fluids tend to rise when the temperature is high, in higher layers the temperature drops, and the fluids return down. This leads to thermal conduction.

Heat convection is present in the air around the board and the components, but its contribution is small with respect to the other mechanisms, so it will not be considered in detail.

It is still important to remember, as a rule of thumb, that the more space through which the air must flow, the less the thermal resistance in that area.

2.3 Heat radiation

Every object emits electromagnetic radiation that transfers internal energy which translates in heat.
This heat is based on the Stefan-Boltzmann Law of Radiation equation and is given by:

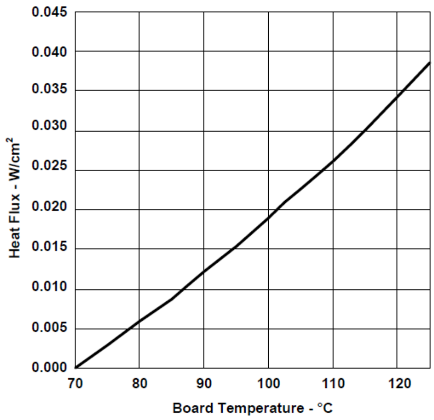
$$H = e\sigma T^4$$

Where

- e = emissivity (0-1).
- T = Kelvin temperature [°K]
- σ = Stefan-Boltzmann constant = 5.67 10^{-8} x [W/(m²+K^4)]

It turns out that heat transfer due to radiation, if the radiating surface temperature is greater than the ambient temperature, is approximately ½ the amount of heat transferred by convection. The heat transfer contribution by thermal radiation is often ignored in any analysis, due to its added complexity, and should be considered only for very precise applications.

Figure 3. Heat radiation



2.4 Thermal resistance

To easily visualize how heat flows, it is useful to understand thermal resistance, defined as:

$$\theta = \frac{L}{kA}$$

where:

- θ is the thermal resistance [K/W]
- k is the thermal conductivity coefficient [W/(m*K)]
- L is the thermal path length [m]
- A is the cross section area through which heat flows [m²]

Material with high thermal resistance can decrease thermal conduction between points at different temperatures. This can be useful when different parts of a board should be thermally separated.

As an example, the thermal resistance of a 1 cm² section (with thickness 1.6 mm) of PCB (material:FR4) along one of the 1 cm dimension (with thickness 1.6 mm) has θ calculated as:

$$\theta = \frac{1x10^{-3}}{0.25 * 1x10^{-3} * 1.6x10^{-3}} = 2500\left[\frac{°C}{W}\right]$$

while a section with the same dimensions but different thickness (typical 35 µm) of copper has θ equal to:

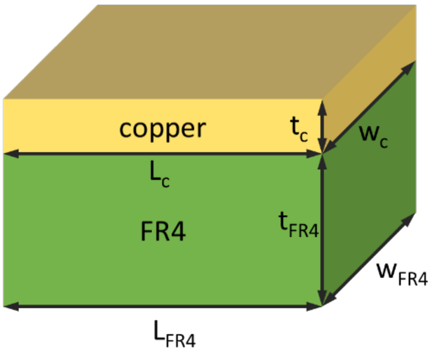
$$\theta = \frac{1x10^{-3}}{385 * 1x10^{-3} * 35x10^{-6}} = 74.21\left[\frac{°C}{W}\right]$$

The copper, even if it is much thinner, has a resistance that is lower by a factor of almost 34, so its layout should be designed with caution, especially around the temperature sensor.

It is to be noted that the total thermal resistance of a 1 cm² PCB with a layer of copper is the parallel resistance of the two previously calculated:

$$\theta = \frac{2500 * 74.21}{2500 + 74.21} = 72.07\left[\frac{°C}{W}\right]$$

Figure 4. Block for which θ_{tot} is calculated from one side to the opposite (thickness not to scale)



Then it is useful to calculate the thermal resistance from one side of the PCB to the other, considering a large section as a via: a cylinder long as the board (1.6 mm) with diameter 0.3 mm.

This section (filled FR4) has a thermal resistance of 90541.

For a non-filled via with a copper thickness of 35 µm, the thermal resistance drops to $0.143x10^{-3}$ considering the air inside the via as negligible (because the thermal resistance of the air is so high that the parallel resistance results in just the copper conducting).

If the via would be totally filled with copper, the thermal resistance should further drop to $0.059x10^{-3}$ (but this improvement comes with a higher cost of the filled vias).

3 Mounting guidelines for temperature measurements

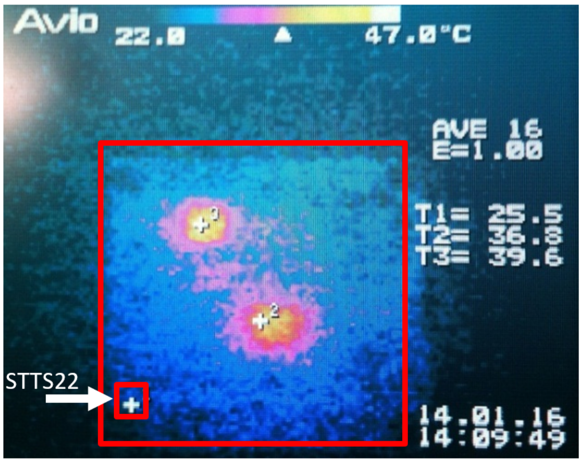
Knowing that the best thermal coupling between the sensor and the target is achieved by providing the lowest possible thermal resistance between the two and that the thermal resistance depends on the distance and material between the objects, we can derive some general guidelines for mounting a temperature sensor.

