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# MEMS in Aircraft Engine Monitoring

## *A Humidity Sensor*


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*PWGSC Contract Number: W7707-756865*
*CSA: Dr. Nezih Mrad, Defence Scientist, 613-993-6443*





**Defence R&D Canada – Atlantic**

Contract Report
DRDC Atlantic CR 2011-069
July 2011


Canada

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# Abstract

In order to fully understand and exploit MEMS technologies for engine condition monitoring applications, issues impeding the implementation of MEMS sensors on aircraft engines need to be addressed. This effort introduces the first step in such implementation process. It develops, characterizes and demonstrates the deployment of a MEMS-based humidity sensor in anticipation of further development of engine condition monitoring sensors (e.g. NOx that monitor the level of pollution).

Two capacitive-type MEMS sensor prototypes were designed, developed and built. The results demonstrated a linear response to changes between 11% and 97% of relative humidity.



# Résumé

Pour comprendre et exploiter à fond la technologie microélectromécanique (MEMS) à des fins de surveillance de l’état des moteurs, il faut d’abord régler les problèmes qui nuisent à la mise en place de capteurs MEMS dans des moteurs d’aéronefs. Ce travail marque la première étape du processus de mise en œuvre. Il permet de développer, de caractériser et de démontrer le déploiement d’un détecteur d’humidité MEMS en prévision du développement d’autres capteurs qui serviront à la surveillance de l’état des moteurs (p. ex. les oxydes d’azote [NOx] qui permettent d’évaluer le niveau de pollution).

Deux prototypes de capteurs MEMS de type capacitif ont été conçus, développés et fabriqués. Les résultats ont indiqué une réponse linéaire aux changements d’humidité relative situés dans une plage de 11 à 97 pour cent.

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# Executive summary

## MEMS in Aircraft Engine Monitoring: A Humidity Sensor

**Mourad El-Gamal, DRDC Atlantic CR 2011-069; Defence R&D Canada – Atlantic; July 2011.**

**Introduction:** Engine condition monitoring continues to be one of the main challenges for enhanced engine performance, engine life extension and life cycle cost reduction. Considerable effort has been expended in the development of advanced sensors; however, for several reasons, most fall short in the ability to operate in the harsh aircraft engine environment. For instance, the fabrication of miniature monitoring instruments for harsh environments is very challenging—only few materials are suitable for such applications, e.g. diamond, but their desirable "tough" mechanical properties also make them extremely difficult to process.

To fully understand and exploit MEMS technologies for engine condition monitoring applications, issues impeding the implementation of MEMS sensors on aircraft engines need to be addressed. This project introduces the first step in the implementation process. It develops, characterizes and demonstrates the deployment of MEMS-based humidity sensors in anticipation of further development of engine condition monitoring sensors, including CxHy sensors that monitor the state of combustion, NOx that monitor the level of pollution, and CO, CO2, and O2 sensors.

**Results:** Two capacitive-type MEMS sensor prototypes were designed, developed and built as an initial step in anticipation of further development of engine condition monitoring sensors, including CxHy sensors to monitor the state of combustion. The sensor provided a linear response to changes between 11% and 97% of relative humidity. The sensor, IC interface, and printed circuit board (PCB) were custom designed and manufactured by MEMS Vision.

**Significance:** The project significance resides in laying out the fundamental platform (IC interface and printed circuit board (PCB)) for the development of engine condition monitoring sensors. This platform could be exploited for chemical, bio-chemical and environmental sensing, as well as wireless structural health monitoring.

**Future plans:** In addition to the integration of chemical, bio-chemical and environmental sensors within the developed sensor platform, future implementation of miniaturized and highly integrated single PCB solution with a small form factor is anticipated.

# Sommaire


## MEMS in Aircraft Engine Monitoring: A Humidity Sensor

**Mourad El-Gamal, DRDC Atlantic CR 2011-069, R & D pour la défense Canada – Atlantique, juillet 2011.**

**Introduction :** La surveillance de l'état des moteurs s'avère toujours le principal défi à relever pour améliorer les performances, prolonger la durée de vie et réduire les coûts du cycle de vie des moteurs. On a déployé des efforts considérables pour développer des capteurs améliorés. Toutefois, pour diverses raisons, le fonctionnement de la plupart d'entre eux n'est pas à la hauteur dans le rude environnement des moteurs d'aéronefs. Par exemple, la fabrication d'instruments de surveillance miniatures convenant à un environnement hostile pose de grands problèmes; seuls quelques matériaux, comme le diamant, conviennent à une telle application, mais leurs propriétés mécaniques résistantes en font également des matières très difficiles à transformer.

