ROBotic Open-architecture Technology for Cognition, Understanding and Behavior

# Project no. 004370

# RobotCub

# Development of a cognitive humanoid cub

Instrument: Integrated Project
Thematic Priority: IST – Cognitive Systems

# RC_IST_102_D_000_03_HALLSENS

# Hall Sensors for Position Sensing in the Cub Head

# Internal Report

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|---|---|---|
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# 1. Introduction

The aim of this experimental study is to evaluate the use of Hall sensors for angular position sensing in the iCub's neck mechanism (3 joints – pan, tilt, swing). Hall sensing systems for measuring angular position are constituted by one or several sensing elements and magnets to create a magnetic field. In the context of the iCub Head, the main goals of the sensing system are:

1. to allow home positioning of the joint, to be used, for instance, in a power on situation;
2. to allow the detection of joint sliding, possible because these joints are clutch actuated and, in an overload situation, they may move differently from the motor axis.
3. to allow the acquisition of absolute position measures, in order to facilitate the homing procedure.

Considering independently each of the goals, we can list the following desired properties for the response function of the sensing system:

1. the homing position should be attainable from any initial position, i.e. it should correspond either to a zero crossing in a monotone response function or to a maxima/minima of a unimodal function.
2. for joint sliding detection, ideally the response function should be injective, but in practice it is enough not to have significant "dead zones".
3. For absolute positioning, the response function should be injective.

We will evaluate three classes of solutions with different balances between cost/compactness *versus* performance/ease of use. We start by presenting two sets of solutions based on the Honeywell SS495 sensor and combinations of different types of magnets. These solutions are economic and compact, with the caveat of not providing linear absolute positioning. The final solution tested is based on the GMW360ASM sensor, from GSM Associates. This sensing system has a linear response over its entire range although it is not as compact and cheap as the previous ones.

# 2. Hall sensor Honeywell SS495 with small cylindrical magnets

The Honeywell hall sensor SS495 is a small magnetic field sensor, from the SS490 family described in deliverable D7.2. In this section we present experiments performed with arrangements of small cylindrical magnets. These magnets are convenient because they are very compact, cheap and easy to assemble.

Because of mechanical constraints, in the 3 joints of the neck, the magnets should be at ±12.5mm far from the joint's rotation axis (Figure 1), and must be at ±1mm from the hall sensors.

Another important objective is to have the simplest and cheapest possible solution, not only for the mechanical system, but also for the computational point of view.

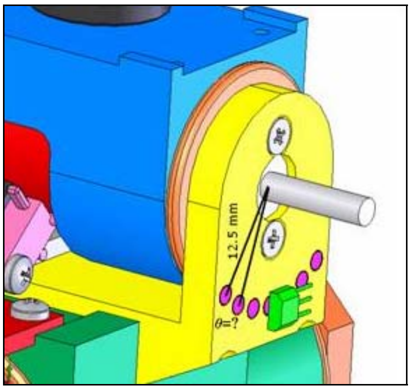


**Figure 1:** Neck swing joint

## *2.1 Characterization of the magnet/sensor system*

In order to reproduce the movements of the joints, an assembly was built, where 2 magnets (dimensions: Ø=2mm and L=1.5mm) were fixed to a turning disc and a hall sensor (Honeywell SS495) was fixed to an external bar, in such a way that its distance to the disc could be changed (Figure 2).

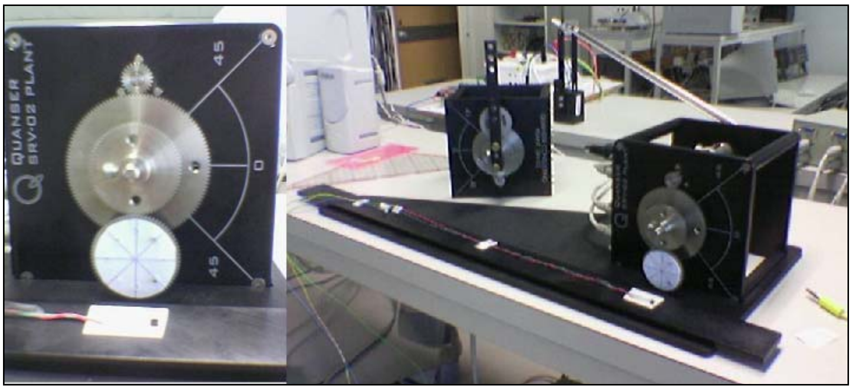


**Figure 2:** The testing assembly

To evaluate the characteristics of the sensing assembly, four different tests were made, using different distances sensor/magnet and different velocities of rotation.

The distance magnets/rotation axis was 12.5mm and the angle between the 2 magnets was 90º (Figure 3).

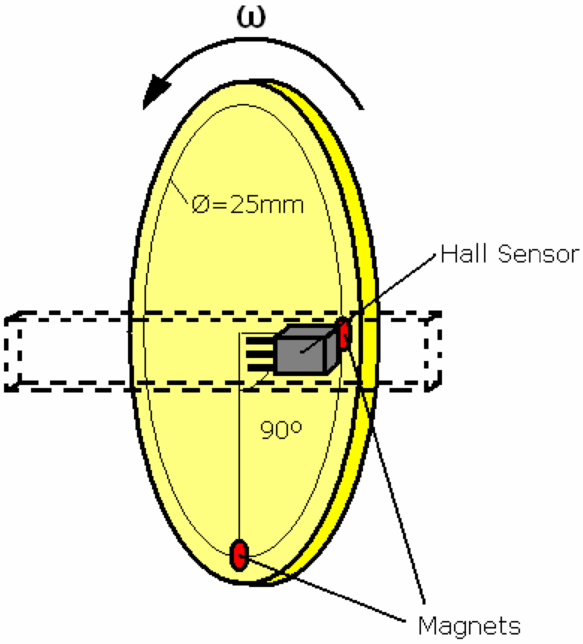


**Figure 3:** Representation of the testing assembly

The following table describes the 3 different tests performed.

**Table 1:** Performed Tests.

| | Test 1 | Test 2 | Test 3 |
|---|---|---|---|
| Distance Magnets/Centre of rotation (mm) | 12.5 | 12.5 | 12.5 |
| Distance sensor/magnet (mm) | 1 | 0.2 | 2 |
| Angle between magnets (º) | 90 | 90 | 90 |
| Angular velocity (º/sec) | 18 | 18 | 18 |

The following figures show the output of the hall sensor for different angular displacements, for the three experiments.

