ANGULAR POSITION SENSORS FOR SPACE MECHANISMS

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ABSTRACT

Angular position sensors are used on various rotating mechanisms such as solar array drive mechanisms, antenna pointing mechanisms, scientific instruments, motors or actuators.

Now a days, potentiometers and encoders are mainly used for angular measurement purposes. Both of them have their own pros and cons.

Potentiometers are easy to implement but they are not so accurate. They have a low lifetime and a dead zone. Encoders have high accuracy but are complex to interface.

As alternative, Ruag Space Switzerland Nyon (RSSN) is developing and qualifying two innovative technologies of angular position sensors which offer easy implementation, medium to very high lifetime and high flexibility with regards to the output signal shape/type.

The Brushed angular position sensor uses space qualified processes which are already flying on RSSN's sliprings for many years. A large variety of output signal shape can be implemented to fulfill customer requirements (digital, analog, customized, etc.).

The contactless angular position sensor consists in a new radiation hard Application Specific Integrated Circuit (ASIC) based on the Hall effect and providing the angular position without complex processing algorithm.

1. INTRODUCTION

RSSN core business is the design and manufacturing of electrical rotary joint mechanisms. They are commonly called "sliprings" when able to continuous angular rotation. They are commonly called "twist capsule" when limited in angular rotation. Theses "sliprings" or "twist capsules" are usually integrated in mechanisms where the angular position need to be known and therefore an angular sensor is required. In order to offer a comprehensive solution in the electrical transfer and the position sensing of rotary joint system, Ruag Space Switzerland Nyon is developing and qualifying two innovative technologies of angular sensors, the brushed technology and the contactless technology.
Current angular sensors in space applications are usually potentiometers or encoders.

Potentiometers cover low accuracy and low lifetime applications. They have the advantage of being easy to implement, they are small size and low cost. The electrical interface is typically 0-5V and the output is an analog voltage proportional to the angular position. On the other hand, potentiometers suffer from the sliding contact technology (carbon brushes onto metallic resistive coil or track) which has a high wear rate and therefore a quite low accuracy. They are not suitable for high lifetime applications such as for radiometers.

Encoders are used when high accuracy and/or resolution is required. They suffer from being complex to integrate (very sensitive to mechanical tolerances and misalignment). They also suffer from having complex electrical interface (serial or parallel interface). Encoders are sensitive to harsh environment and thus need additional shielding which increases the mass of the system.

1.1 Brushed sensor

RSSN has developed brushed angular sensors taking advantages of its expertise in the slip rings design. These sensors are rotary switch based on a gold-gold contact technology which generates low wear and low electrical noise. Their design are similar to pancake sliprings with the difference that in the rotor, tracks are segmented (instead of continuous like in a sliprings) and connected into electrical circuits to generate the wanted position signals. These sensors may be an interesting alternative to potentiometers as a potentiometric signal and digital signals (such as end limits) can be combined easily on the same sensor. The section 2 gives more detailed descriptions of contact sensor.

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1.2 Contactless sensor

For the contactless technology, one ASIC is developed and qualified. This ASIC combines advantage of potentiometers (simple electrical and mechanical interface, radiation hard and small size) as well as advantage of encoders (high resolution).

Its measurement principle is based on the measurement of the direction of a magnetic field generated by a permanent magnet. Unlike commercial angular sensors that use 2 axis sensitive Hall structure, RUAG technology is based on a circular sensitive structure which provides directly the angular position (analog voltage and digital output compliant with SPI standard) without the use of complex algorithm (then Digital Signal Processing). These DSPs increase the complexity of the surrounding electronics and makes the entire system more sensitive to harsh environments and more expensive. The section 3 gives a more detailed description of the contactless sensor.

In addition, a trade off of brushed sensor technology and contactless sensor technology is presented in section 4.

2. BRUSHED SENSOR

2.1 Principle

The brushed angular sensor technology is based on the rotary switch principle. The sensing element or output of the sensor is the brush wire sliding over a segmented track. Because the track segments belong to different electrical circuits, the electrical values of the sensing brush wire changes according the segment in contact.

In the switch analogy:

- the brush wire corresponds to the output of a Single Pole switch and is the output of the sensor.
- the different electrical circuits corresponds to the input ports of the switch. The number of circuits determines the number of electrical level on the output. They may be interconnected to the rotor or rerouted to the sensor stator through a continuous track and an additional brush.
- The tracks segments determine the number and the locations of the switching.

