

Simulation and Measurement of Comfort Related Microclimate

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Abstract: Although microclimate is only one aspect when it comes to look at comfort determining factors, it decisively gains importance with increased wearing or using cycles of apparel, seating and laying systems. One of the challenges arising with validation of climate comfort are suitable test and evaluation standards in order to achieve high reproducibility and reliable forecasts. These requirements can only be met economically with human-physiologically adapted climate simulation combined with a suitable measuring technique for temperature and humidity distributions. The unique combination of the SWEATOR climate simulation and the SWEATlog sensor mats meet this requirements in an outstanding way. Apart from realistic and physiologically relevant microclimate simulations, the application of special, precise and bus-compatible combi-sensors for temperature and humidity offers the calculation of heat and humidity maps for visualization. Using specific clustering methods and numberless correlation results from occupant tests, the calculation of various material parameters, such as thermal or vapor resistances, as well as comfort indicators can be realized for valuable and reliable comfort forecasts.

Keywords: Microclimate measurement, Heat and humidity map, Microclimate simulation, Comfort assessment.

1. Introduction

Many products in our day to day live are assigned to be ergonomical and comfortable with high usability and conformity. Especially for apparel, seats and mattresses we have learned, that they should be breathable, waterproof and climate managing. But how can these attributes be assessed and what is the importance respectively the true advantage for the user?

Regarding the climate comfort in particular the physiological requirements of the thermoregulation as well as the individual sensations have to be analyzed. When humans are asked, whether they prefer warm or cool respectively dry or humid climate, the answers indicate a clear preference for dry. Warm or cool remains to be evenly distributed. This is although

humans do not have any moisture receptors. Hence the concept of warm or cold sensations must be a combination of heat and humidity developments. This confirms the slogan “some like it warmer, some colder, but all prefer dry!”. So how does a moisture sensation arise and what role does the temperature and humidity level play for a comfort perception? Which measurement technology enables the quantification of this comfort aspect, which is one of the decisive factors for product quality?

2. Comfort

When searching for a meaningful description of comfort, a simple but also extremely appropriate

formulation may be: comfort is not just less but no uncomfortable perception at all. So it seems to be better to have a look at discomfort instead of comfort.

Example: Wearing new shoes the first times will generate pressure points, tight sensations, warm and humid perceptions and local skin irritations, often resulting in red skin or even blisters. Consequently comfort has a biomechanical as well as a climatic proportion, whereas the perception of discomfort is primarily determined by biomechanical aspects, which are complemented and maybe even overruled by climatic factors with increasing wearing times. The decisive point of a climate comfort view reveals within the resulting microclimatic conditions, quantified by temperature and humidity.

In practice many investigations on general climate comfort have been published. The majority sets focus on various ambient temperature, humidity and air flow, even radiation, resulting in recommendations of comfortable and uncomfortable areas or zones depending on workloads and clothing situations (see Fig. 1) [3, 4, 5, 15].

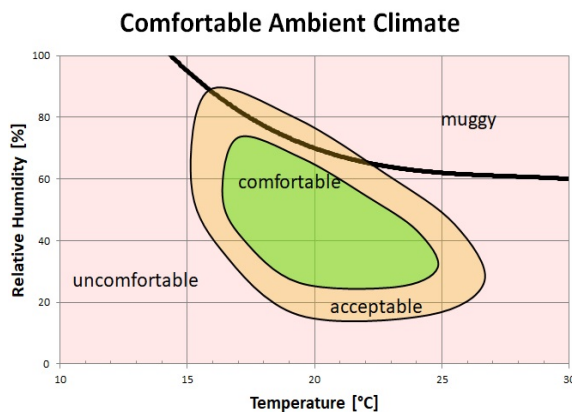


Fig. 1. Areas of comfortable and uncomfortable perception for environ's climates under certain clothing and physical situation.