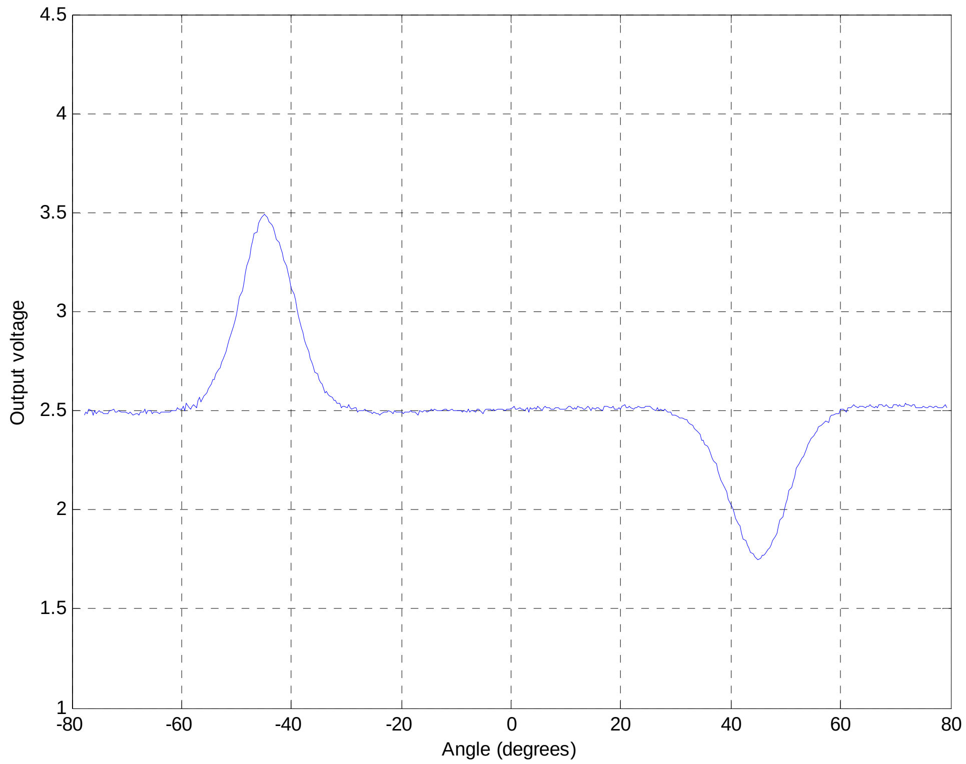


**Figure 4:** Results of Test 1

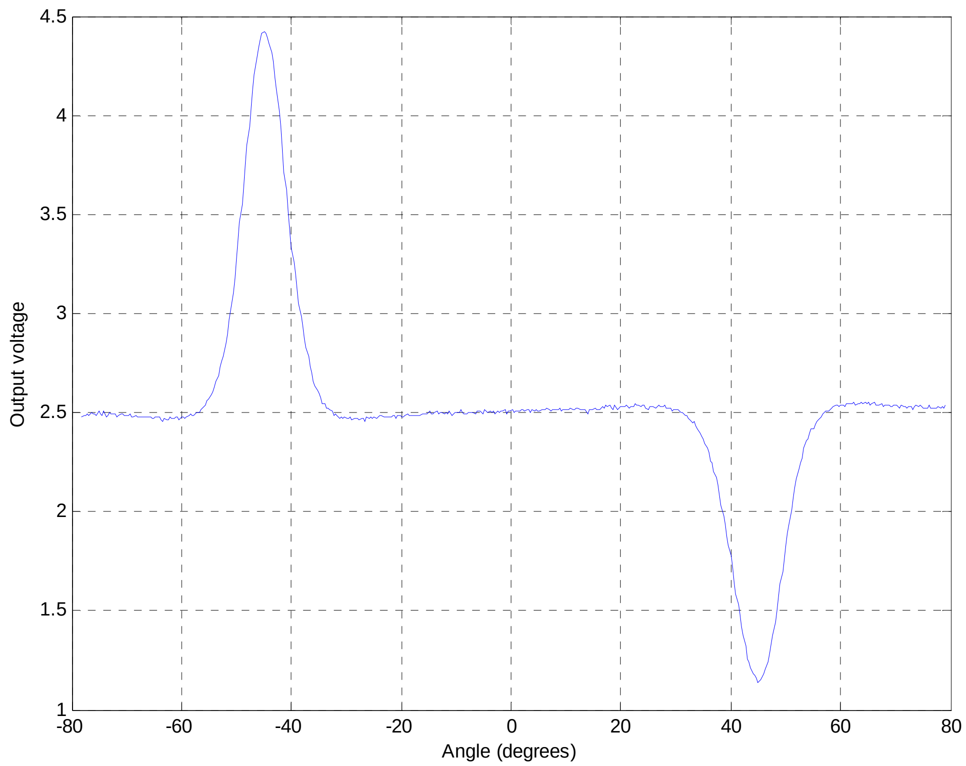


**Figure 5:** Results of Test 2

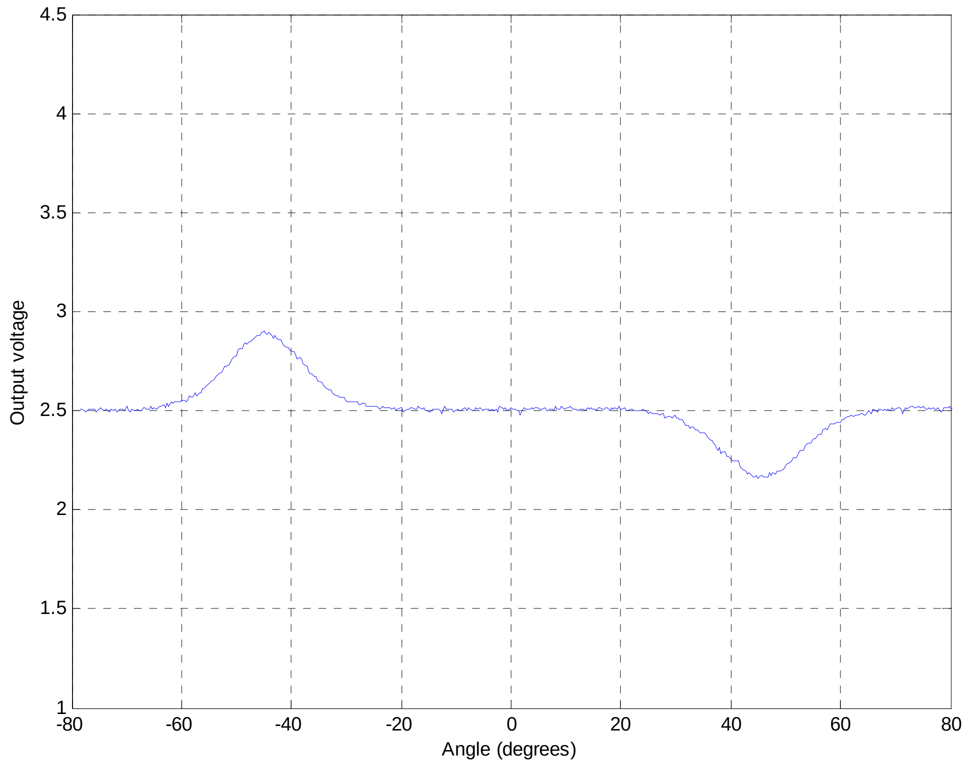


**Figure 6:** Results of Test 3

After the 3 experiments, we can conclude that:

- the average working range of the magnets, measured by the sensor is 20º;
- increasing the distance sensor/magnet decreases the peak value measured by the sensor and slightly increases the working range;
- as the range of movements of the 3 neck joints are: 90º(tilt), 80º (swing) and 110º (pan), the use of just 1 sensor and 2 magnets seem to be insufficient for absolute positioning because the sensors' working range is only a small fraction of the full working space;

## *2.2. Extending the working range*

After getting some information about the hall sensors performance, a few suggestions can be made for the sensor system design.