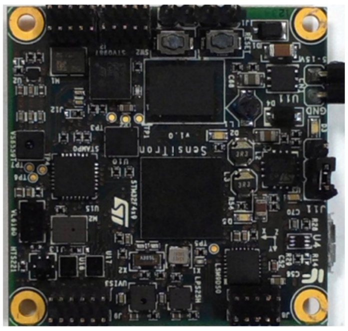
The main mechanism involved in heat propagation is thermal conduction, so we can state that **the distance between the target and the sensor should be kept to the strict minimum and the material between the two should have a high thermal conductivity.**

Meanwhile, the thermal resistance of the target and the sensor from outside heat sources should be as high as possible. For this reason, these **heat noise sources should be kept far and material with low thermal conductivity should be placed around them.**

The following figure shows an infrared picture of a board, where the critical sources of heat are the LDO and the microcontroller. In this case the aim of the sensor was to check the temperature of the environment, so it was placed in the left corner, far from the heat noise sources.

Figure 5. **STTS22 placement and thermal (infrared) image**





Different use-cases of a temperature sensor will be taken into consideration in more detail in the following sections.

3.1 Measuring temperature on the board

The following tips are useful in designing a layout in which the temperature sensor is able to detect the temperature of the board with the highest accuracy possible.

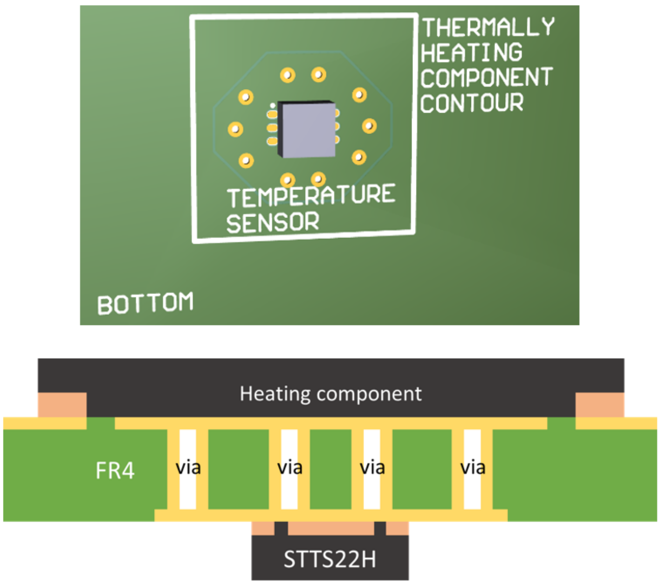
3.1.1 Temperature of specific components on the board

When measuring a specific component temperature, the problem is how to maximize thermal coupling (minimizing thermal resistance), in other words, how to impose that the sensor temperature and the target device stay at the same temperature without thermal delay due to the heat propagation.

Recommendations for having good thermal coupling between the sensor and the target device are as follows:

- **Connect devices to the same ground plane**:
  Metal is the material with the best thermal conductivity on the board, so the ground plane is the main conductor of heat. Having a direct link between the sensor and the component to be measured with the ground plane is the most important step.
- **Place the sensor behind the component, on the other side of the board**:
  Design a symmetric structure formed by vias that connects the temperature sensor to the component with the smallest possible thermal resistance, by having a high number of vias between two metal planes (an example is shown in Figure 6). These vias could be metal filled for better conductivity (with a higher production cost) or just coated (this practice is not always recommended because a metal plane under the component could be a problem, so point 3 should be considered).
- **Place the sensor near the GND pin of the component:**
  The closer the sensor is to the component's GND pin, the better the conductivity. (see example in Figure 7)
- **Size the design elements in order to minimize heat convection**:
  Heat convection in the area around the sensor should be avoided, so having a small space between the sensor and the outside case (if present) is a better option.

Figure 6. Example of sensor mounted on the back of the heat component (bottom of the board and cross section)



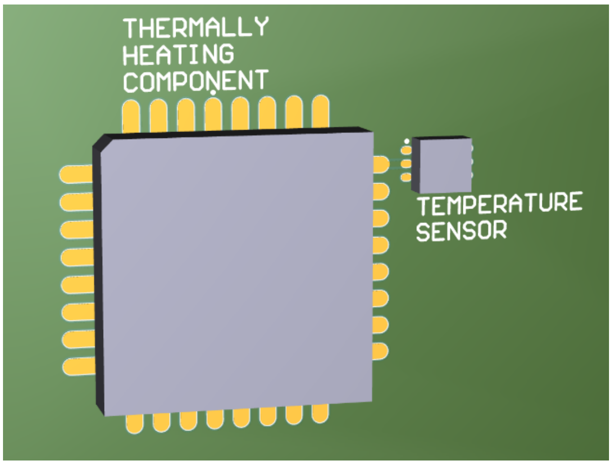


Figure 7. **Example of sensor mounted near the heat component**

An additional point to consider is to minimize or possibly nullify the effect of other components that could thermally interfere with the correct measurement of temperature.

Recommendations for making good thermal decoupling between the temperature sensor and the control board (excluding the target device) are as follows:

1. Protect the target device and the temperature sensor from heat convection with insulation barriers.
2. Design the mechanical case for moving the possible air flows far from the target zone.
3. Design a different ground plane of the target zone from the rest of the PCB in order to avoid heat conduction and interference.
4. Avoid the use of material with high thermal capacity in the target zone.

Once the design is completed, and the first prototype is built, it is recommended to perform a first order verification using an infrared camera for understanding and monitoring the critical heat sources at the different operating conditions.

At the same time, with the intent of verification, it is recommended to introduce thermistors placed in key positions with the intent to verify the design.

3.1.2 Temperature of the entire electronic board

If the thermal target is the whole board, the design should have as target to have the board at the same temperature in its entirety. In this case, the recommendation is to design only one ground plane for all the components, with an almost symmetric structure in terms of routing and vias. This leads to having a single component contribute to the thermal heating and cooling of the entire board.