Such information on general climate comfort however disregard the fact, that regional discomfort conditions have a decisive influence on the resulting perception of general comfort. Coming back to the example with the shoes, imagine that you are waiting for the bus in winter, wearing warm clothing, but standing in the slush, shoes are wet and feet are cold. It becomes obvious that this regional discomfort in the feet area will mainly influence and maybe overrule the general comfort perception (see Fig. 2).

This aspect of regional discomfort has been investigated barely and results are just available for feet, hand and seat/backrest region [1, 9, 14].

To understand the central role of microclimate on the comfort perception, a look at human thermophysiology will help. Its goal is the production of heat to stabilize the core temperature at about 37 °C. According to thermal or physical load this heat production will vary. In case of too much heat the

necessity of discharge will increase, otherwise heat loss is decreased and additional heat production (trembling) will start. Heat loss is physiologically controlled by a change of blood circulation and, in particular the increase, also by evaporation. In both cases the clothing system should assist the thermoregulation by adjusted isolation respectively heat and humidity transmission. These mechanisms will change the temperature and humidity in the microclimate of the boundary layer between skin surface and textile.

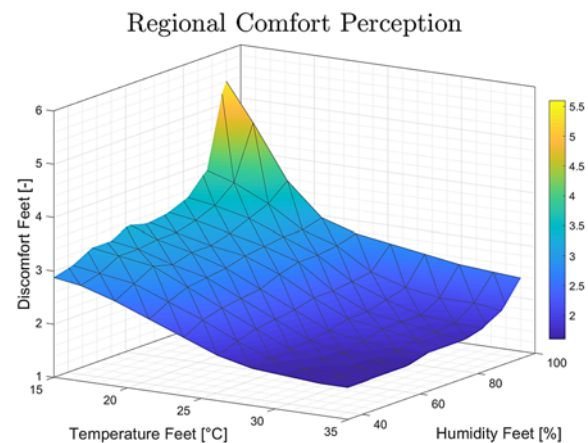


Fig. 2. Local discomfort perception in the feet sector for various microclimates in the shoe.

Based on many trials with human occupants on seats, in beds, and with diverse apparel products the human thermoregulation behavior measured as the microclimate close to the skin can be separated into three phases (see Fig. 3):

Phase 1: thermal neutrality, characterized by:

- Low temperature changes with up to ± 1 °C within the comfort range 31.5 °C – 35.5 °C.
- The heat balance is even, sweating as active body own method to influence the heat only happens in little doses (fine tuning).

- Dynamic regulating activity of low sensitive perspiration with slightly upward and downward developing absolute humidity levels occur, which over time do not accumulate in the human/textile interface.

Phase 2: Tendency to feel cold, characterized by:

- Decrease of the skin temperature below the comfort zone, risk of a reduction of the body core temperature.

- Demand for heat supply increases. Sensitive (active) sweating shuts down; humidity gradients decrease or remain stable.

- Lowest sweat emission, only insensitive sweating with very little absolute humidity and low to zero dynamic.

Phase 3: Tendency to overheat and sweat, characterized by:

- Increasing skin temperature over the comfort level, increasing tendency of the body core temperature.

- The demand for heat release increases; growing sweat activity with higher upward trends of humidity levels.

- In the measurable view a medium to high accumulating absolute humidity in textile layers can be seen.

Thus, the decisive conclusion from the measured assessment of climate comfort is to focus on the directly developing microclimate at the human/textile interface providing kind of a blueprint of the thermoregulation processes [11].

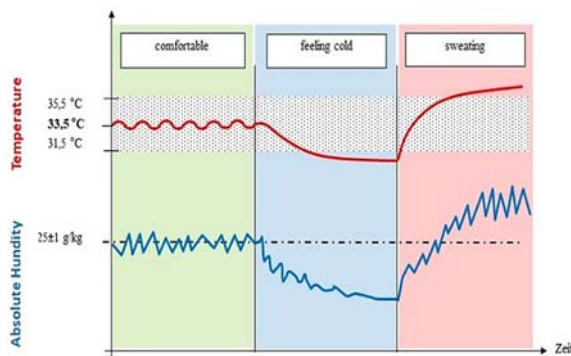


Fig. 3. Characteristics of thermoregulative phases.