### 2.2.1 – Bigger magnets

One possible solution could be the use of 3 bigger magnets (for instance, magnets with 2 mm of diameter and 3 mm of length), with one single hall sensor.

An experiment was made, for 110º of range.

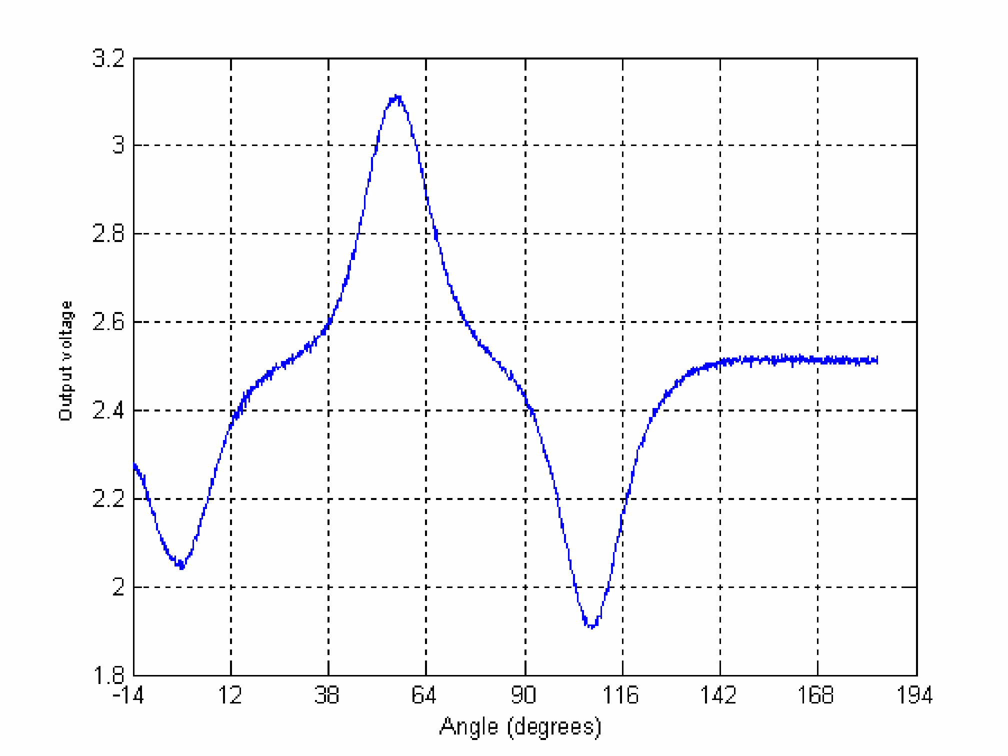


**Figure 7:** Test with bigger magnets.

We observe that the range of the sensor increases to about 50º. More importantly, the dead zone exhibited in the previous experiments, is now absent, which allows to detect joint slippage.

From the plots we have modelled the response of the sensor as a sum of gaussians plus an offset, each Gaussian with amplitude 0.5 V and standard deviation 10 degrees. Gaussian noise of variance 0.005 V is also included in the model. Results of a simulation with such model are shown in the next figure.

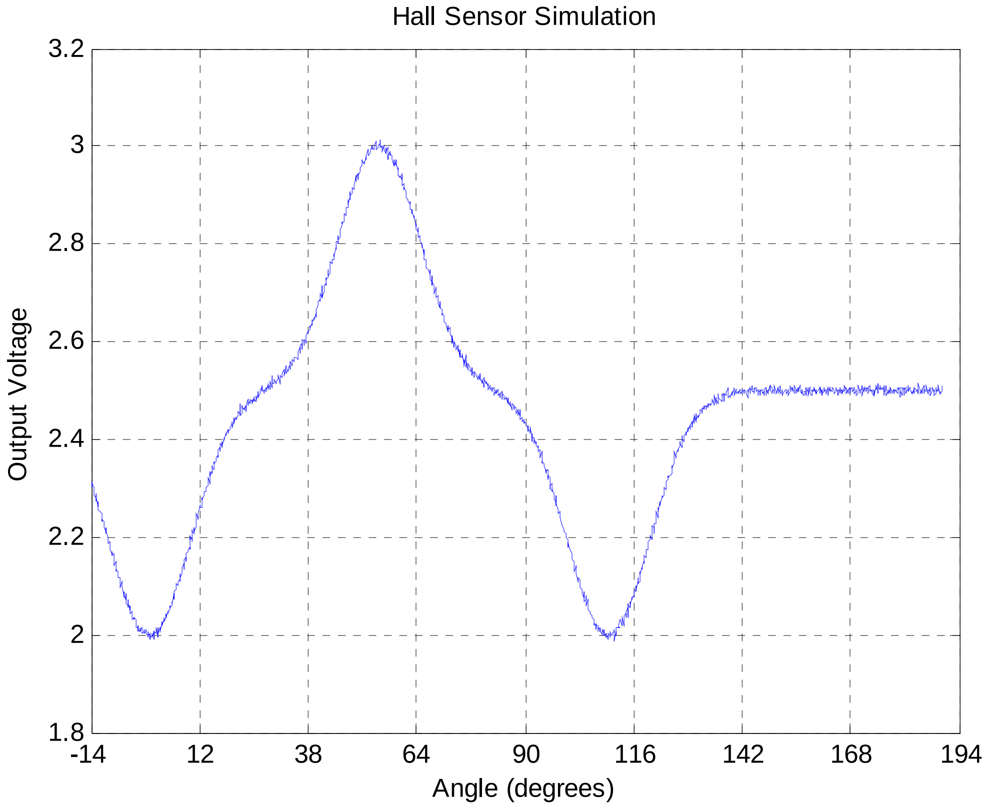


**Figure 8:** Simulation of the hall sensor response in the conditions of test with bigger magnets.

With a single sensor it is not possible to have absolute positioning. A homing procedure would require prospective motions to estimate the gradient of the signal and drive the motors toward the peak corresponding to the home position. To investigate possible solutions to this problem we have performed the following simulations, considering the biggest angular range required for the iCub head system (110º).

### 2.2.2 - 3 magnets and 2 sensors

We have designed a simulation with 3 magnets (the ones with a bigger size) and 2 quadrature hall sensors, as shown on the following picture.

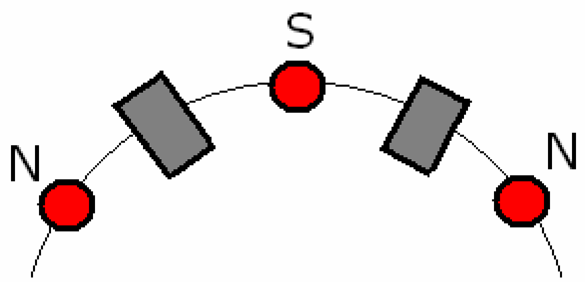


**Figure 9:** Magnet and sensor configuration for simulations.

With 2 sensors in quadrature it is possible to have absolute positioning. The next figure shows a simulation of this case.