Using more layers of solid ground reduces the operating temperature of the board, but the fact that it can reduce the temperature uniformity as well should be considered.

3.2 Measuring temperature of an off-board target

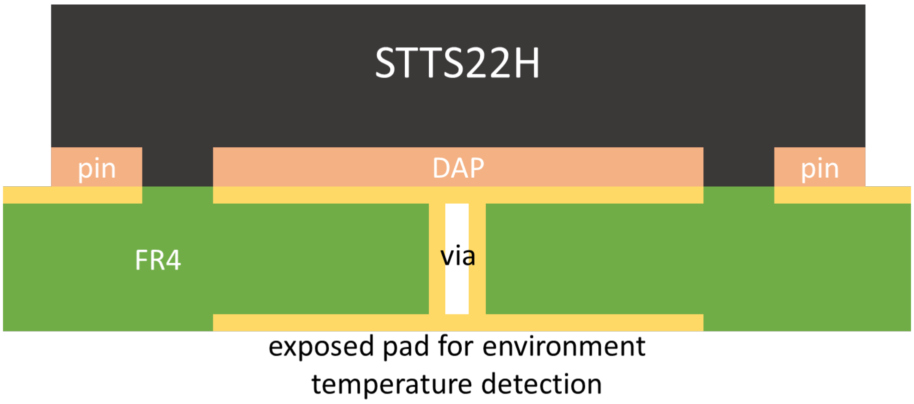
This section introduces design guidelines for using a sensor to measure the temperature of an object or of the inside of a machine or equipment where it could be necessary to keep temperature inside a given range.

The following sections explain how to boost accuracy for everything that is not an on-board device. This includes also environmental temperature when an outside case for the board and sensor is not needed.

3.2.1 Exposed pad for coupling with external target

If the target to be measured is not on the board, the temperature sensor accuracy benefits greatly from the presence of an exposed pad under it, on the opposite side of the board, as shown in the following figure.

Figure 8. Cross section of a good thermal connection to the bottom side



This exposed pad should be connected to the ground plane of the sensor (in the example in Figure 8 the ground plane is under the Die Attach Pad of the STTS22H, that is the main way for heat to be transferred to the sensor to be measured). The means of connecting the exposed pad to the GND plane are vias, that can be filled or not, depending on the accuracy needed for the application.

The exposed pad becomes the main thermal conductor of the sensor, so it should be placed near what is to be measured. If it is possible to not have a case between the sensor and the object to be measured, the accuracy and response are increased.

If the application needs to measure the temperature of a specific zone in some equipment, the coupling needs to be done between the temperature sensor and the confined environment of the application.

Recommendations for making good thermal coupling between the sensor and the confined environment (any object can substitute the confined environment) are as follows:

1. Minimize rapid power dissipation:
   a. Design appropriately the sensor ground plane
   b. Design the routing to the sensor in order to minimize heat conduction
2. The sensor should be in contact with the part that has to have its temperature checked:
   a. Expose the sensor to the environment (if not harsh) to be measured, if possible, to maximize the thermal exchange with the environment
   b. Place the sensor in a representative point of the chamber to be measured

3.2.2 Guidelines for internal decoupling

When positioning the sensor, the main rule to follow is to keep the sensor far from the heat sources of the PCB.

The most immediate way is to put the sensor in the farthest possible location from the other components, but there are ways of enhancing this effect.

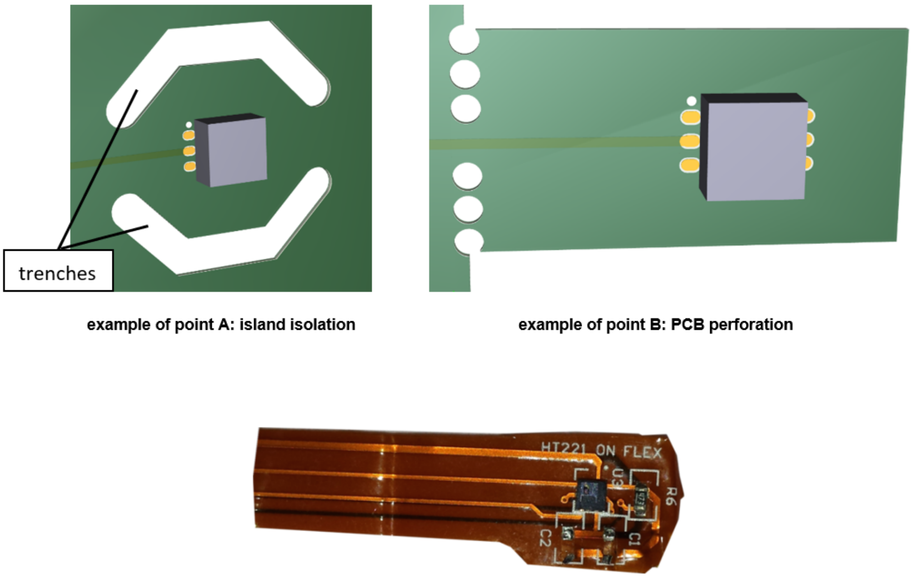
A. The most common and easy-to-use method is island isolation: cutting trenches in the PCB around the sensor increases the thermal resistance. These trenches should be as large as possible and should be placed between the sensor and the heat sources.

B. Another method is creating a section for the sensor placement and using PCB perforation to isolate it just like with the isolation island. This method involves typically an enlargement of the PCB, with only a slightly better thermal isolation with respect to option A.

C. If it is possible, a flex board should be used: thermal resistance is much higher due to the isolation provided by the connectors and it even increases thermal resistance to the other part of the circuit thanks to the lower thickness of the flex board with respect to the PCB.

