A Control Technique of Stepper Motors for Simulated Altitude Indicator Development Used in Helicopter Simulator

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Abstract

A helicopter simulator has to be built to fully resemble the real cockpit environment including its instruments. A simulated instrument incorporates mechatronics technology where a mechanical system is electronically controlled to indicate a certain flight variable. This paper describes development of a simulated altitude indicator (SAI) used for a super puma helicopter simulator. This indicator has a main pointer which can rotate 100 times, a small pointer which can rotate 10 times, and a triangular pointer which can rotate once. The novel feature of this paper is that the main and small pointers are actuated by ready on the self stepper motors, instead of commonly used synchros. A control technique is proposed to rotate the motor, and the positioning error is minimized by software compensator. From the repetitive precision experimental result it was obtained that the developed SAI could work well with the degree of precision of 0.03 (dial memory) for the main pointer and 0.22 (dial memory) for the small pointer.

Keyword: *helicopter, simulator, altitude indicator, stepper motor, control technique.*

Abstrak

Sebuah simulator helikopter perlu dibuat agar benar-benar mirip dengan lingkungan cockpit sebenarnya termasuk instrumentasinya. Sebuah instrumen tersimulasi menggunakan teknologi mekatronika dimana sebuah sistem mekanik dikontrol secara elektronik untuk menunjukkan variabel terbang tertentu. Makalah ini menjelaskan proses rancang bangun sebuah indikator ketinggian tersimulasi yang digunakan pada sebuah simulator helikopter super puma. Indikator ini memiliki sebuah jarum utama yang dapat berputar 100 kali, sebuah jarum kecil yang dapat berputar 10 kali, dan sebuah jarum segi tiga yang dapat berputar sekali. Fitur keterbaruan makalah ini adalah bahwa jarum utama dan jarum kecil digerakkan oleh motor stepper sebagai pengganti syncro yang umumnya digunakan. Sebuah teknik kendali diusulkan untuk menggerakkan motor, dan kesalahan posisi diminimalkan memakai kompensator peranti lunak. Dari hasil eksperimen tingkat presisi berulang-ulang diperoleh kesimpulan bahwa indikator ketinggian tersimulasi yang dirancang bangun dapat bekerja dengan baik dengan tingkat ketelitian 0,03 (dial memory) untuk jarum utama dan 0,22 (dial memory) untuk jarum kecil.

Kata kunci: *simulator, helikopter, indikator ketinggian, motor stepper, teknik kendali.*

1. Introduction

In order to ensure safety as well as to reduce cost, a flight simulator is commonly used for training pilots. A flight simulator has to be built to fully resemble the real cockpit environment including its instruments indicating air speed, vertical speed, altitude, and other flight variables. A simulated instrument incorporates mechatronics technology where a mechanical system is electronically controlled to indicate a certain flight variable. This paper describes development of a simulated altitude indicator (SAI) used for a super puma helicopter simulator. To indicate the altitude with span from -10,000 to 50,000 feet, this indicator has a main pointer, a small pointer and a triangular pointer which can rotate 100 times, 10 times, and once respectively [1].

Torque synchro system that uses torque synchros can be used to rotate the pointers multi turns. A torque synchro system is composed of a torque receiver synchro which is used as an actuator to move pointers and a control transformer synchro which sends 3 phase ac signal as a command signal. The command signal may also be sent by a digital processor through a digital to synchro card. However, this torque synchro system is very sensitive against friction disturbance and back-lash, so it requires high quality high cost frictionless material to construct pointer driving mechanism. When 3 pointers have to be controlled and rotated in one center, like in the SAI, it becomes very hard to realize the system using a torque synchro system. To compensate such disturbance, a control sinchro system may be used. A control synchro system is a system that uses control synchros to control a servo system. The servo system, in conjunction with the control synchro system, is used to move heavy loads as well as to bear against mechanical disturbance [2]. A control synchro system uses synchro for sensing the feedback signal, power amplifier, and electrical motor so that it requires more space than a torque synchro system.

In this paper, a SAI is developed under 2 stringent constrains i.e. small dimension and availability of components. The novel feature of this paper is that the main and small pointers are actuated by ready on the self stepper motors instead of using synchros. To satisfy the design specification, a control technique is proposed and the rotational error is then compensated by software.