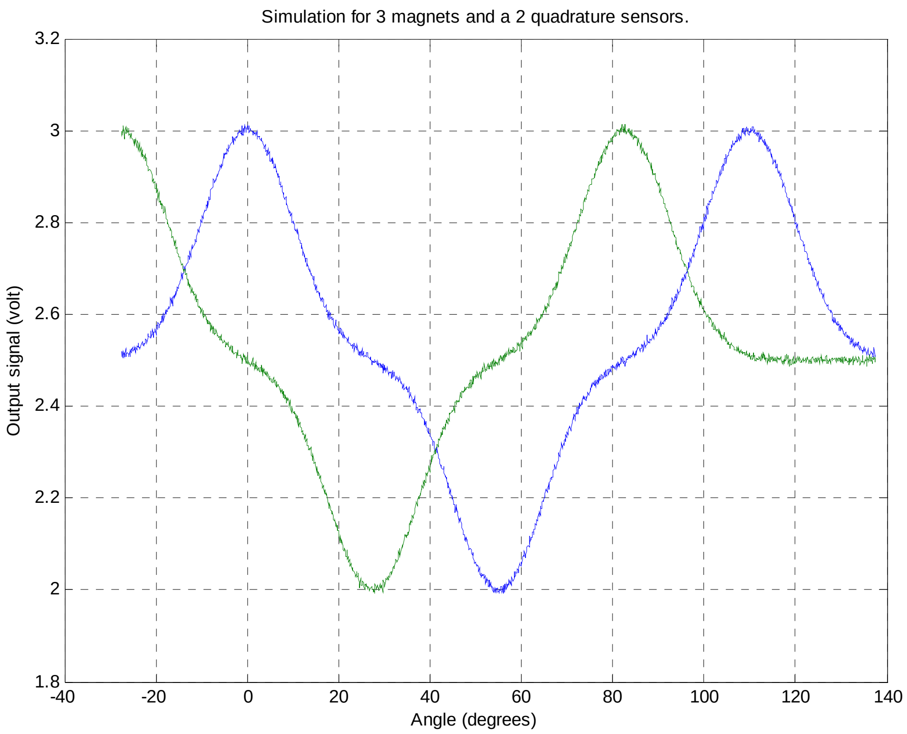


**Figure 10:** Simulation of the response of 2 sensor/3 magnet configuration.

To obtain estimates of the absolute position, an algorithm that reasons about the signs of the two signals and chooses and normalizes the signal with better linearity is used. In the next lines we present the Matlab code to perform such computations, including the simulation:

```
%****************************************
% Definition of the sensing configuration
fullrange = 110;
magnetspacing = fullrange/2;
sensorspacing = magnetspacing/2;
%Simulation of the sensor reponses
gain = 0.5;
offset = 2.5;
std = 10;
noisevar = 0.005;
t = -sensorspacing:0.1:fullrange+sensorspacing;
g1b = gain*exp(-1/2*(t+sensorspacing).^2/std^2);
g2b = -gain*exp(-1/2*(t-sensorspacing).^2/std^2);
g3b = gain*exp(-1/2*(t-magnetspacing-sensorspacing).^2/std^2);
g1a = gain*exp(-1/2*(t).^2/std^2);
g2a = -gain*exp(-1/2*(t-magnetspacing).^2/std^2);
g3a = gain*exp(-1/2*(t-fullrange).^2/std^2);
sa = offset+g1a+g2a+g3a+noisevar*randn(size(t));
sb = offset+g1b+g2b+g3b+noisevar*randn(size(t));
plot(t,sa, t, sb);grid;
%Computation of the absolute position signal
for i = 1:length(t),
    if (sa(i)-offset)>=0,
        if (sb(i)-offset) >= 0,
            c(i) = (sa(i)-offset)/gain*sensorspacing+magnetspacing+sensorspacing;
        else,
            c(i) = -(sb(i)-offset)/gain*sensorspacing;
        end;
    else,
        if (sb(i)-offset) >= 0,
            c(i) = (sb(i)-offset)/gain*sensorspacing+magnetspacing;
        else,
            c(i) = -(sa(i)-offset)/gain*sensorspacing+sensorspacing;
```

```
        end;
    end;
end;
figure;plot(t,c);grid;
%****************************************
```

The results of the position estimation are shown in the next figure.


**Figure 11:** Simulation for absolute positioning response of 2 sensor/3 magnet configuration.

However, as can be observed in the plot, close to the motion range boundaries (0º, 110º), there is a severe instability in the estimate due to noise, which reduces the usable range. Since it is likely that the head is often close to its limits when requiring homing, this solution seems to be not robust enough.

### 2.2.3 - 4 magnets and 2 sensors

Simulation of this case is shown in the next figure.

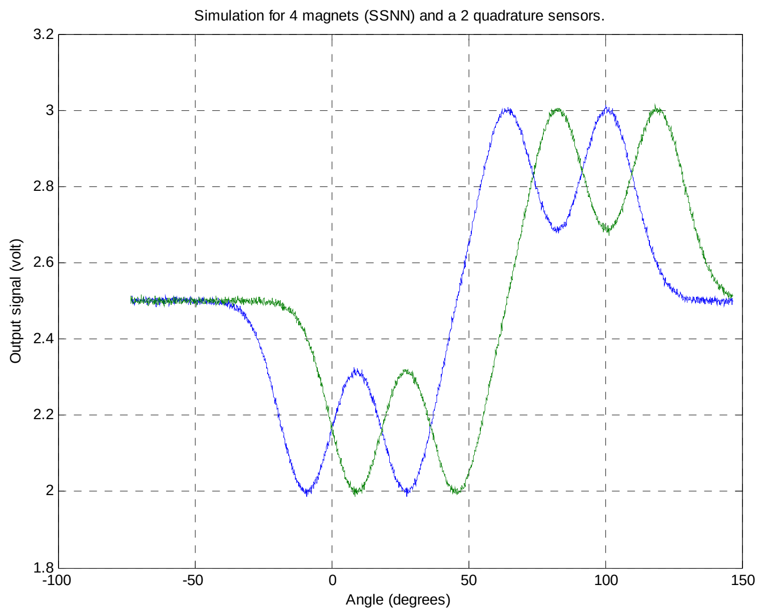


**Figure 13:** Simulation of the response of 2 sensor/4 magnet configuration.

A simple sum of the two signals will give the following results:

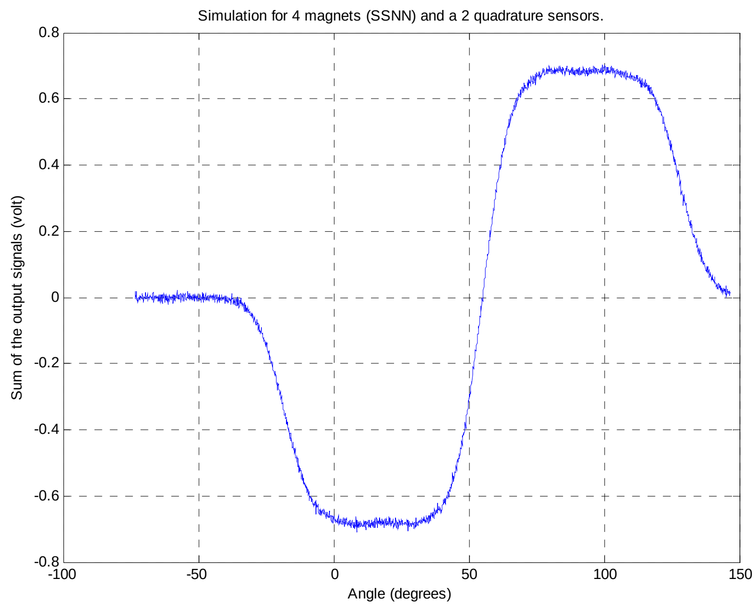


**Figure 12:** Sum of the response of 2 sensor/4 magnet configuration.

The obtained signal linearity is not as good as the previous but it is good enough for the homing procedure (the sign indicates the direction for homing motion and it is linear close to the homing position.). Moreover, this solution is immune to noise in the motion range. However, there is a dead zone near the boundaries which limits the detection of slippage in these areas.

The following table summarizes the characteristics of the alternatives presented in this section:

**Table 2:** Comparison of different magnet/sensor configurations

| | A (1 sens/ 3 mag) | B (2 sens/ 3 mag) | C (2 sens/4 mag) |
|---|---|---|---|
| Homing | Gradient | To Zero | To Zero |
| Slip Detection | Good | Very Good (except at the boundaries) | Good (except at the boundaries) |
| Abs. Position | Not monotone | Good Linearity | Bad (at the boundaries) |
| Simplicity | Good | Bad | Average |
| Robustness | Good | Bad (at the boundaries) | Good |
| Wires | 2 | 4 | 4 |

### *2.3. Discussion of Results*

None of the solutions is good at all desired properties. From the point of view of homing, alternatives B and C are preferable because a simple proportional control algorithm can be employed. From the point of view of slip detection, alternatives B and C are bad at the boundaries because, respectively, of noise sensitivity and low dynamic range. With respect to absolute positioning, only B is feasible. Taking into consideration issues like simplicity of assembling and wiring/input port requirements, we think that the first solution (using just 1 hall sensor and 3 bigger magnets) seams to be the best compromise.

# 3. Hall sensor Honeywell SS495 with ring magnets

From the previous section's results we have concluded that small magnets are not capable of generating and shaping the magnetic field to accomplish all our requirements. In this section we will evaluate larger magnets, of the ring and disc type, magnetized across the diameter (see Fig. 13).

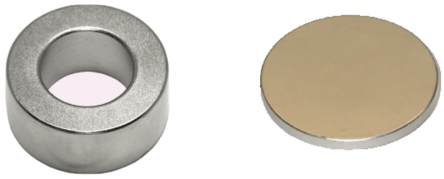

**Figure 13:** Neodymium ring and disc type magnets.

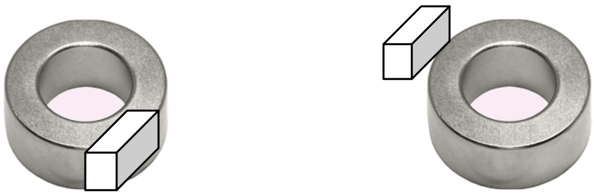

**Figure 14:** An hall sensor is placed at the edge of a large magnet, magnetized across the diameter. The sensor can be placed frontally (left) or laterally (right).

These magnets provide a solution not as compact as the previous one but with an extended range of working angles.

## *3.1. Mechanical assembly.*

The use of large ring or disk magnets, requires a different mechanical assembly. In particular the assembly is simpler if the magnet is placed at the encoder side instead of the motor axis side. Preliminary tests have shown that, even though the encoders are magnetic, placement of the magnet close to the encoders do not interfere with the measurements.
Another advantage of placing the magnet at the encoder side is that fixation is easier (glued). Also, disc magnets (thinner and lighter) can be used without having to be machined.

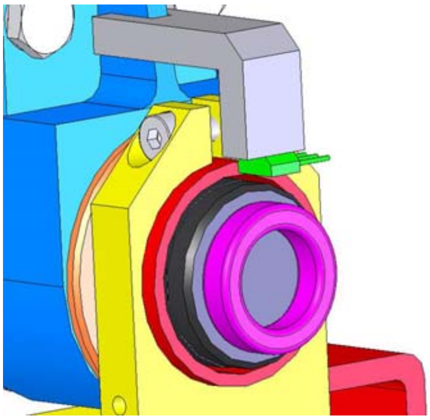

**Figure 15.** Hall sensor and ring magnet. Mechanical assembly.

### *3.2. Experiments.*

An hall sensor is placed at the edge of the magnet (see Fig.14). When the magnet rotates along its center, the amplitude of the magnetic field measured in the sensor has a sinusoidal shape. Figs 15 and 16 show the signals measured by the sensor as a function of magnet rotation. Several conditions are tested: distance sensor/magnet and sensor positioning (frontal/lateral). The employed magnet is a R1008A neodymium ring magnet from www.supermagnetman.com (12mm outer diameter, 3mm thick).