Pour bien comprendre et exploiter la technologie MEMS utilisée à des fins de surveillance de l'état des moteurs, il faut d'abord régler les problèmes qui nuisent à la mise en place de capteurs MEMS dans des moteurs d'aéronefs. Ce projet marque la première étape du processus de mise en œuvre. Il permet de développer, de caractériser et de démontrer le déploiement d'un détecteur d'humidité MEMS en prévision du développement d'autres capteurs qui serviront à la surveillance de l'état des moteurs, notamment les capteurs CxHy qui vérifient l'état de la combustion et les NOx qui évaluent le niveau de pollution, ainsi que les capteurs CO, $CO_2$ et $O_2$.

**Résultats :** Deux prototypes de capteurs MEMS de type capacitif ont été conçus, développés et fabriqués en prévision du développement d'autres capteurs qui serviront à la surveillance de l'état des moteurs, y compris les capteurs CxHy servant à déterminer l'état de la combustion. Le capteur a donné une réponse linéaire aux changements d'humidité relative situés dans une plage de 11 à 97 pour cent. MEMS Vision a conçu et fabriqué sur mesure le capteur en question, l'interface à circuits intégrés et la carte de circuits imprimés.

**Importance :** L'aspect le plus important du projet s'avère la conception de la plate-forme de base (interface à circuits intégrés et carte à circuits imprimés) qui servira au développement des capteurs de surveillance de l'état des moteurs. La plate-forme en question pourrait être exploitée à des fins de détection chimique, biochimique et environnementale, ainsi que pour la surveillance à distance de l'état des structures.

**Perspectives :** Outre l'intégration de capteurs chimiques, biochimiques et environnementaux dans la plate-forme de détection déjà développée, il est prévu de mettre en œuvre une unique solution de carte de circuits imprimés miniaturisée et hautement intégrée de petites dimensions.

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# 1 Introduction

Engine condition monitoring continues to be one of the main challenges for enhanced engine performance, engine life extension and life cycle cost reduction. Considerable effort has been expended in the development of advanced sensors; however, for several reasons, most fall short in addressing or meeting the aircraft engine harsh environment. For instance, the fabrication of miniature monitoring instruments for harsh environments is very challenging—only few materials are suitable for these applications, e.g. diamond, but their desirable "tough" mechanical properties also make them extremely difficult to process.

To fully understand and exploit MEMS technologies for engine condition monitoring applications, issues impeding the implementation of MEMS sensors on aircraft engines need to be addressed. This project introduces the first step in the implementation process. It develops and characterizes MEMS-based humidity sensors and delivers a prototype system for further measurements in engines and other realistic environments, in order to determine suitability for diagnostic, prognostics, and health management systems.

This report presents measurement results for MEMS-based humidity sensors, as well as the prototype system comprised of the sensors and integrated circuit (IC) interface. The sensor, IC interface, and printed circuit board (PCB) were custom designed and built by MEMS Vision.

# 2 Humidity Sensor

The humidity sensor is based on a capacitor with a moisture sensitive dielectric. This causes the capacitance to change with the level of relative humidity in the sensor's surroundings, and this can be detected by a suitable integrated circuit. Figure 1 shows how the capacitance of the sensor varies with relative humidity over the range of 11% to 97%. It can be seen that the curve is very linear, even at high humidity levels. This feature allows for accurate measurements without extensive (and costly) calibration schemes.

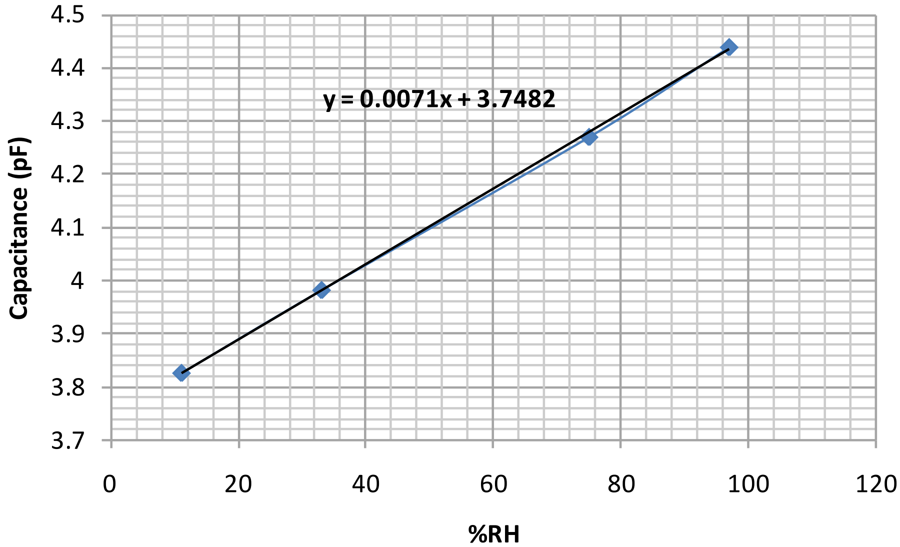


*Figure 1: Measured capacitance of the humidity sensor over the relative humidity range of 11% to 97%.*

# 3 The Sensing Solution

Two versions of the prototype humidity sensing PCB were designed, and these are shown in Figure 2. Each system is comprised of the MEMS sensor, an IC designed to detect changes in capacitance, a header used to interface the PCB to a control FPGA, and various switches and test points for diagnostic information. For standard humidity measurements, all of the switches should be in the off position.