2. Development Methodology

The simulated altitude indicator is functionally intended to indicate the simulation of the aircraft altitude indication with relation to a reference level, in standard temperature and pressure condition. It operates in the range from -10,000 to 50,000 feet, with three pointers and one altitude reference index disk window which give respectively altitude indication and reference of the following magnitude: the main pointer, 1 turn per 1,000 feet; the small pointer, 1 turn per 10,000 feet; the triangular pointer, 1 turn per 100,000 feet; the altitude reference index disk window, a potentiometer system control knob located in the lower corner, used to set an altitude reference.

Physically, the case of the SAI shall be the same as the original standard air craft part. The case shall be 16 cm maximum in length. The front face of the case shall be the same as the standard aircraft part. Rear face of the SAI comprises an electrical connector, ensuring the electrical connection of the unit with the external interface to enable altitude and altitude reference indications.

Electrically, the SAI shall be operated on 28 VDC power with nominal range of 24 VDC to 32 VDC and maximum 3 A load. Two power input lines with a common ground are required i.e. Primary 28 VDC and Secondary 28 VDC. In the event no power on the primary power line, the SAI shall automatically switch to the secondary power line. It shall be operated on 28 VDC lighting power with nominal range of 24 VDC to 32 VDC and maximum 1 A load.

2.1 Mechanical System

In order to satisfy the above mentioned specification (functional, physical, electrical), a conceptual design of driving mechanism has been drawn as shown in figure 1. Again, the availability of components and the small dimension have been considered as the most significant constrain in this design.

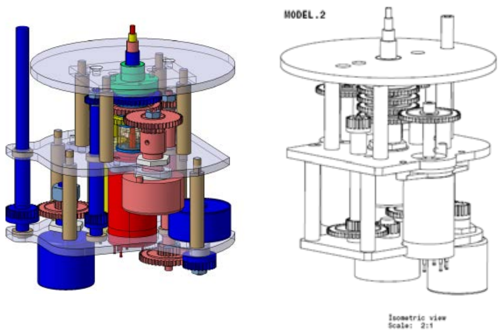


Figure 1. Conceptual design of driving mechanism

This design locates in the center one solid shaft and 3 hollow shafts. The solid shaft has the smallest diameter, located in the most inner position where the main poiter is attached. Outside the solid shaft there exists the hollow shaft of the small pointer, and outside the small pointer shaft there exists the hollow shaft of the triangular pointer. At the outest position there exists the hollow shaft where the altitude reference index disk is attached. Two stepper motors are used. One stepper motor rotates the main pointer shaft and the other rotates the small pointer shaft. Reduction gear is used in each stepper motor to increase the resolution of the motion of the pointers as well as to accomodate offset between rotating pointers' shaft and rotating stepper motors' shaft. The triangular pointer shaft is rotated by a dc motor through a reduction gear, while the position of the shaft is monitored by a potentiometer to construct a servo mechanism. The reference index disk is rotated by the knob through a series of reduction gear.

This conceptual design has been selected after trial and error experiments. Theoretically the main pointer shaft, the small pointer shaft dan the triangular shaft are dependent each other with the rotation rasio 100:10:1. Ideally, these 3 pointers' shaft can be driven by a single actuator which rotates the main pointer shaft. However, this simple concept did not work because there exist friction, back-lash and play between one rotating shaft and others that effect the position of the pointer tips in unpredictable random manner.

The body of the designed SAI is constructed by plats and spacers. The plats hold actuators, sensors, and rotating parts, while the spacers link the plats to each other. Figure 2 shows the exploded drawing of the indicator mechanism and body.

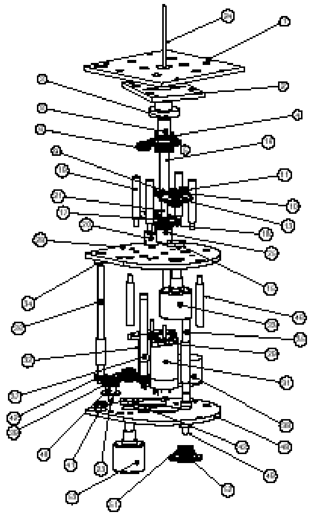


Figure 2. Exploded drawing

This design has 5 plats i.e. head plat, bushing plat, gear plat, potentiometer plat, and stepper motor plat. Below the stepper motor plat, there is a compartement for electronics circuit.