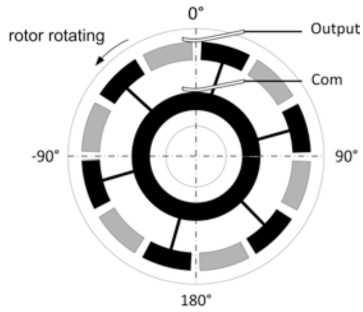

Figure 1. *Mechanical representation of the sensor*

On the rotor and on the stator, PCBs are used to provide the mechanical support and for the interconnection of the electrical circuits needed for the operation of the sensor.

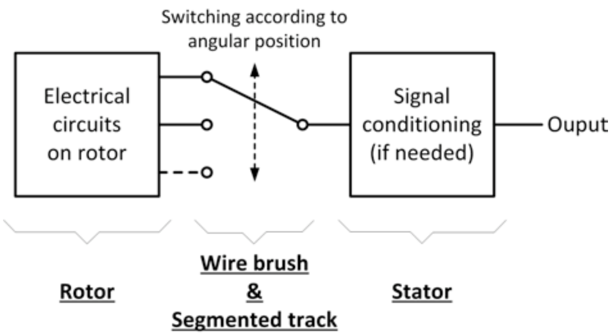

Figure 2. *Brushed sensor block diagram*

The gaps between the segments are designed so that the wire brush remains always connected to at least one segment. During the transitions, the wire brush is connected to both the next and previous segments. This has the following consequence:

- Thanks to the metal to metal contact and the brush and tracks geometry, the transition is punctual and repeatable.
- During the transition the wire brush doesn't touch the substrate preventing the smearing of insulator material on the tracks.
- The electrical transition is a "Make-Before-Brake" (MBB) switching. Thus the electrical circuit design must consider punctual short-circuit between segments.
- The contacts of the wire brush during the transition limits the maximum angular velocity.

In order to achieve good performances, the electromechanical operating principle of the sensor implies to have an accurate location of the rotor wrt. the sensing brush tip. This implies:

- Parts manufactured and assembled with tight tolerances
- The mechanical bearing of the rotor must be accurate.

Any deviations will impact the accuracy and then the performances of the sensor.
Brushed sensors may be also bearing less, resulting to a very simple mechanism. In this case, the rotor location (thus the final performance) depends on the tolerances of the sensor interface.

2.2 Output signals
The combination of the rotary switch and the flexibility of PCB for the implementation of electrical circuits allows the implementation of several output signals on the same rotor. In addition electronic filter can be easily added on the stator.

Different electrical quantity (e.g. electrical continuity, impedance, current and voltage) may be used depending on the application.
Independently from the electrical quantity chosen for the output signal, the signal shapes have the following characteristics:

- o The signal is constant over each segment leading to a step shaped signal
- o The number of segments is limited by the minimum segment length.

Below are the typical signal implemented on the brushed sensors:

- **Open/Closed contact (digital)**, the angular sensor acts as a switch and is connected to a digital input through a pull-up resistor. The corresponding switch is a SPDT (Single Pole Double Throws) where the 1st input is connected to a fixed potential, while the 2nd input has a floating potential. For EMC reasons, the 2nd input may also be connected through a resistor of high impedance to the 1st input to allow the electrical charge dissipation. This is the simplest configuration of the sensor as it requires only 2 tracks (1x segmented, 1x continuous). The typical signal shapes in this configuration are:
  - o **Angle sign**
  - o **Incremental**
  - o **Limit switch**