D. Using an edge connector is also possible: thermal resistance gets very high, but the connector occupies a large volume on the plane perpendicular to the board.

Figure 9. Examples of decoupling from on-board components



example of point A: island isolation

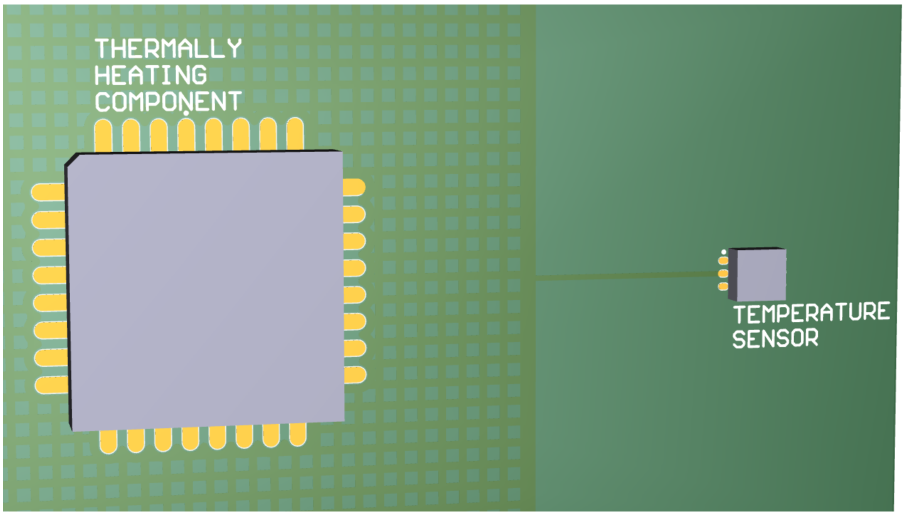
example of point B: PCB perforation

example of point C: flex PCB

The ground plane is the main medium with which temperature propagates around the board. This means that if one component generates heat, this heat is transferred to the sensor mainly along the ground plane.

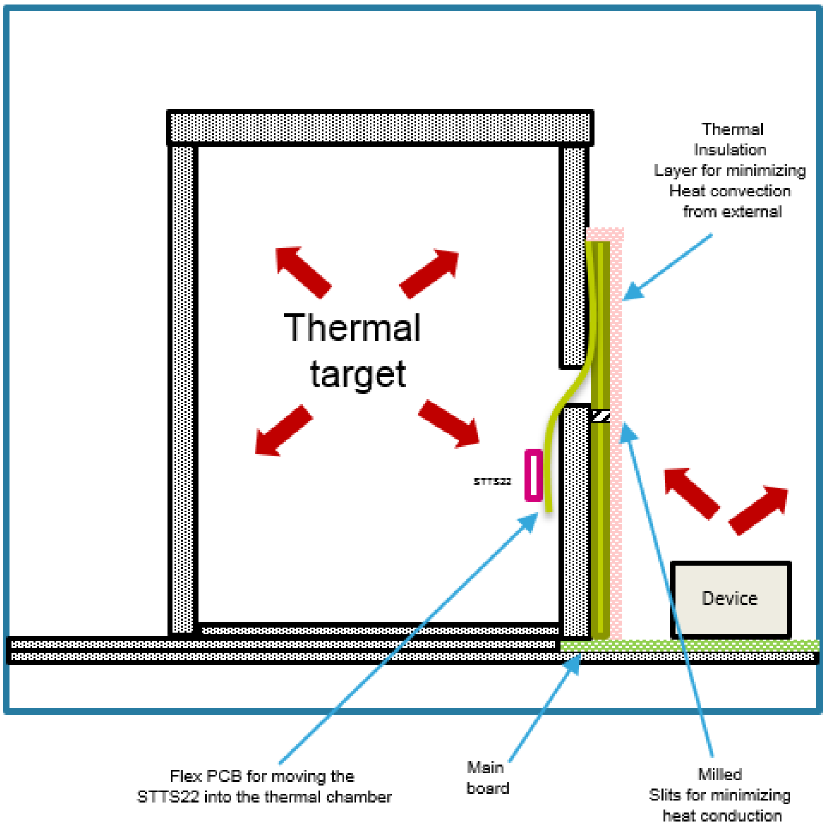
For this reason, **the temperature sensor should not be surrounded by a ground plane**. In fact, the further it is from the ground plane, the better for thermal isolation. Another good practice is to hash the ground plane, designing it as a lattice instead of a filled plane. This leads to a higher thermal resistance that improves isolation.

Figure 10. **Sensor far from the heating component and no GND plane around the sensor**



The following figure shows a configuration with the intent to measure the temperature in the zone indicated as the thermal target. The use of a thermal insulation layer for minimizing the effect of external heating sources and the use of milled slits for minimizing heat propagation by conduction from the main board to the temperature sensor are visible. The use of a flex PCB for moving the sensor closer to the thermal target and more immune to external heat sources is present.

Figure 11. **STTS22 for temperature measurement in a chamber inside the application embodiment**



3.2.3 Other tips

The thickness of the PCB determines the overall thermal conductivity along it: a higher thickness brings higher conductivity, as stated in the previous sections. This means that for isolating the temperature sensor the user should think of using a thinner PCB: this should bring a higher thermal resistance of the sensor to the heat sources and a lower thermal resistance between the two sides of the sensor pads.

Signals should be routed to the bottom side of the board (if the components lay on the top side), in order to have the least thermal contamination possible along the board.

All ICs generate heat when power is applied to them. For this reason, a temperature sensor can increase its temperature if kept active for long time due to measuring and communication resources. It is recommended, where possible, to reduce the temperature sensor duty cycle in order to avoid the effect of self-heating to the temperature measurement.