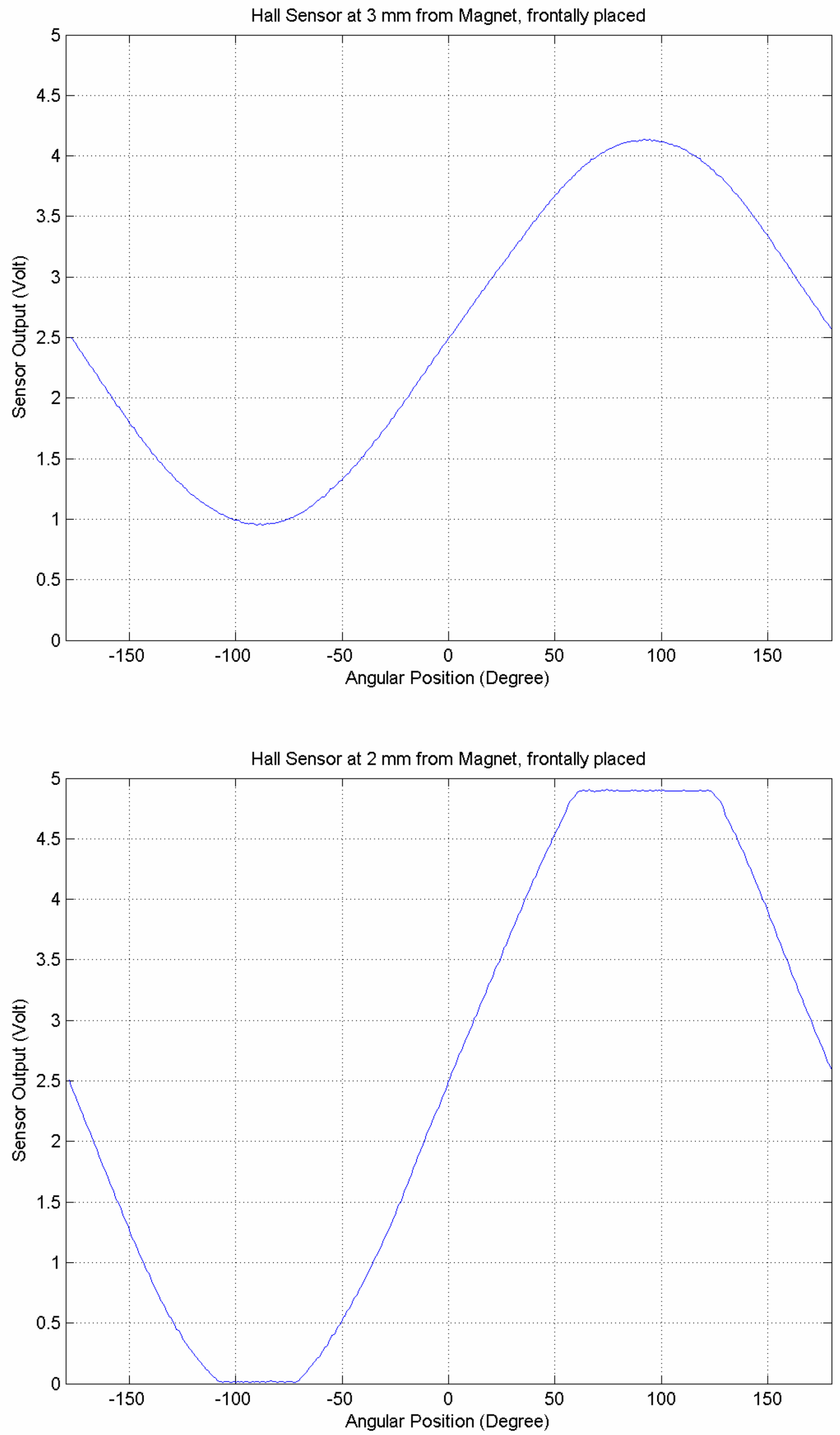


**Figure 16.** Frontally placed sensor. Output as function of magnet rotation. Notice saturation when sensor is placed at 2mm from the magnet.

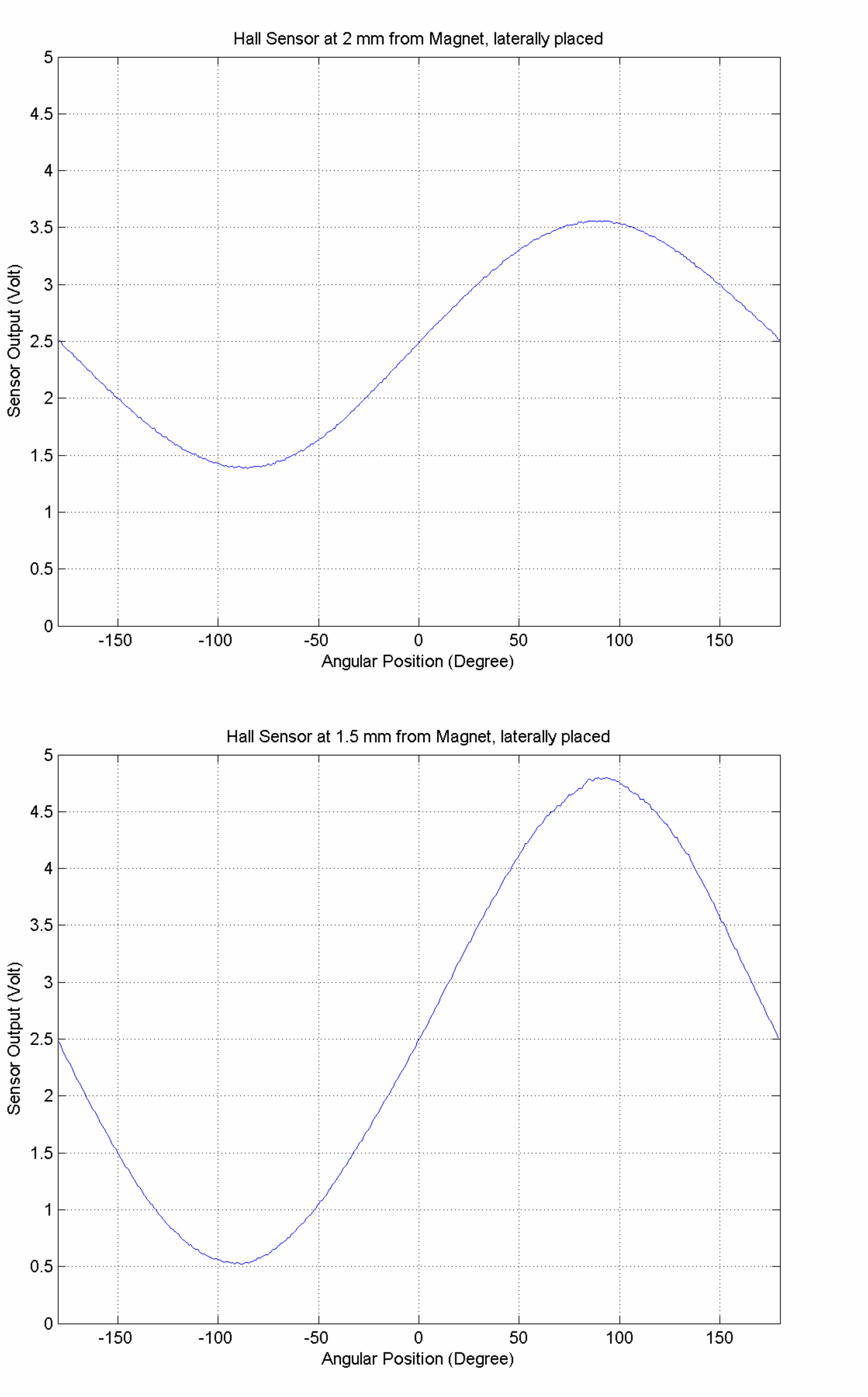


**Figure 17.** Laterally placed sensor. Output as a function of magnet rotation.

We can observe that the signal is very much alike a sinusoid, with low noise levels, which allows a working range of almost 180º. Care must be taken however in the choice of the magnet and the placement of the sensor because very strong magnets of very closely placed sensors may saturate the measured signal.

Within the -90º to 90º range it is possible to linearize the characteristic curve by applying an *arcsin* function to an appropriately scaled and shifted signal. The calibration required for the linearization may however be tricky because the amplitude of the field is prone change due to external factors and mechanical vibrations and lead to instabilities in the absolute position measurement.

# 4. Magnetic Field Direction Sensor GMW360ASM

GMW Associates (www.gmw.com) has recently developed a sensor capable of 360º angular sensing with linear output. It is a cylindrical package with 12.70mm diameter and 5.08 mm thick.