The head is mainly constructed by a bezel, a rubber ring seal, glass, dials, and a gasket. The driving mechanism is attached to the head by screwing the head plat to the gasket. The rotating parts including pointers and disk, and the dial are set above the gasket. Theese parts are then covered by the glass which is sandwitched between the gasket and the bezel. The rubber ring seal is set bewteen the glass and the bezel to fixed the glass firmly and safely. Figure 3 shows the front view of the original altitude indicator (AI). The original AI meausres altitude based on air pressure measurement. The dial shows 1,000 feet per 360˚ divided by 50 strips. The smallest scale between two strips at the dial indicates 20 feet which corresponds to 7.2 ˚.

Figure 4 shows the wiring diagram of the designed SAI. To rotate the main pointer, the host computer sends analog signals REF HI (MAIN) and REF LO (MAIN)/ground to the driver where as the driver delivers command pulses to pins U, V, W and X. Similarly, to rotate the small pointer, the host computer sends analog signals REF HI (SMALL) and REF LO (SMALL)/ground to the driver where as the driver delivers command pulses to pins P, R, S, and T. To rotate the triangular pointer, the host computer sends analog signals REF HI (ALT) and REF LO (ALT) to the driver where as the driver delivers analog signals to pins G and H. The altitude reference signal is set by the operator/pilot through the potentiometer system control knob having pins K and L. These reference signals are sent through the driver to the pins SET POINT HI and SET POINT LO at the host computer.

Figure 3. Front view of the original AI

2.2 Electronic Controller

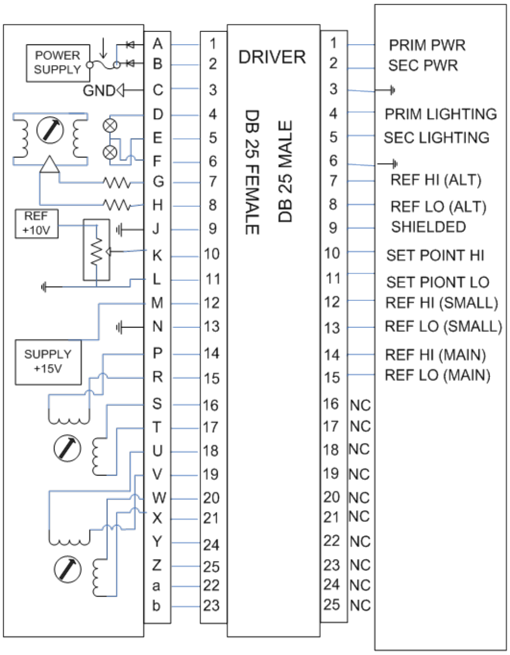


Figure 4. Wiring diagram of the designed SAI

Stepper motors can be classified into unipolar and bipolar ones. In this paper, bipolar stepper motors are used. Principly, a stepper motor is used to control speed of motion by applying electric pulses. Usually, the specification of a stepper motor is identified by the number of pulses per rotation N_p. Thus, rotational speed ω (rpm) is determined by the speed of electric pulses per second (pps) which are sent to the motor as given by the following equation.

$$\omega = \frac{60pps}{N_p} \text{ [rpm]} \qquad (2.1)$$

Moreover, the resolution of a stepper motor is ideally given by:

$$\psi = \frac{360}{N_p} \text{ [degree/pulse]} \quad (2.2)$$

Therefore, rotational position of the stepper motor can be calculated as follows.

$$\theta = \psi \times N_c \quad \text{[degree]} \qquad (2.3)$$

where: N_c denotes the number of electric pulses sent to the stepper motor driver circuit (0 and positive integer).

Note that gear rasio between stepper motor shaft and pointer shaft, R_g, leverages the resolution of the pointer position ψ_p.

$$\psi_p = \frac{\psi}{R_g} \qquad (2.4)$$

According to the spesification of the dial, theoretically the resolution of the pointer position should be a value equals to 7,2 ° per pulse divided by a certain positive integer value α. However, the ready on the self components give N_p = 49 and R_g =32/9 that yields ψ_p =2.066° per pulse.