To close the gap between measured microclimate and occupant's perception specific investigations have been conducted with the confirming result: microclimate is the best matching indicator for climate comfort by close correlation to perception. (Fig. 4).

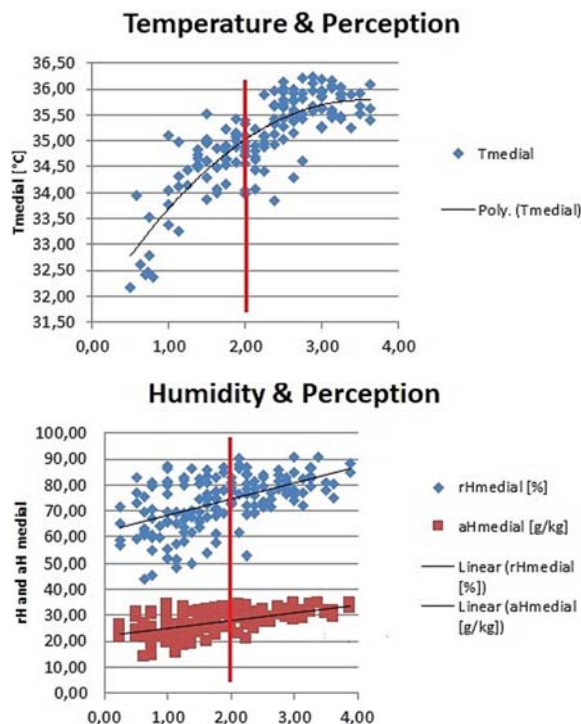


Fig. 4. Combined temperature and humidity perceptions of proband tests in shoes under various climate and physical stress conditions.

Fig. 4 shows the perception scores for various microclimate situations in the feet section as well as possible regressions to the measured values:

- Very good fitting of perceived heat to measured temperature;

- Weak correlation between measured relative humidity and their perception;

- and best between the comfort perception and absolute humidity, which combines relative humidity and temperature.

But Fig. 4 visualizes also a widespread diversity between the individuals. To get reproducible and valuable results many occupants and many tests are necessary, what is cost and time consuming. This justifies a standardized heat and humidity source.

3. Simulation of Microclimate

As a consequence of the standardization demands for climate tests artificial systems are applied. Those emit heat and humidity aiming to measure and calculate physical material parameters such as heat conduction and vapor transmission respectively storage. Others aim to simulate the human heat and humidity emission (thermoregulation) creating a certain microclimate with the test object, which allows a reliable prediction of the climate comfort [2, 6, 10, 12]. Such climate dummies can be found either as whole-body manikins or formed as single body parts. They are mostly of highly complex technology and sometimes come with instable processes. Standards have been available for decades like Sweating Guarded Hotplate (SGHP) respectively Hohenstein's Skin Model [16] but without a focus on microclimate.

Apart from standardized test conditions, e.g. ambient climate, measurement spots and sensor quality, the particular challenge for the setup and operation of such climate simulation systems is the best possible replication of the physiological human evaporation and the combination of heat and humidity emissions. Only this way defined climatic conditions and energy rates will ensure realistic heat and moisture flows and stationary microclimate situations.

According to the necessary features of a standardized heat and humidity source the SWEATOR system has been developed [7]. This technology is based on a water-filled, heat controlled hollow body with a special water vapor permeable membrane coating. The test specimens can be manufactured in different shapes (see Fig. 5), with different permeable membranes and without or with different surface perforations. The heating and water circulation are controlled by a touch screen control unit. Energy inputs from a few Watts to 400 W per square meter and sweating rates between 50 and 600 ml/m²×h are possible. For human physiological simulations under normal conditions, settings of 30 - 50 W/m² or 90 - 120 ml/m²×h are used. After pre-conditioning the device to the desired values, the SWEATOR manikin is applied to the confectioned test objects. In the boundary layer between SWEATOR surface and

material probe the microclimate distribution is measured with single sensors resp. a sensor array at defined locations (see chapter 4). The test trials take place under climatically defined room conditions including additional convections, if necessary. The SWEATOR technology thus enables realistic test conditions and non-destructive testing options with ready-made products.