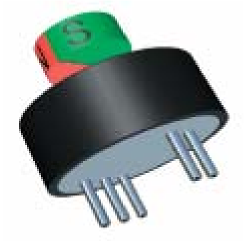


**Figure 18.** The GMW360ASM sensor from GMW Associates measures direction of the magnetic field.

It is constituted by two hall sensors in quadrature and a microprocessor that computes the direction of the magnetic field based on the quadrature measurements. Its output is a linear function of the angular position between the sensor and the magnet, with a precision of about 1 degree (see fig.).

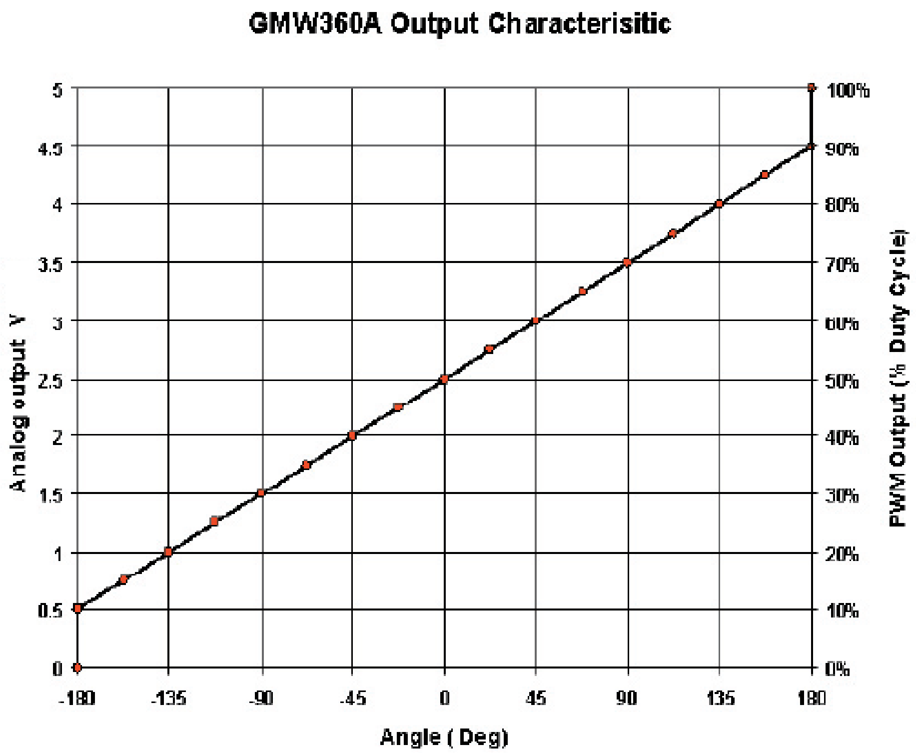


**Figure 19.** Output characteristic of the GMW360ASM.

Other features of this sensor are:

- output indicating magnet out of range.

- mode for resetting the zero position.
- PWM output.

We have tested the sensor with ultra-thin disc magnets (10mm diameter x 0.5 mm thick) magnetized across the diameter, reference D1057A, from www.supermagnetman.com.

### 4.1 Mechanical Assembly

The magnet-sensor arrangement can be assemblied as shown in Fig. 20.
The thin disc magnet (in violet) is glued at the motor encoder cage and the sensor is fit in a metallic arm (yellow) rigidly attached to the rotating part of the joint (green).

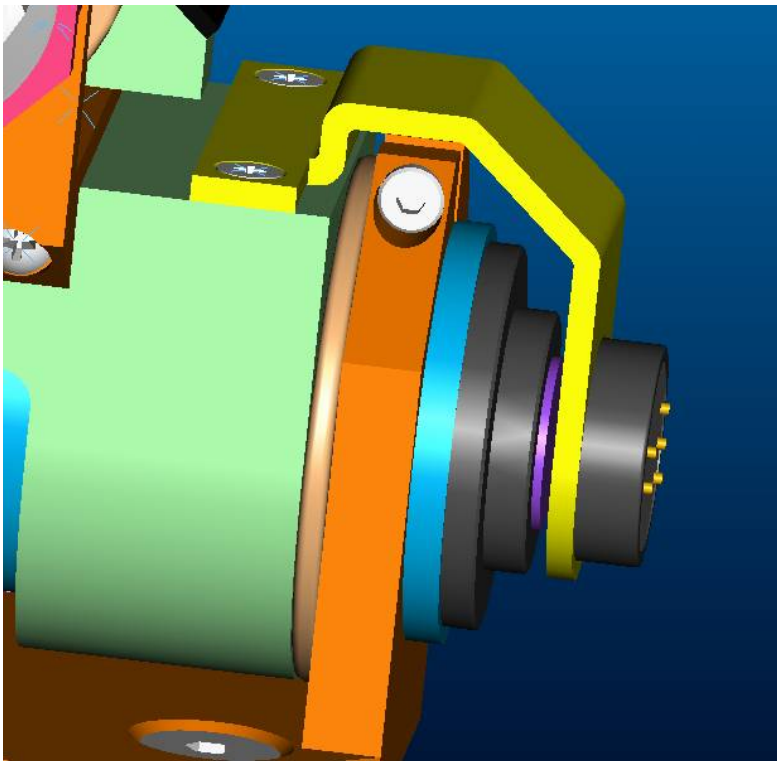

**Figure 20.** Mechanical assembly of the GMW360ASM and ultra-thin magnet in the iCub head.

### 4.2. Experiments

In the following figures we present the results obtained with different distances between the magnet and the sensor.