The condition where the pointer lays just on the top of a strip at the dial is acieved when $\varepsilon_\psi = 0$. It is evident that the condition is satisfied by ($S = 5k$; $N_c = \frac{N_p R_g}{10} k$) where $k = 0, 1, 2, 3, \cdots$. The pointer comes to the initial point when $k = 10j$ where $j = 0, 1, 2, 3, \cdots$.

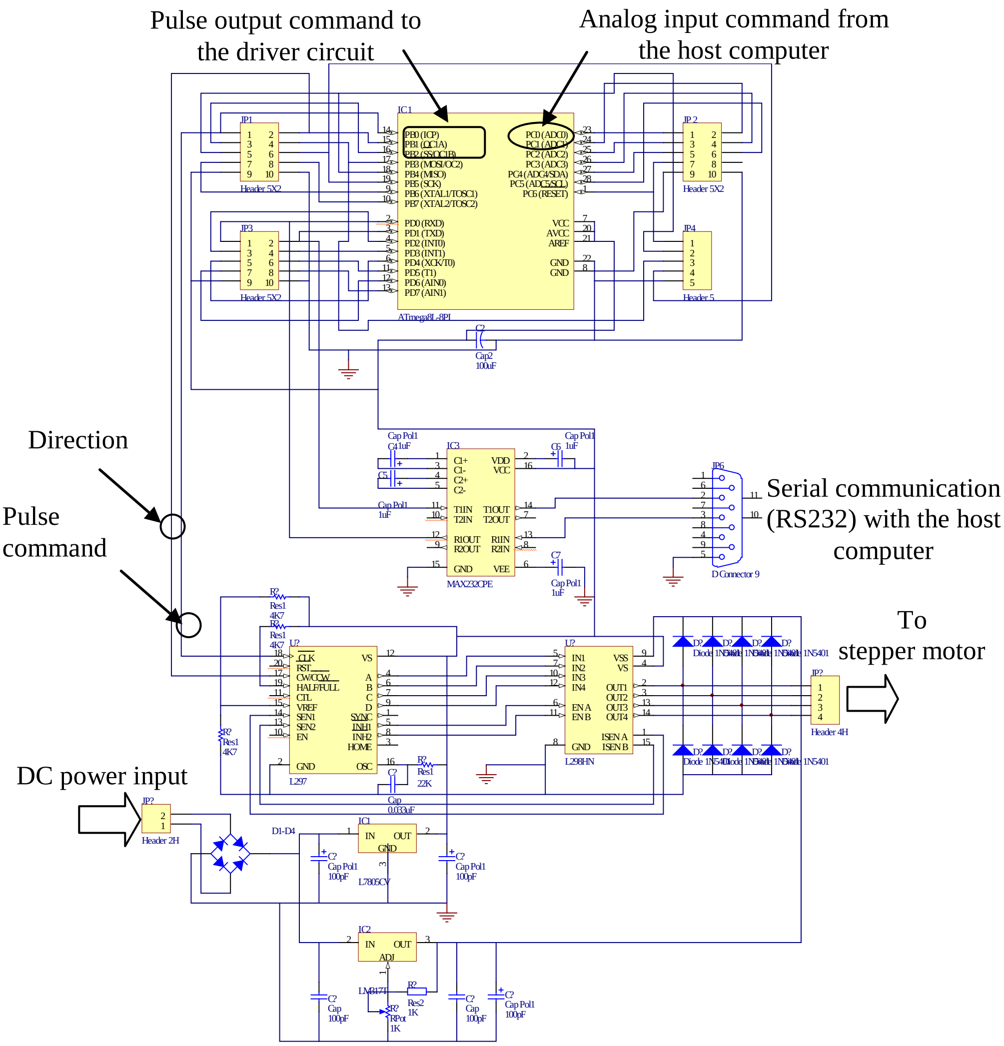


Figure 5. The developed stepper motor controller ciruit

According to the requirement, the maximum vertical speed of the helicopter simulator $v_{v\max}$ is 3,000 feet per minute for both climbing and sinking. This corresponds to 3 rpm or one rotation per 20 second. Thus the following maximum pps is obtained.

$$pps_{\max} = \frac{1}{20} N_p R_g \qquad (2.7)$$

When the stepper motor is in idle condition, to avoid heating, in practice the microprocessor sends no pulse to the stepper motor driver circuit. Figure 5 shows the electronic circuit of the stepper motor controller designed in this paper [3],[4],[5].