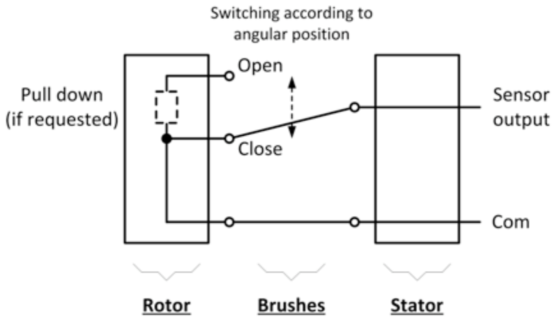

Figure 3. *Digital signal electrical diagram*

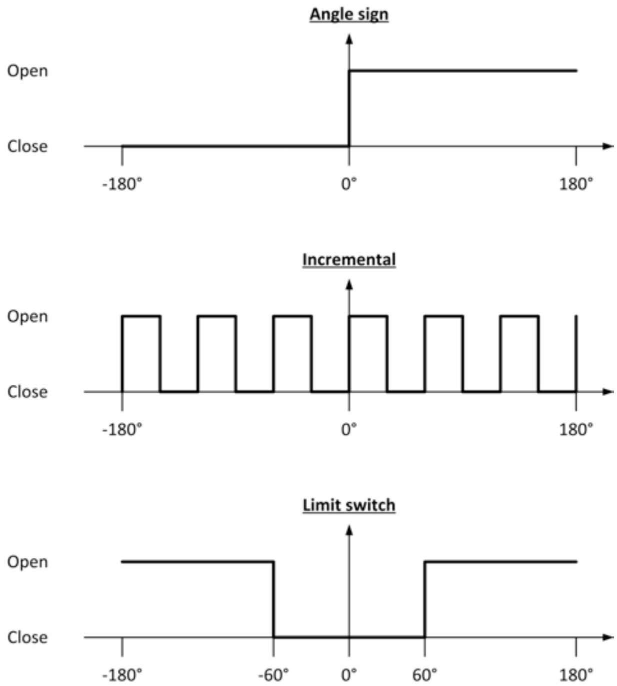

Figure 4. *Digital signal type*

- **Voltage output (analog),** different electrical voltage are generated with a voltage divider. The corresponding switch is a SPNT (Single Pole N Throws) where the number of throws depends on the number of voltage levels required. As the voltage divider is implemented on the rotor, the sensor needs three ports (three tracks): 1x output, 1x power supply and 1x common (0V). The main application of the output voltage is:
  - o **Step potentiometer**
  - o In addition of the ramp shape, various different signal shapes may be implemented.

Note : Step potentiometer signals differ from regular potentiometer signals :

- Step potentiometers have discrete voltage output.
- Step potentiometers can be implemented without any dead zone.

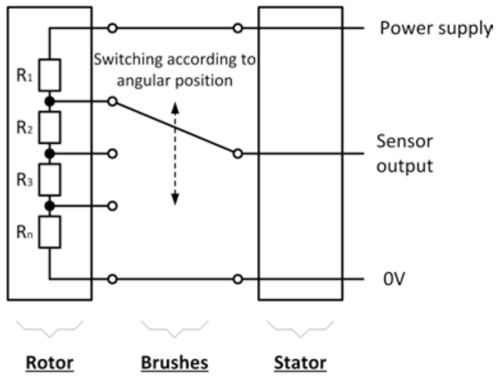

Figure 5. *Analog signal electrical diagram*

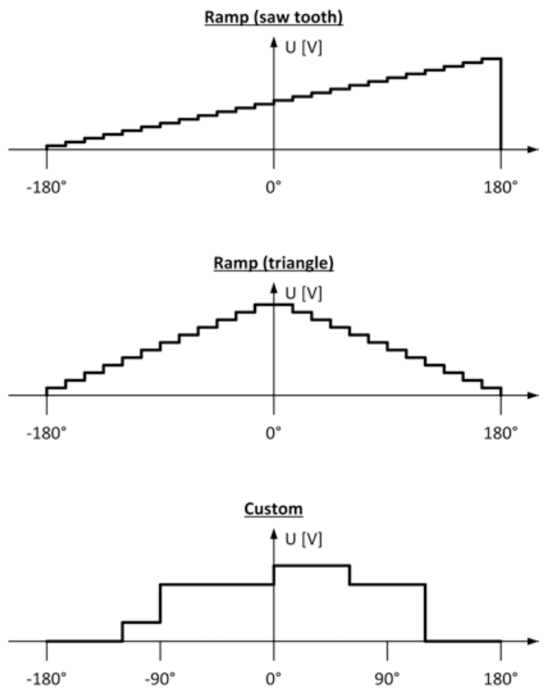

Figure 6. *Analog output signals*

2.3 Application example

A brushed angular sensor (G3AAS) has been developed for the 3rd generation of Solar Array Drive Mechanism (SADM) for the SpaceBus satellites platform. This sensor is a bearing less sensor mounted on the back of the SADM.