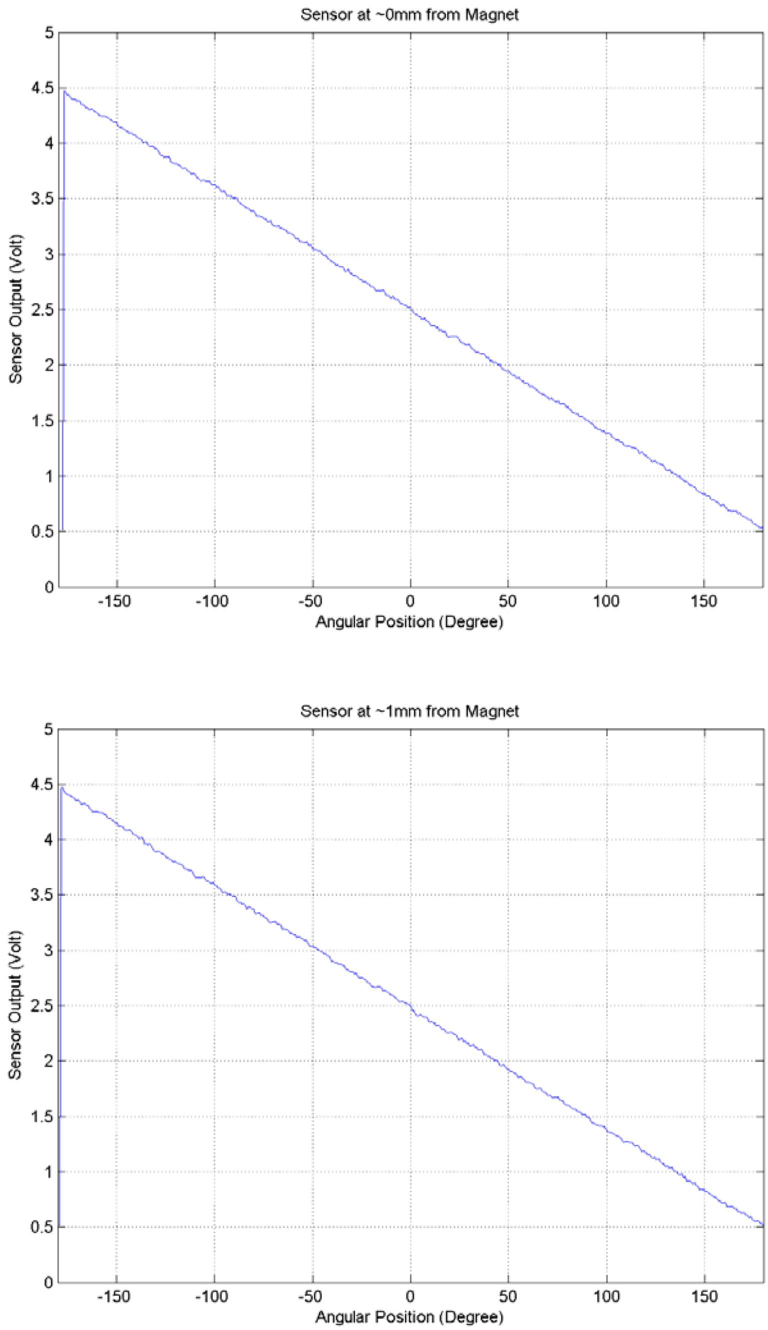


**Figure 21.** Magnitude of sensor output as a function of angular position. Cases where the magnet and sensor are at close proximity.

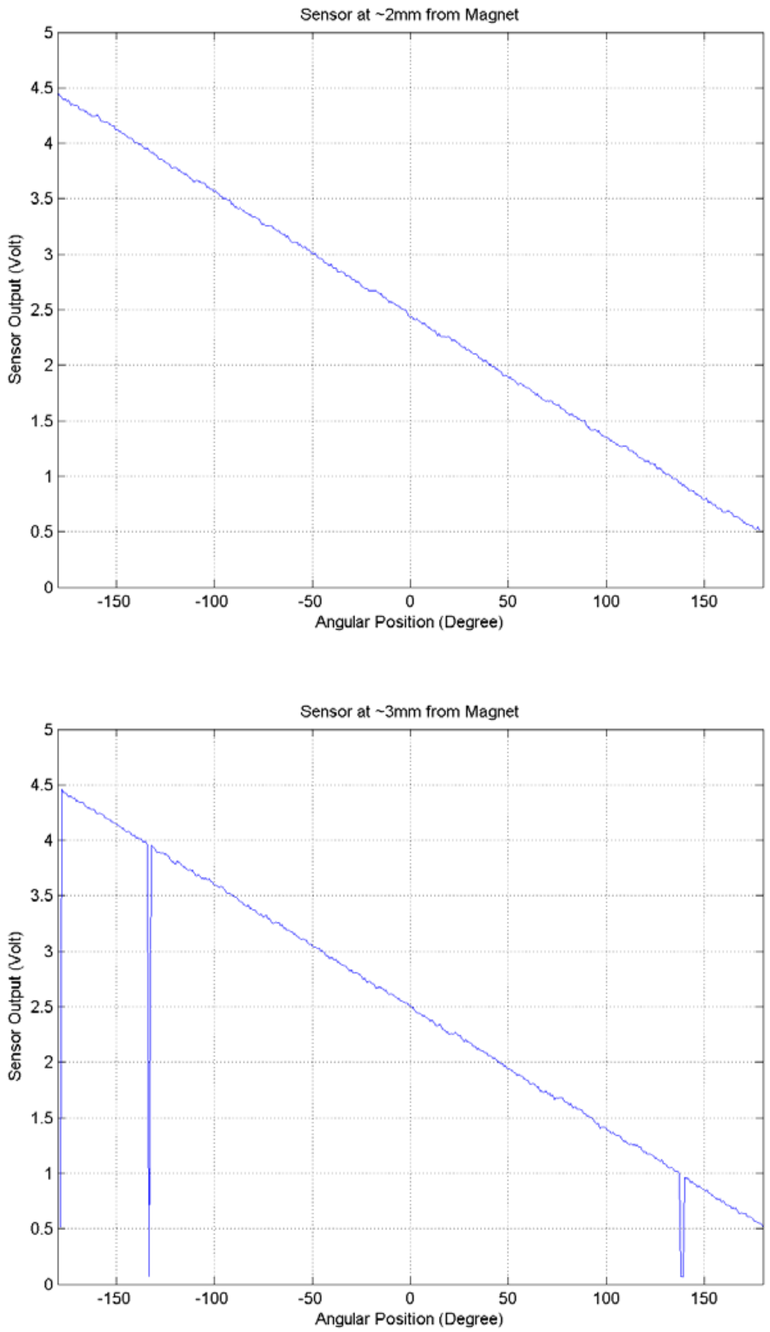


**Figure 22.** Magnitude of sensor output as a function of angular position. Magnet and sensor are separated apart about 2mm and 3mm.

We can observe that the characteristic curve is linear with angular displacement and the signal-to-noise ratio is very acceptable. Additionally the positioning of the magnet and sensor is not critical provided that are closer that 2mm. Positioning at 3mm may result in signal losses as can be observer in figure 22 (bottom).

# 5 .Conclusions

In this report we have presented three different alternatives to the non-contact position sensing in the iCub's head.

1 - The first alternative consists on combinations of hall effect sensors type Honeywell SS495 and small cylindrical magnets. Small cylindrical magnets are practical to assembly but their working range is very limited. Arrangements of several magnets and sensors can slightly improve the performance of the sensing system but increase significantly the complexity of the system.

2 – The second alternative increases the working range of the Honeywell SS495 sensor by the use of large circular magnets, magnetized across the diameter. This provides simple solutions, both mechanically and computationally, the disadvantages being a slight increase in the dimensions of the mechanical assembly and the calibration requirements.

3 – The third alternative makes use of an magnetic absolute position sensor GMW360ASM, and a very thin disc magnet, magnetized across the diameter. This solution provides linear response with angular displacement, and low noise levels, and very easy calibration. The disadvantages are the higher cost and a less compact assembly.

These presented solutions have different balances between cost/compactness *versus* performance/ease of use. In the following table we compare the different solutions in terms of these criteria.

**Table 3 – Comparison of the three main alternatives**

| Solution / Characteristic | Price | Size* | Perform. | Usability | Overall |
|---|---|---|---|---|---|
| SS495 + small magnets | 3€-7€ | 0mm | Limited | Poor | Poor |
| SS495 + large magnets | 3€ | 2mm | Good | Good | Good |
| GMW360ASM | 18€ | 5mm | Very good | Excellent | Very Good |

* - Specifies neck length increment

We think the third alternative is the best solution due to its linear characteristics and easy utilization and calibration. Also, the increase in the head dimensions is not critical and its cost, despite higher, is very acceptable and not important in face of the overall cost of the system.