Fig. 5. SWEATOR torso with test jacket, SWEATOR foot and SWEATOR head with safety helmet.

The SWEATOR control unit records and stores the supplied energies, weight changes and microclimate conditions even within various textile layers or outlets of ventilation channels.

Regarding the thermal system self-loss, the moisture quantity, stored in the sample during the experiment, and the mass flow, converted by use of approximately constant evaporation energy of approx. 2400 J/g, the most important values of heat flow H_c and moisture flow H_e , each with the unit Watt, are calculated. This means that the result variables

- Moisture Vapor Transmission Rate MVTR [g/h];
- Evaporative Capacity EC [W];
- Storage from the vapor phase ΔW_p [g]

can be determined. Including the measured microclimate parameters temperature, relative humidity or water vapor partial pressure at different spots even the thermodynamic material parameters;

- Thermal resistance R_{ct} [$K \times m^2/W$];
- Water vapor transmission resistance R_{et} [$Pa \times m^2/W$] are calculated.

4. Sensors for Microclimate Measurement

As discussed before the additional demand on reproducible and valuable (substantial) measuring values has to be respected either.

Usually, the measurement of the microclimate is carried out with discrete combi-sensors for temperature and humidity [13]. The inaccuracies that occur in sensor location and occupancy or coverage lead to a scattering of the measured values and limit the quality of the information.

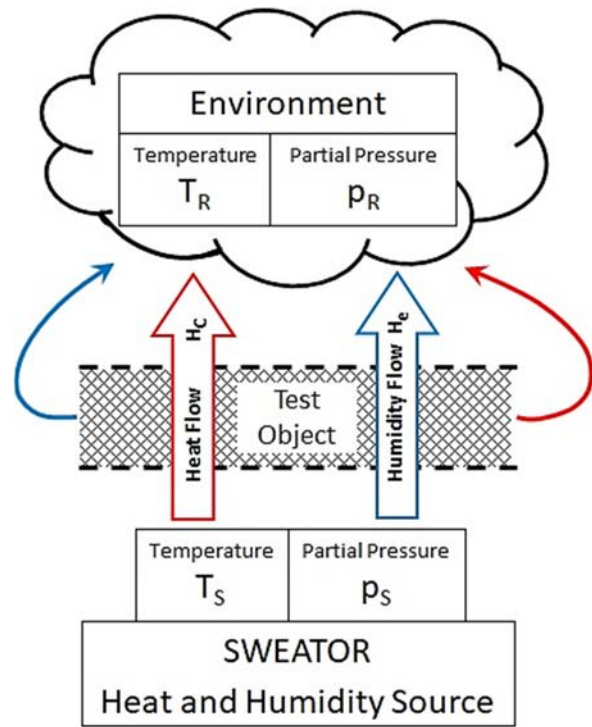


Fig. 6. Heat and moisture transport in SWEATOR simulation.

A solution to avoid the difficulties with single sensors is a defined array of up to 60 sensors combined with an interpolation algorithm calculating the temperature and humidity distribution with all discrete sensor readings. To reduce cable and technical complexity bus-compatible combi-sensors with I2C interface are built into a flexible, thin and compressible spacer mat, which enables two- and even three-dimensional recordings of the microclimates [8].