The difference between the two prototypes is the location of the sensor. In the PCB on the left, the sensor is packaged separately, while it is directly bonded to the IC package on the PCB on the right. This second PCB shows that the sensor is small enough to be included inside the package, once the diagnostic outputs from the IC are not needed. This would result in a complete system in package (SiP) solution, further reducing the form factor and increasing the robustness of the system.

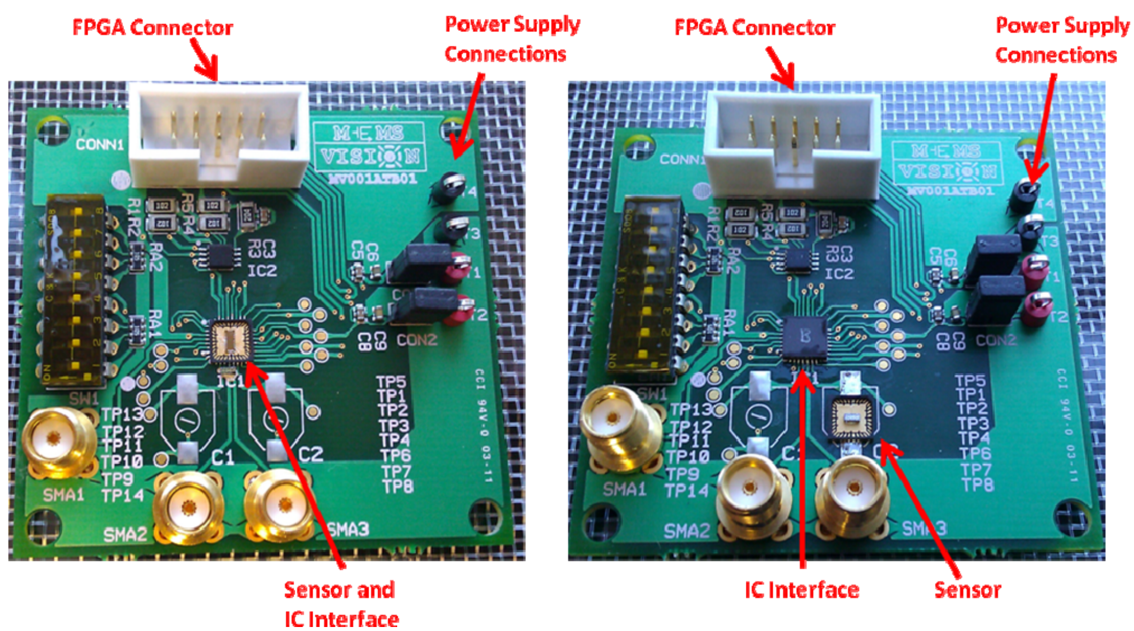


*Figure 2: The prototype humidity sensor PCBs with diagnostic capabilities.*

The sensor interfaces with the FPGA (or a suitable microcontroller) through an industry standard 2-wire I2C bus, and these are the only two necessary external connections (other than the 3.3V power supply). All commands, including resetting the chip and making a humidity measurement, are performed through this interface. The clock and data pins for the I2C interface are located on the header CONN1, whose pinout is shown in Figure 3.

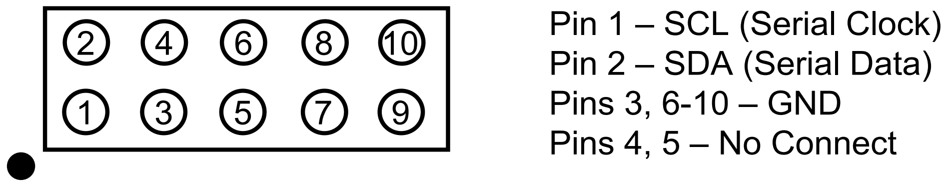


*Figure 3: Pinout of the FPGA connector.*

The control chain for the humidity sensor prototype is shown in Figure 4. The necessary Verilog HDL code to synthesize an FPGA controller, and the software to communicate through a computer's serial port, accompany this document—their descriptions are given in Annex A and B, respectively.