It is electrically redundant and includes three signals outputs:

1. Angle Sign (Digital)
2. Incremental (Digital)
3. Step potentiometer (Analog)

2.4 G3 AAS BBM performances

A bread board model (BBM) of the G3 AAS has been manufactured with a geometry and materials that are representative of the Qualification Model (QM) excepted for:

- the PCBs are industrial grades.
- the resistors are industrial grades.
- the signal characteristics may change upon the final application needs.
- the gold platting.

The mass and dimension of the BBM is given below:

Parameters	Values
Housing Diameter	Ø93mm
Height	17.8mm
Mass with wires	91gr

Table 1 *G3 AAS BBM Dimensions*

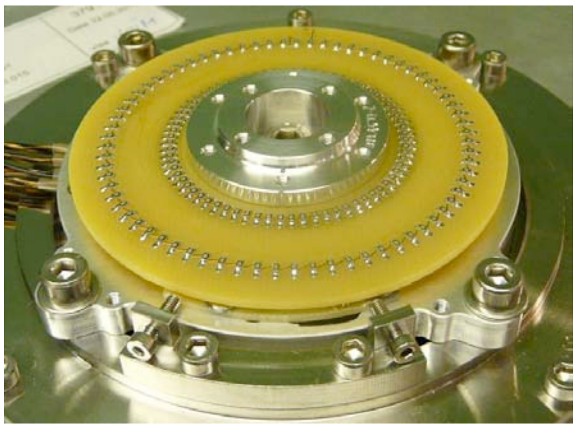

Figure 7. *G3 AAS BBM, without housing, on the test bench*

The BBM performances tests have been performed with the conditions below:

Parameters	Values
Pressure	Atmospheric Pressure
Temperature	Room Temperature
Reference sensor	Heidenhain ROD 486 (accuracy 0.0036°)
Acquisition system	National instruments: cRIO 9075 (Real time DAQ system) NI-9401 (DI module) NI-9205 TBC (AI module)
Sensor interface	Run-out 0.01mm
Maximum operating velocity	1rpm

Table 2 *G3 AAS Test conditions*

The performances measured on the BBM are reported below. The incremental signal has a relatively good resolution, because the tracks segments corresponding to the open contact state are not connected. The step potentiometer signal has a lower resolution limited by the number of resistors needed to generate the voltage levels and their interconnections with the segment.

Digital Signal (Angle Sign & Incremental signals)	
Parameters	**Values**
Transition times	<220ms
Repeatability	From ±0.016° to ±0.029° (track radius dependent)
Accuracy	±0.1°
Incremental Resolution	240 inc/turn

Table 3 *G3 AAS BBM digital signal performances*

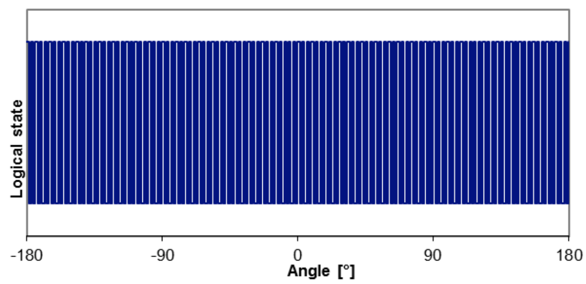

Figure 8. *Measured BBM incremental signal*

Analog Signal (Step potentiometer signal)	
Parameters	**Values**
Repeatability	±0.06° (track radius dependent)
Angular Resolution	72 inc/turn
Voltage levels	72
Max output voltage	5.09V
Output voltage noise RMS	0.9mV

Table 4 *G3 AAS BBM analog signal performances*

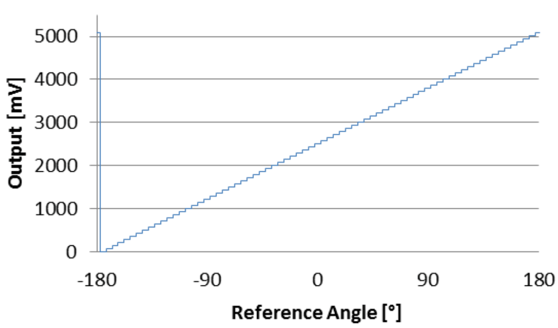

Figure 9. *Measured BBM step pot signal*

2.5 Discussion

The performances measured on the BBM might differ from those of the QM due to the following reasons:

- The quality of space grade PCBs and resistors foreseen on the QM are higher than the components used on the BBM. This might improve slightly the accuracy on the QM.
- The tolerances of the SADM/G3 AAS interface might have a lower tolerances than the BBM test setup. This might change the performance of the sensor
- The thermal environment and the wear might have an impact on the performance as well.