By laborious market analysis two suitable sensors (Fig. 7) with different specifications and disadvantages have been identified:

- Honeywell HIH8xxx:
 - I2C with up to 128 programmable addresses;
 - $\pm 2\%$ humidity resolution;
 - $\pm 0.5^\circ C$ temperature resolution;
 - Measures: $4 \times 5 \times 2 \text{ mm}^3$;
 - Response time ca. 33 ms;
- Sensirion SHT3x:
 - I2C with 2 selectable addresses;
 - $\pm 1.5\%$ humidity resolution;
 - $\pm 0.1^\circ C$ temperature resolution;
 - Measures: $2.5 \times 2.5 \times 1 \text{ mm}^3$;
 - Response time 4 – 15 ms.

So the Honeywell HIH8xxx can be directly implemented in an array on one bus line, has a sufficient but low resolution in temperature and is bigger than the Sensirion chip. The main disadvantage of the SHT3x is the restricted address range (just 2) for I2C operation with up to 60 sensors on one bus line. To get it also operated an additional PIC is implemented for each SHT3x which serves as a bus respectively address manager.

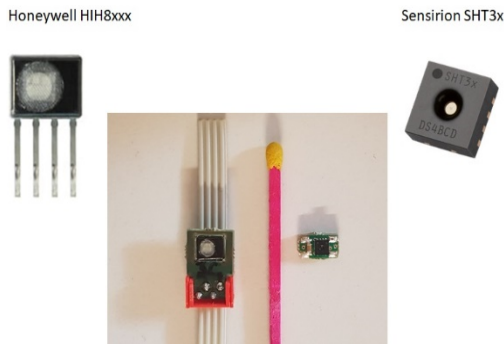


Fig. 7. I2C-sensors processed for measuring microclimate distribution.

This solution offers a so called flash-mode, where converting of all sensors is simultaneously started. The collection of the converted temperature and humidity values is then sequentially. This mode makes sure, that the complete sensor array is read within a few milliseconds, while the reading of 30 Honeywell sensors takes about 1 second.

To connect each sensor unit the SMD sensor chips are mounted on a tiny circuit board (PCB) which allows also the integration of a special crimp connector for the I2C wires and, in case of SHT3x, of the PIC (Fig. 7). Before implementation the programming of different addresses to HIH8xxx as well as address managing routine to PIC of SHT3x is necessary.

By use of a 4 wire ribbon cable the sensor-PCBs can be arranged in any distance or matrix dimensions very quick. To finish the sensor array it will be prefixed on a spacer material and is sewed and covered by a highly breathable mesh material (Fig. 8). The resulting sensor mat is about 4 - 5 mm thick and has for seat or backrest application a typical dimension of $500 \times 500 \text{ mm}^2$. Compared with single sensor measurement the SWEATlog mat takes nearly no influence on the microclimate, is highly flexible and confirms mechanical robustness (connector, cable, sensor-PCB) within many tests.



Fig. 8. SWEATlog logger and sensor array (mat) with up to 60 HIH8xxx sensors at one I2C ribbon (4 wires).

The SWEATlog sensor mats are operated by a logger which works either as stand-alone or USB-controlled. In the USB mode the SWEATlog-app allows an online monitoring and visualisation of the registered values as a heat and humidity map (Fig. 9 and Fig. 10), otherwise these are processed from the data stored on the internal SD-card.

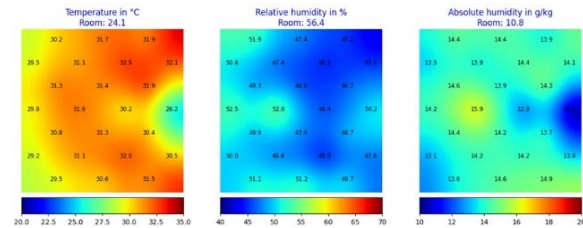


Fig. 9. Heat and humidity map of a proband on the seat of an office chair.