Lastly, if the application requires having the board remain still for a long time, it is good practice to position the board itself in a vertical position. The reason for this is that it prevents dust from depositing on the sensor’s pads (this can lead to a change in the detected temperature) and it improves air flow.

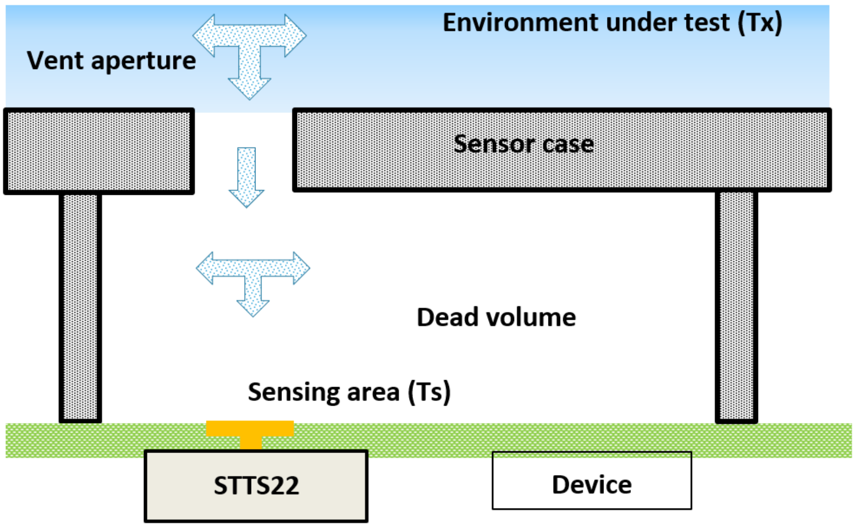
3.3 Sensing temperature outside the case

When the target to be measured is located outside the case in which the board and the sensor are, there are some recommendations to follow, in addition to the ones seen in Section 3.2 Measuring temperature of an off-board target.

3.3.1 Indoor and outdoor temperature measurements

The typical scenario for sensor integration with the intent to measure the indoor or outdoor temperature is illustrated in the following figure where the case of the sensor has to be designed in order to render the temperature of the environment under test (Tx) and the temperature around the sensor sensing area (Ts) as close as possible (ideally to the same temperature, reducing the thermal resistance to zero).

Figure 12. Temperature sensor system integration - typical scenario



Therefore, in order to get a reliable and consistent measurement, all the parameters involved in the mechanical design must be dimensioned to get the maximum sensor exposure to the external environment, to get the fastest response time, in terms of temperature, compatible with the required design specifications.

Any change in the target temperature condition must be reflected as a sensor-consistent measurement, as well as in the case of fast temperature variations. Therefore, the integration design must guarantee that the temperature of the environment matches the sensing area temperature, not only in steady-state (static conditions), but also in dynamic conditions.

Deviations between the target condition and the temperature around the sensing area are also influenced by heat sources, like other devices close to the sensing area.

Based on the above considerations, the design optimization consists of determining:

- the placement of the sensor in the system
- the sensor embodiment and housing
- protection of the sensor from dust, water, or chemical solvent by a sensor chamber, in the presence of a harsh environment

These elements are further described in the following sections.

3.4 Mechanical design rules

The main constraints and features of the mechanical design to be considered are described below. The purpose is to introduce a set of basic rules as good design practices for successfully integrating the sensor in the context of a final application.

3.4.1 Sensor placement

The sensor must be positioned in order to maximize the exposure to the environment where temperature is measured, in static and dynamic operating conditions.

In **static conditions** (steady-state), the sensing area temperature must be the same as the temperature under test, after a change in temperature environment and their stabilization, or very close to the target value, depending on the application tolerance and specifications.

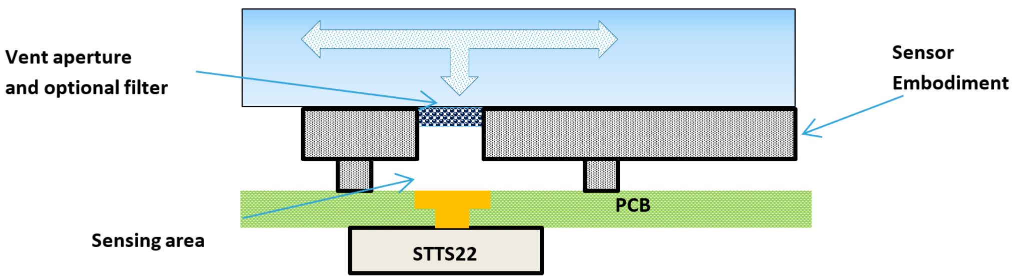
In **dynamic conditions** (fast changing temperatures) the sensor must be able to provide a reliable measurement output able to follow the changes of the environment.

In order to maximize the sensor performance in static and dynamic conditions, the following guidelines are recommended, with reference to Figure 13:

- Place the sensor as close as possible to the vent aperture in order to get the best connection with the environment under test.
- Large dead volume will increase the response time; therefore, it is recommended to minimize the volume, trying to shape a tailored housing around the sensor geometry.
- Vent aperture should be as large as possible (a good approximation is giving it the dimensions of the sensing area); depth of the vent aperture must be minimized. The aperture dimensions provide a strong contribution to the temperature response time.
- Materials that can absorb heat have to be avoided in the dead volume.