The performances of the BBM give the order of magnitude of the final performance of the QM, but the final performance of the G3 AAS will be known only at the end of the qualification test campaign.

3. CONTACTLESS SENSOR

3.1 Principle

A scheme of the sensor operating principle and its design is presented here after.

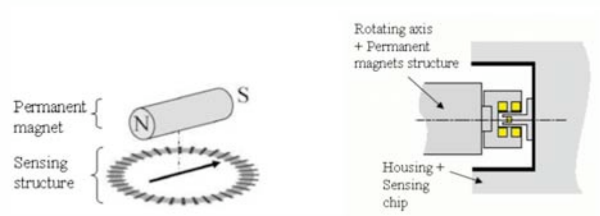

Figure 10. *Operating principle (left)*
Sensor design principle (right)

The full sensor consists of a sensing circular structure with signal conditioning and readout interface as well as a permanent magnet (standard magnets or custom magnet such as Halbach structure).

<u>Sensing element</u>

The sensing element is an n-doped ring with N contacts equally distributed on the ring surface. By the mean of switches, each contact can be connected to the current source, to the ground or to the voltage amplifier.

To perform measurements, 5 adjacent contacts are grouped in 5 **C**ontacts **V**ertical **H**all elements (5CVH). The current is injected trough the outer contacts and collected in the middle contacts. The voltage difference between the two remaining contacts (the Hall voltage V_H) is proportional to one component of the in-plane magnetic field.

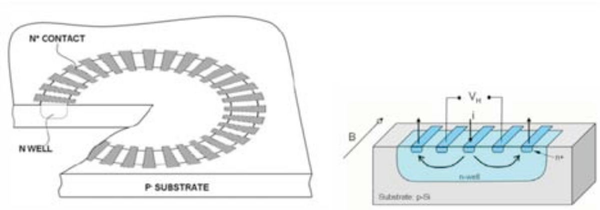

Figure 11. *Integrated hall structure*

<u>Measurement sequence</u>

At a time t, a series of 5 next to each other contacts are connected in such a way to form a 5CVH. On a perfect device, the output voltage is proportional to $B\cdot\cos(\alpha)$, where α is the angle between **n** (a unitary vector normal to the middle contacts of the 5CVH) and **B.** At each clock time, the 5CVH elements is shifted by one contact and the Hall voltage $B\cdot\cos(\alpha+2\pi/n)$. Over a full turn, the Hall voltage exhibits a sine function with its amplitude proportional of the in-plane field and its phase equal to the field direction. The information about the field direction is contained in the first harmonic over a full turn period.

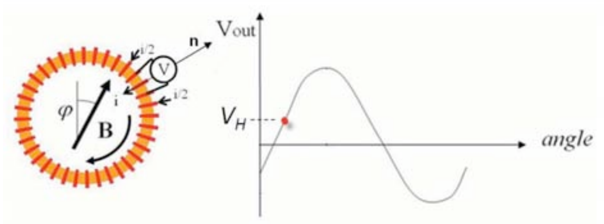

Figure 12. *One step of the acquisition*

<u>Signal processing and implementation</u>

The selected technology for the sensor implemention is a conventional CMOS 0.35-µm high-voltage technology. The supply voltage is 3.3 V. The sensing part is composed of an n-well ring with 64 n-doped contacts. The ring is formed by a deep n-well layer with about 6 µm of depth. The ring outer diameter is 50 µm. The ring width, contact number, size and shape were determined by optimizing the sensitivity using finite element calculations. A logic circuit ensures the correct switching sequence. There is 256 (4 x 64) measurement steps per full measurement sequence.