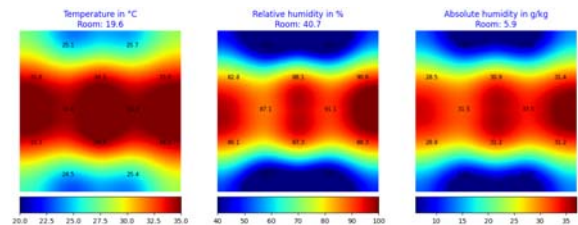


Fig. 10. Heat and humidity map of SWEATOR Torso controlled at 35°C.

The visualizations are calculated by use of each sensor value with a special interpolation algorithm to get the continuous heat and humidity distributions. Additional clustering methods supports the processing of the characteristic values of thermodynamical or physiological relevance [8, 9]. Fig. 9 shows the typical distribution of a proband sitting on a chair showing the contact zones of the buttock and the upper thighs impressively in the heat map, whereas the map of the relative humidity is nearly homogeneous and in the range of the ambient humidity, seeming that the occupant is not sweating. But a look at the absolute humidity map confirms an increase of the humidity in the microclimate as an indicator for additional slight sweating.

To prove the homogeneity of the heat and humidity production of the SWEATOR climate simulation the torso is placed on the sensor mat lying on a seat upholstery. The results displayed in Fig. 10 show quite even distributions of the heat and the humidity in the range of physiological values.

So it can be assumed that the simulated microclimate combined with cluster analysis enable comfort prognosis.

5. Comfort Prognosis

The focus of the SWEATOR simulation combined with SWEATlog sensor mats is primarily set on the

analysis of heat and moisture transport routes and, in particular, on the generation of realistic microclimates for direct comfort assessments. This requires, on the one hand, a secure mapping between regional microclimate conditions (seat, bed, jacket, etc.) and the corresponding comfort sensations of the users, and on the other hand, the appropriate choice of parameters for the simulation system.

For this purpose, a variety of studies on comfort correlations in seating systems, footwear and apparel components could be linked to the comfort areas. After evaluation and harmonization of the rating scales (e.g. [15]), the transition temperature and humidity were determined to reach discomfort in warm temperatures at about 35.5 °C respectively 25 g/kg [7].

The results in Fig. 11 emphasize the correlation between proband and simulation test as well as to the perceptions of the various climate situations (test phase) appearing on car seats with active cooling systems during driving. As expected the humidity perception is weak, but the temperature and comfort perception presents a very good correlation.

This knowledge, in particular the comfort limits can be used to assess various ski boots, tested under 0°C evirons temperature with the SWEATOR foot controlled at 35°C and with adjusted sweat rate to about 15 g per hour and foot. The microclimate has been registered close to the skin (surface of manikin) in the toe area and the medial arch as well as between sock and inside the shoe lining. The results of absolute humidities in Fig. 12 make the comfort prognosis related to the humidity limit of 25 g/kg possible, as just acceptable for the types 2 and 4 and unacceptable for the others.

Consequently any comparison between occupant and simulation results proves the good agreement between the microclimates that occur. Therefore a reliable comfort prognosis based solely on the simulation becomes a practicable and economical option.

6. Conclusions

Following the slogan “what you cannot measure, you can’t improve”, applied on the assessment of climatic product features, requires reproducible and valuable analysis of the microclimate situations between skin and contacting textile, e.g. of apparel.

Although comfort perception shows a high correlation to microclimate’s temperature and humidity the occurring individual diversity of the probands makes the corresponding analysis laborious. To realize precise and economic tests, a heat and moisture source with emission rates adapted to human physiology and the flat or spatial recording of the microclimate in the boundary layers must be available.

Regarding the demands on the microclimate sensor, i.e. precision, placement orientation and at least reproducibility, a special measuring device had to be developed. The SWEATlog system uses combined temperature and humidity sensors with I2C

interface placed in a defined array and fixed in a flexible mat. The visualisation as a heat and humidity map is realized by use of selected algorithms. Interesting thermodynamical as well as comfort related microclimate values are calculated within defined cluster areas.