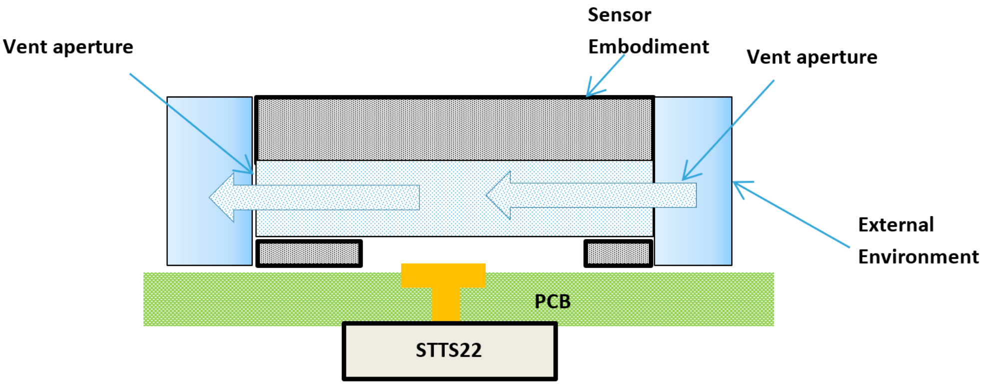
In the design shown in Figure 13 a filter membrane protection has been added in order to protect the sensor from water or a harsh environment.

Figure 13. Temperature sensor integration and embodiment reference



A different implementation, more expensive but more efficient in terms of sensing performance, is the design with an air flow structure, described in Figure 14: the design with multiple vent apertures is always preferable, even if there is simple contact with the environment, without laminar airflow over the sensor.

Figure 14. **Temperature sensor integration and embodiment with airflow channel**



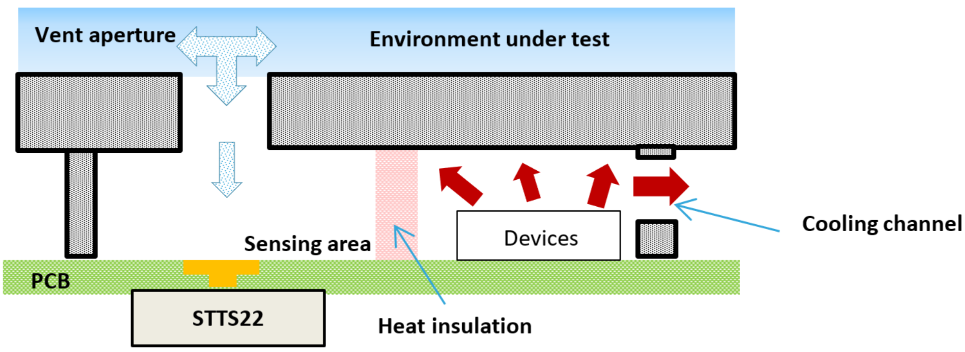
As seen in the previous sections, the presence of heat sources near the sensor can degrade the performance by modifying the temperature measurement as well as generating thermal gradients around the sensing area, affecting the accuracy. From a physical point of view, these local sources act like thermal capacitors placed in parallel to the thermal model of the sensor and they can contribute to a difference in local temperature. Local thermal sources around the sensor can also modify temperature measurement by heat convection because of changes of local conditions around the sensing area.

Typical sources are as follows:

- power management devices (LDO)
- processors and microcontrollers
- LCD displays

Therefore, besides placing the sensor at a distance from these heat sources and guaranteeing the appropriate isolation, it is recommended to adopt heat insulation structures inside the case as described in Figure 15. It is also recommended, according to the specific layout, to implement a vent aperture close the heat source, acting as a cooling channel.

Figure 15. **Heat insulation implemented to protect the sensor**



3.4.2 Mechanical stress

The placement of the sensor shall be such to avoid any mechanical force applied to the sensor, either direct due to an incorrect mechanical system design or indirect due to user interaction with the system as in the case of wearables or portable devices.

To avoid mechanical stress on the sensor, the case should not touch the sensor under any condition, so the dead volume should be big enough to sustain an external force without letting the walls touch the sensor itself.

3.4.3 Sensor case and housing

The sensor embodiment in the system shall match as much as possible the recommendations previously highlighted for the sensor placement and, additionally, has to meet all the features of the specific application (waterproof, water-resistant or resistant to harsh environments) in case it is required.

Furthermore, the design of the customer's device shall guarantee air circulation from the environment to the sensing area, first from the environment (outside) to the customer's device (inside), then internally from the aperture to the sensor housing and sensing element as well. The more efficient the air circulation in this path, the better the performance will be.

The air path shall be well-identified and sized in order to maximize the airflow, and as a result, the final performance of the integrated system.

3.4.4 Sensor protection

Optional filters can be implemented as protection of the sensor from dust, water, or chemical solvents by using a sensor chamber, in presence of harsh environments or for waterproof applications. The key parameter for this kind of implementation is the appropriate choice of the material of the membrane: it must be considered that the membrane will provide a slower response time.

Figure 16. **Summary of main guidelines for different use cases**

	board measurement		external target measurement	
	specific component	whole board	in contact with sensor pad	outside the case
sensor placement	close to the component	far from hot components	far from hot components	far from hot components
GND plane	same GND for sensor and component (divided from main GND)	same GND for whole board	sensor GND divided from main GND	sensor GND divided from main GND
case design	air should flow away from component	no specific constraints	no specific constraints	air should be able to flow freely from outside but a small dead volume and a big vent aperture are recommended