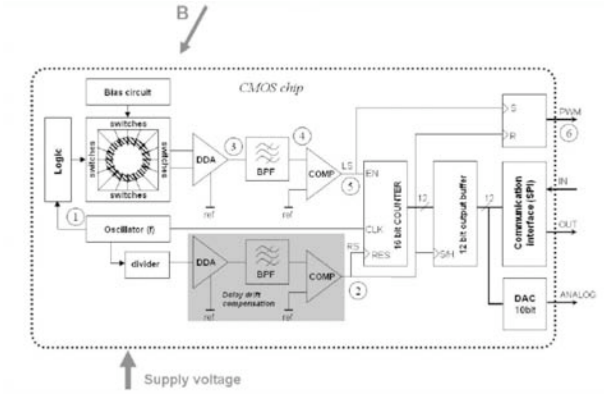

Figure 13. *Bloc diagram*

The processing to extract the angle is based on the phase measurement between the detected signal (5) and the reference signal (2). Switches realized by NMOS transmission gates connect the sensing structure to the bias circuit or Differential Difference Amplifier (DDA). The bias current generated in the bias circuit is derived from a bandgap cell. Oscillator, Logic and Divider blocks are realized by digital standard cells available from the foundry. The DDA, Band-Pass Filter (BPF) and Comparator (COMP) are optimized for low-noise, wide temperature range. The output signal is available in three different forms:

- Pulse Width Modulation (PWM)
- Serial Peripheral Interface (SPI)
- Analog output

3.2 Test campaign and test results

The development and testing of this angular sensor has been conducted in different phases.

The first phase consists in the validation of the measurement concept by designing and testing a none fully space compliant sensor. Especially, at this level, the sensor is not radiation hard.

The second phase consists in implementing the radiation hard structure and integrating the chip in its final packaging.

The packaging which has been selected is an LCC16 nonmagnetic package which is presented here after :

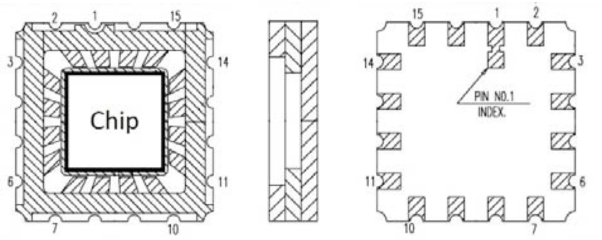

Figure 14. *LCC16 Package*

Within this second phase, 2 versions of the sensors are designed and tested:

- Version 6.7
  Dedicated to medium speed and medium resolution applications.
- Version 6.8
  Dedicated to low speed and high resolution applications. This sensor is exactly the same than version 6.7 excepted that a filter has been implemented on the analog output in order to improve the resolution of the sensor.

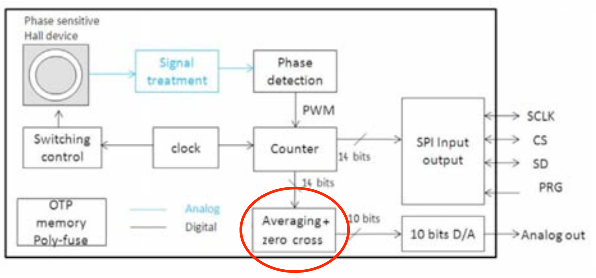

Figure 15. *Low pass filter on sensor v6.8*

The second phase test campaign is not a full qualification of the sensor, but only a pre-evaluation test campaign, which includes the following tests :

- Encapsulation tests
- Functional tests under ambient condition
- Thermal tests (powered ON and powered OFF)
- TID (Total Ionization Dose)

Typical output of the sensor version 6.7.

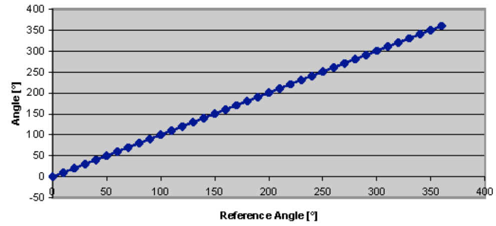

Figure 16. *Sensor v6.7 analog output signal*

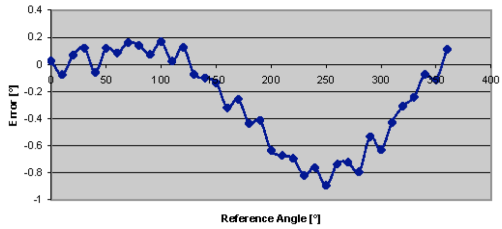

Figure 17. *Sensor v6.7 output error*

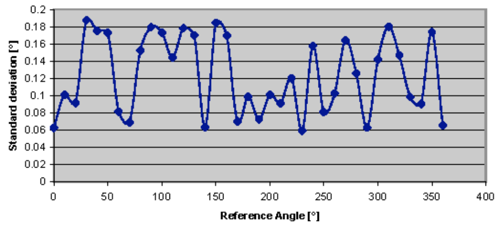

Figure 18. *Sensor v6.7 output standard deviation*

Typical output of the sensor version 6.8.