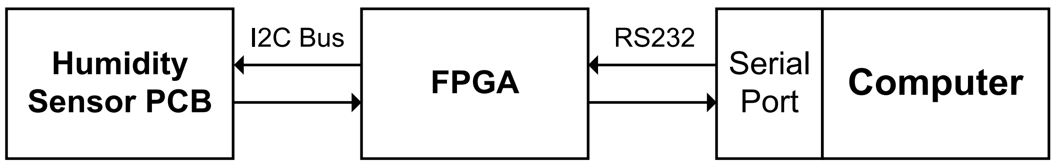


*Figure 4: Control chain to interface with the humidity sensor.*

In future implementations, the FPGA can be replaced with a microcontroller to create a single PCB solution with a small form factor.

# 4 Conclusions

Two capacitive-type MEMS sensors prototypes were designed, developed and built as an initial step in anticipation of further developments of engine condition monitoring sensors, including CxHy sensors that monitor the state of combustion, NOx that monitor the level of pollution, and CO, CO2, and O2 sensors. The sensor provided a linear response to changes between 11% and 97% of relative humidity.

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# Annex A Description of the Verilog RTL Code

The RTL files needed to synthesize the humidity sensor controller on an FPGA is in the "RTL" directory on the accompanying CD. The file descriptions are as follows:

- mv001a_chip.v: The top level module.
- sync_reset.v: Synchronizes the release of the global reset signal.
- sync_level.v: Synchronizes the I2C bus and RS232 input signals with the controller.
- sync_if.v: The top level interface.
- clk_divider.v: Generates the I2C and RS232 clocks.
- i2c_master.v: The I2C physical interface.
- sm_ctrl.v: The I2C state machine controller.
- rs232.v: The RS232 physical interface.
- rs_ctrl.v: The RS232 state machine controller.
- chip.ucf: A sample port mapping for an FPGA.

The I/O ports in the top level module (mv001a_chip.v) will need to be mapped to the correct ports on the FPGA being used. Their descriptions are as follows:

- REF_CLK – The master clock input. This is responsible for all timing operations.
- RST_N – The global reset input. This is an active low signal.
- RS232_RX – The received RS232 data line. This must be connected to the RX pin of the serial port on the FPGA board.
- RS232_TX – The transmitted RS232 data line. This must be connected to the TX pin of the serial port on the FPGA board.
- SCL – The clock of the I2C bus. This must be connected to an I/O pin on the FPGA board, which must be connected to pin 1 of CONN1 on the prototype humidity sensor PCB.
- SDA – The data line of the I2C bus. This must be connected to an I/O pin on the FPGA board, which must be connected to pin 2 of CONN1 on the prototype humidity sensor PCB.

The instantiations for the I2C and RS232 clock generators will also need to be changed based on the frequency of the reference clock. The relevant variables are the "size" and "stop" variables on lines 221 and 222 for the I2C clock, and on lines 232 and 233 for the RS232 clock.

The original test setup used a 27MHz clock, and the division ratios can be calculated as follows:

- I2C clock [400kHz]:

$$stop = \frac{27MHz}{2 \times 400kHz} - 1 = 32.75 \cong 33 \quad \text{(rounded to the nearest integer)}$$

$$size = log_2(stop) = 5.04 \cong 6 \quad \text{(rounded up to the next highest integer)}$$

- RS232 clock [115.2kHz]:

$$stop = \frac{27MHz}{2 \times 115.2kHz} - 1 = 116.19$$
$$\cong 116 \quad \text{(rounded to the nearest integer)}$$

$$size = log_2(stop) = 6.86 \cong 7 \quad \text{(rounded up to the next highest integer)}$$

# Annex B Description of the RS232 Computer Interface Software

The RS232 computer interface software is written in C code, and a Linux-based script is used to provide the user interface. The files are located in the "RS232" directory on the accompanying CD, and the file descriptions are as follows:

- rs232.c: The RS232 PC interface in readable C code.
- mv001a.sh: The user interface script.

Before use, the C code must be compiled using the following command:

gcc –o rs232 rs232.c

This will create the compiled binary module that will be accessed by the mv001a.sh script.

In order to open the serial port for RS232 communications, the user needs to have administrative privileges. This can be done by logging in as "root", or by running the script as a super user with the command:

"sudo ./mv001a.sh".

The options included in the script are as follows:

- **Reset CHIP and check status**: This resets the MV001A chip to the default values and checks the register file data.
- **Measure Temperature**: Performs a temperature measurement and returns the temperature in degrees Celsius.
- **Measure Humidity**: Performs a humidity measurement and returns the capacitance value of the sensor.

Data from measurement choices are saved in the directory /rs232/meas_data

A reset command must be issued between measurements.

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MEMS, engine monitoring, humidity sensing.

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