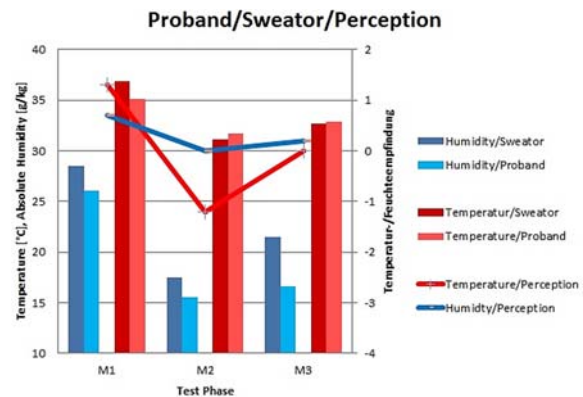


Fig. 11. Comfort correlation of proband and simulation results from seating tests.

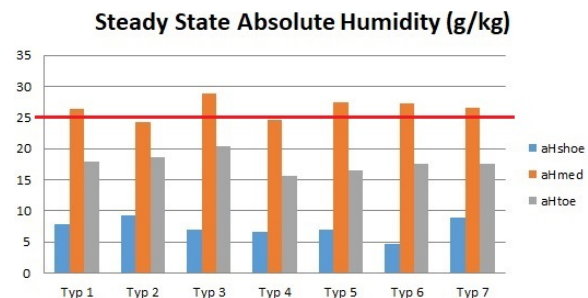


Fig. 12. Comfort prognosis of simulated shoe tests with SWEATOR foot.

The unique combination of SWEATlog sensor mat and the SWEATOR system with anatomically formed and sweating manikins creates the basis for thermophysiological product analyses. Combined with differentiated evaluation methods and with correlations to human comfort perceptions, a reliable comfort prognosis for assessment as well as improvement of clothing or body support products can be achieved.

Future developments should realize an automated clustering of the heat and humidity map by use of AI-technologies (artificial intelligence) to achieve the characteristic evaluation values for climate and comfort management in any microclimate situations.

And, of course, any wireless solution of sensor communication will be preferred to reduce or omit the wiring.

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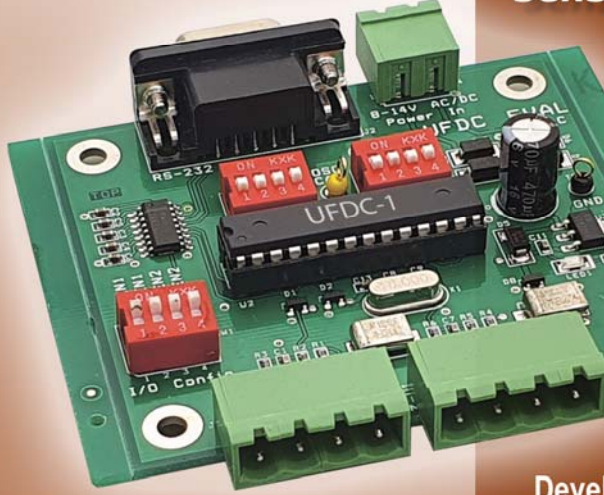
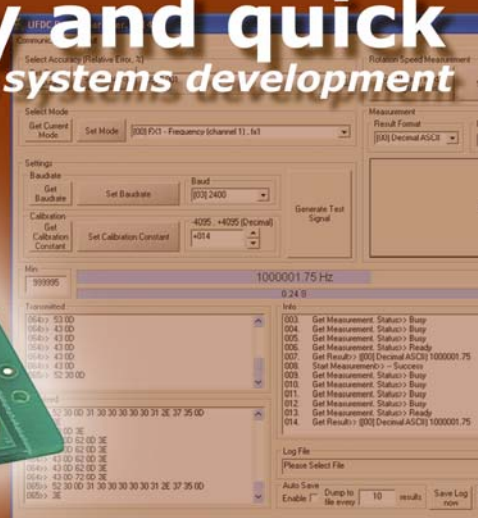
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