In this paper analog command signal u_a is defined from 0 VDC to 5 VDC to express pointer rotational position θ_p from 0° to 360° or equally pulse command signal u_p from 0 pulse to $N_p R_g$ pulse. The micro controller reads analog command signal u_a from the analog digital converter (10 bit), converts this analog signal into pulse command signal u_p, and then delivers this pulse command signal to the stepper motor driver. Controlling a stepper motor needs 3 command information i.e. rotational position u_p (pulse), rotational speed u_{pps} (pulse per second), and direction u_{id} (increment = clock wise or decrement=counter clock wise). In the figure there are 2 command lines between the micro controller and the stepper motor driver circuit. One command line is used for u_{id} which takes value H (5 V) for increment and L (0 V) for decrement, and the other command line is used for u_p and u_{pps}.

Figure 6 shows examples of analog signal command paterns used in this paper. The solid line denotes analog signal command patern with maximum vertical speed (5 V/20 sec), the broken line denotes command patern with vertical speed half of the maximum speed, and the dotted line denotes command patern with vertical speed quarter of the maximum speed. When the pointer rotates with maximum speed it rotates clock wise 2 turns from time 0 sec to 40 sec and then rotates counter clock wise 2 turns from time 40 sec to 80 sec. When the pointer rotates with half the maximum speed it rotates clock wise 1 turn from time 0 to 40 sec and then rotates back to the initial position until time 80 sec. When the pointer rotates with quarter of the maximum speed it rotates clock wise half turn from time 0 to 40 sec and then moves back to the initial position until time 80 sec. The sharp discontinuity expresses that the pointer rotates accross the initial position.

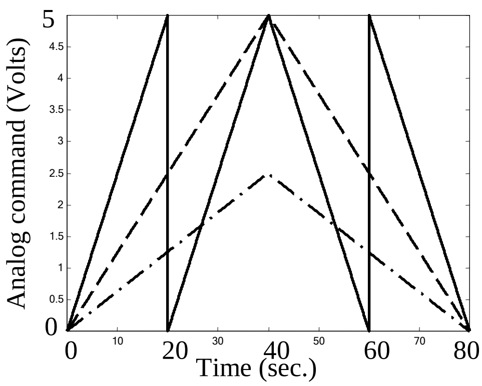


Figure 6. Analog signal command patern

From experimental experience, it was found that the stepper motor can not be rotated by sending pulses higher than a certain pps, namely ppsH. Oppositely, the driver circuit get heated extremly when pulses lower than a certain pps ,namely ppsL, is sent. To avoid the ciruit from extremly be heated when the motor moves slowly, pps command below ppsL is realized using any proper pps which lays between ppsL and ppsH.

Figure 7 gives illustration of this method. It is assumed ppsL=30pps. An example of slow motion of 10 pps is realized using duti ratio the same as ppsL.

Software was developed to make the methods explained in figure 6 and figure 7 work. The software was then implemented to the micro controller to complete the SAI.

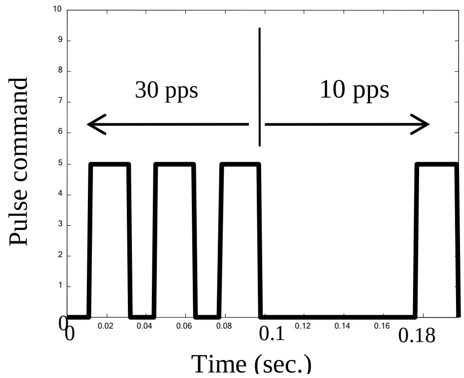
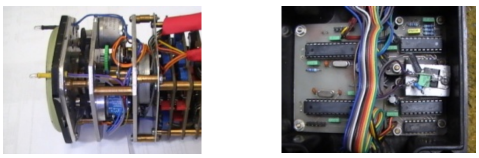


Figure 7. Pulse command to avoid over heat

2.3 The Developed SAI

Figure 8 and figure 9 show the developed simulated altitude indicator (SAI). Photos in figure 8 demonstrate how ready on the self components can be used to construct a simulated altitude indicator which is a complecated mechatronics system. Photo in figure 9 exhibits physical outside view of the SAI where the main, small and triangular pointers, together with the dial can be seen covered by the glass in the bezel.