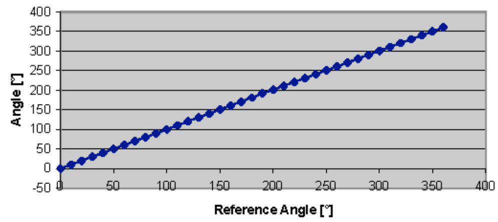

Figure 19. *Sensor v6.8 analog output signal*

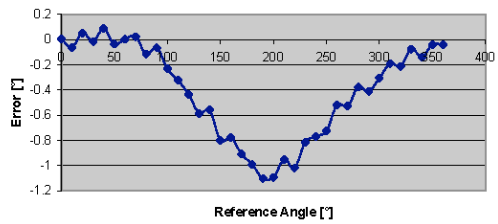

Figure 20. *Sensor v6.8 output error*

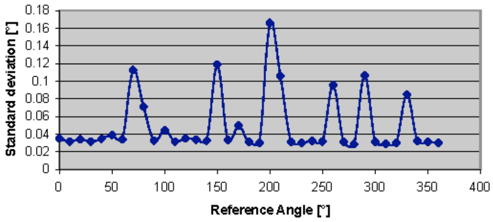

Figure 21. *Sensor v6.8 output standard deviation*

At this level, performances can be summarize as presented hereafter :

Performances of chip v6.7 and v6.8		
Parameters	V6.7	V6.8
Digital output accuracy (without calibration)	7.5 bits (2°)	7.6 bits (1.9°)
Digital output resolution (bit equivalent @ 3σ)	9.3 bits (0.6°)	10 bits (0.35°)
Analog output accuracy (without calibration)	2.5°	2.2°
Analog output resolution (bit equivalent @ 3σ)	8.6 bits (0.9°)	9.4 bits (0.5°)
Power consumption (under 5V)	40mW	40mW
Digital dynamic output refresh rate	1kHz	1kHz
Analog dynamic output refresh rate	1kHz	60Hz
Rotation speed (analog output reading)	150 rpm	5rpm

Table 5 *Performances summary*

The third step is the full qualification test campaign of the chip (integrated in the LCC16 package) according to ESCC2269000.
This phase has not been started yet.

3.3 Discussion of pre-evaluation results

The implementation of an averaging module on the analog output enables to increase the analog output resolution from about 1 bit. This optimization is done to the detriment of the output refresh. This means that version 6.8 shall be used for slower rotation speed applications than the version 6.7.

4. TRADE OFF

Beside the performances, there are important aspects to consider when choosing between brushed technology or contactless technology for a given application. These aspects are presented hereafter:

Properties	Brushed sensor	Contactless sensor
Output customization	Full custom	Electrical zero Rotation direction
Lifetime	Limited by contact wear	Not limited by wear
Speed	Typical 1 rpm	10 rpm (operating) Unlimited (non-operating)
Vibration	Must be considered in the design	Robust
Sensitivity to magnetic field	Not sensitive	Sensitive
Radiation hardness	Only radiation hard material & components	Up to 100 krad
Friction torque	Low	Frictionless
Hollow geometry	Yes	No

Table 6 *Brushed and contactless technologies trade off*

Thanks to the complementarity of these two technologies, a wide range of applications are covered.

5. CONCLUSION

This paper presents the development of two different technologies of angular sensor designed to be integrated onto sliprings or other mechanisms. By their principles, these two technologies are complementary:

- The brushed sensor technology takes benefit from the know-how of RSSN in the design and manufacturing of sliprings.
- The contactless sensor technology has the advantage to be frictionless and wear less.

For each technology, a BBM have been carried out and their accuracy performances fulfill the needs of solar array drive mechanism and many other space applications. These preliminary results must still be confirmed by a qualification campaign that is the next step of the development of each angular sensor.

6. AKNOWLEDGMENTS

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Contactless sensor developed under GSTP founds.