4 Reference designs

4.1 Mobile devices

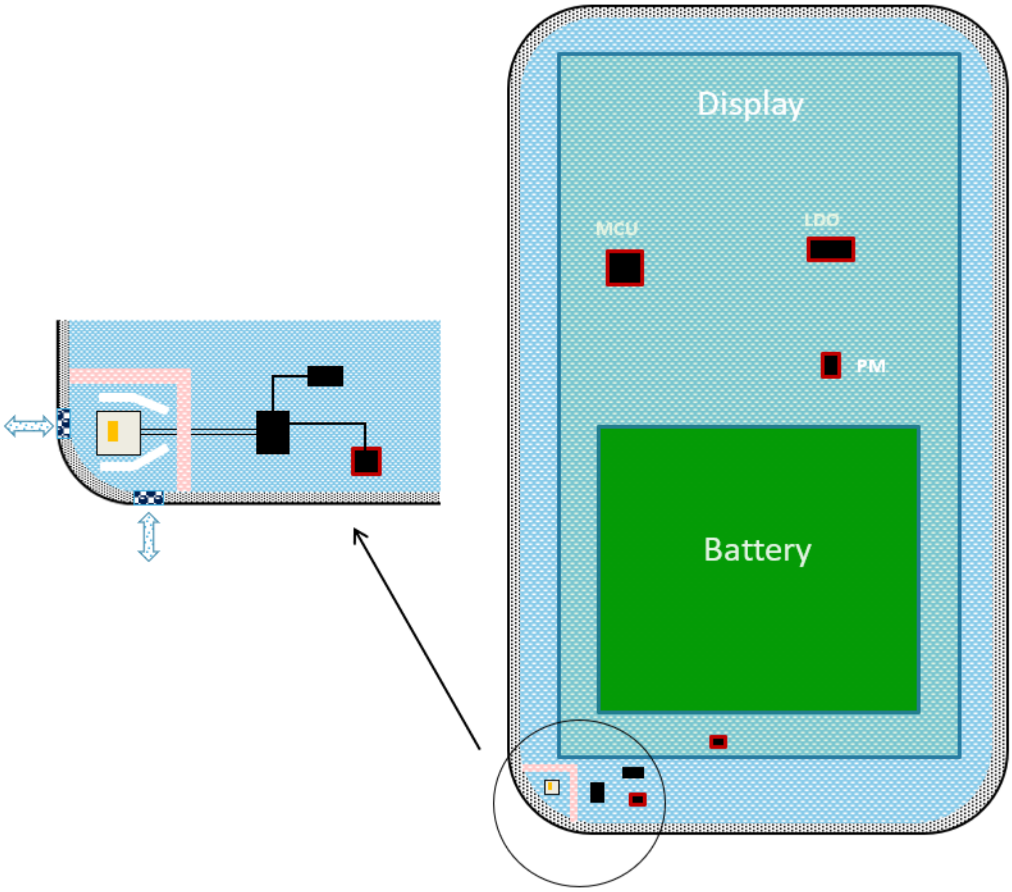
Based on the previous recommendations, Figure 17 illustrates the integration of a temperature sensor in a portable device.

The sensor is placed in the left bottom corner with the intent of measuring the environmental temperature. In this solution, a double vent aperture was adopted with a diameter in the range of 0.8 mm, creating a channel for air to flow through.

Placing the sensor in the left corner was done to simplify the integration with the mechanical case and to maintain the right distance from other sources of heat.

Filter membranes are also inserted for dust and water protection, depending on the specific application.

Figure 17. Sensor integration in a portable device (with detailed view)



4.2 Board for detecting oil bath temperature

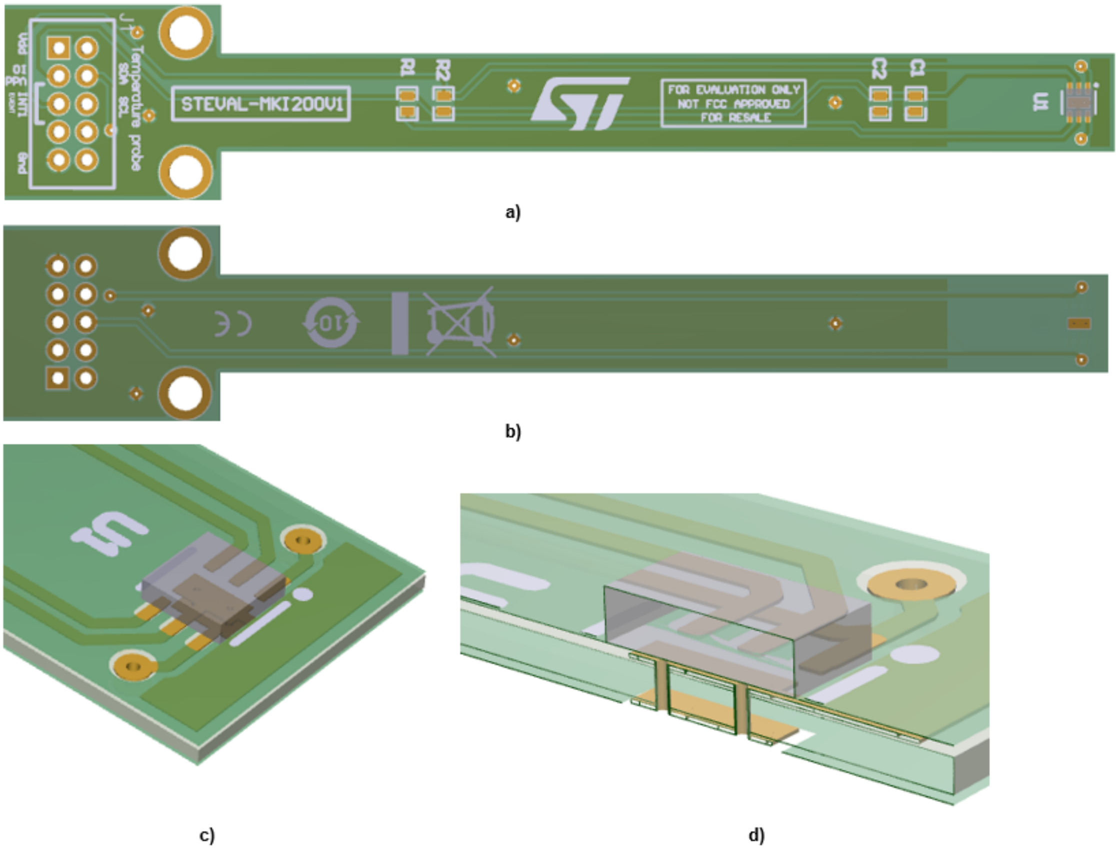
This reference design is a custom board which senses the temperature of an oil bath and requires that all recommendations for sensing the temperature of the environment are considered.

It can be noted in the following figure the view a) top: the total absence of devices that could heat up the board: this is a perfect adapter that is to be linked to the main board with the microcontroller.

Also, the ground plane is not continuous along the entire board: the part around the sensor is isolated from the rest to avoid thermal interference. The fact that the plane is not hatched is due to the absence of heat components on the board.

It is also important to note the exposed pad on the back side of the board, that is linked to the Die Attach Pad of the STTS22H through two vias in order to have a more uniform temperature (view d).

Figure 18. Views of the custom board



a) top
b) bottom
c) zoom on STTS22H
d) cross section

4.3 Exposed pad alternative

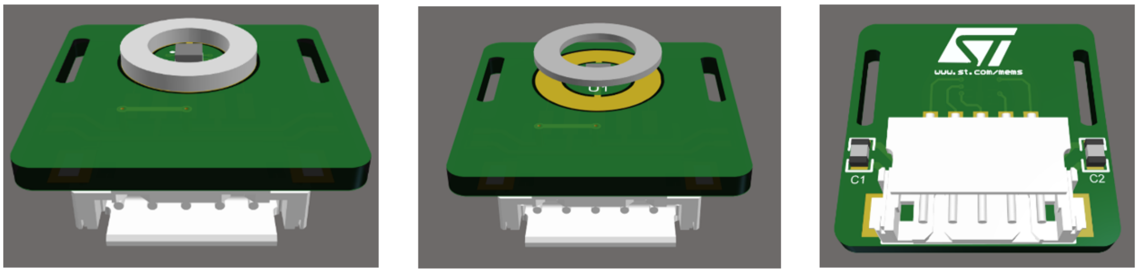
In this design an expansion for the exposed pad was designed to provide even more thermal conductivity with the outside of the board.

For this application it was not possible to use the backside of the board for the exposed pad, so the ground plane linked to the DAP was extended to a metal structure with high thermal conductivity.

Using this extended metal structure makes the exposed pad on the backside useless, or even detrimental, because the low thermal path to the object is already satisfied by the structure.

With this expedient it is possible to achieve a very low thermal resistance between the sensor and the environment, or even with a specific object, if the expansion is put into contact with the target to be measured. As an example, Figure 20 shows the smart nut application where this board is used to sense the temperature of a nut in a difficult place to reach with different equipment.

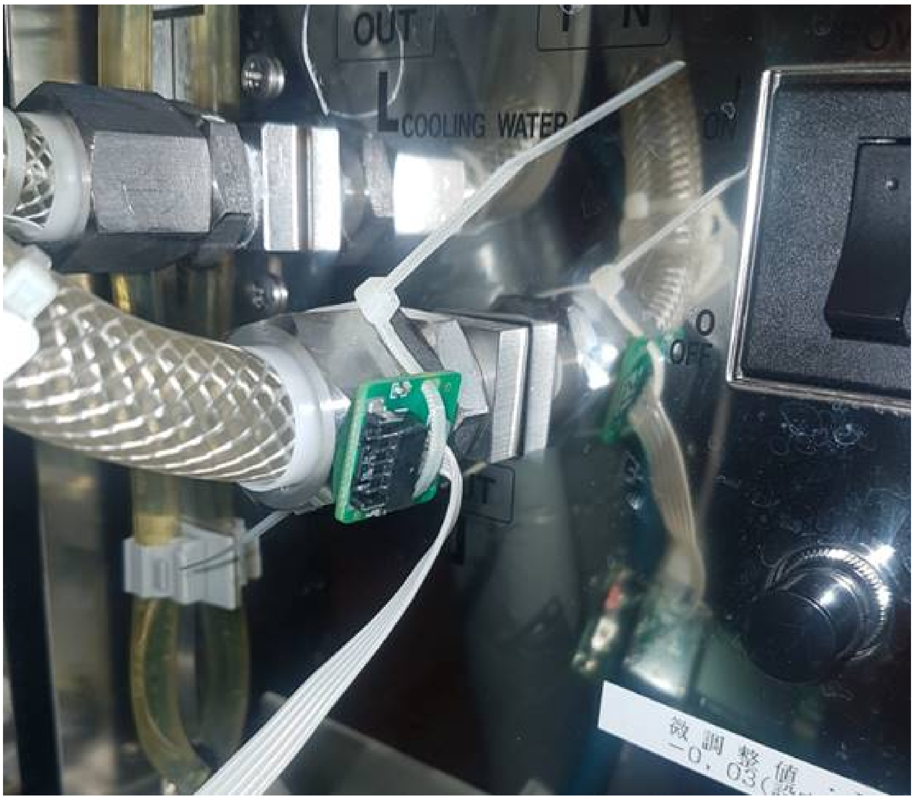
Figure 19. Views of the board



a) b) c)

a) sensor side with concrete expansion b) sensor side with transparent expansion c) back side with connector to main board

Figure 20. Smart nut example



Revision history

Table 2. Document revision history

Date	Version	Changes
01-Apr-2020	1	Initial release

Contents

List of figures