Driving mechanism **Controller**

Figure 8. Inside view of the developed SAI

Figure 9. Ouside view of the developed SAI

Figure 10 shows the super puma helicopter simulator. The developed SAI can be seen attached in the upper right side of the panel.

Figure 10. The developed SAI attached on the helicopter simulator panel.

3. Experiment Result and Discussion

To validate the performance of the developed Simulated Altitude Indicator (SAI) two kinds of experiment were conducted i.e. crossing line experiment and repetitive precision experiment. The crossing line experiment was conducted by applying command signal as shown in figure 6 to both main pointer controller and small pointer controller. From observation during this experiment, it is confirmed that both the main and small pointers can rotate multi turns either in clock wise direction or counter clock wise direction. This observation results prove that the developed SAI performs well in rotating more than one turn.

The repetitive precision experiment was conducted by applying command signal with the same reference position signal 3 times each and recording the position of the pointer on the dial. Then the reference position signal was varied from 0 volt to 5 volt with interval of 0.5 volt to evaluate pointer position precision performance in all working domain. This repetition precision experiment was conducted both to the main pointer controller and the small pointer position. After analyzing the experimental results, an algorithm was built and implemented in the software to compensate positioning error. Again, repetitive precision experiment was conducted in the similar way but with the software compensation algorithm.

The ideal relationship between simulated altitude reference signal v_r (volt) and pointer position θ_r (dial memory) is given by the following equation.

$$\theta_r = a_r v_r \qquad (3.1)$$

where a_r =10 in this paper.

From precision repetition experiment the following estimation function can be derived.

$$\theta = a_0 + a_1 v \qquad (3.2)$$

The following software compensator algorithm is proposed to manipulate reference signal.

$$v^* = \frac{a_r}{a_1} v - \frac{a_0}{a_1} \qquad (3.3)$$

Table 1 shows the repetitive precision experimental result of the main pointer controller both with out compensator (woc) and with compensator (wc).

Figure 11 shows the experiment result listed in table 1. The horizontal axis denotes simulated altitude reference signal and the vertical axis denotes pointer position in dial memory. The broken green line represents the ideal relationship between simulated altitude reference signal and the pointer position, the broken red line expresses the raw data obtained during experiment with out compensator. The experiment result using the proposed software compensator is plotted by blue broken line. From this result, the average absolute rotational positioning error of the main pointer is obtained with out controller 0.43 (dial memory) and with controller 0.03 (dial memory).

Figure 12 shows repetitive precision experimental result of the small pointer. With out compensator average absolute error of 0.56 (dial memory) was obtained. The compensator reduces average absolute error to become 0.22 (dial memory).

The above results prove that the developed SAI with the proposed analog reference signal command pattern and the software compensator works well providing satisfactory performance.

Table 1. Repetitive experiment result

No	v_r (volt)	Pointer position θ (dial memory)		Ideal pos. θ_r
		woc	wc	
1	0.5	4	5	5
2	0.5	4	5	5
3	0.5	4	5	5
4	1	9.0	10.1	10
5	1	9.5	10.1	10
6	1	9.5	10.1	10
7	1.5	14.7	15.1	15
8	1.5	14.7	15.1	15
9	1.5	14.7	15.1	15
10	2	19.7	20	20
11	2	19.7	20	20
12	2	19.7	20	20
13	2.5	24.9	25.1	25
14	2.5	24.9	25.1	25
15	2.5	24.9	25.1	25
16	3	30	30	30
17	3	30	30	30
18	3	30	30	30
19	3.5	34.5	35	35
20	3.5	34.5	35	35
21	3.5	34.5	35	35
22	4	39.5	40	40
22	4	39.5	40	40
23	4	39.5	40	40
24	4.5	44.5	45	45
25	4.5	44.5	45	45
26	4.5	44.5	45	45
27	5	49	-	50
28	5	49	-	50
29	5	49	-	50

4. Conclusion

From the experimental results the following conclusion can be drawn:

1. Both the main pointer and the small pointer of the developed Simulated Altitude Indicator (SAI) can rotate multi turns either in clock wise direction or in counter clock wise direction according to the given analog signal command. This proves that the control technique proposed in this paper works well.
2. The main pointer has average absolute error of 0.43 (dial memory) without compensator and of 0.03 (dial memory) with compensator.
3. The small pointer has average absolute error of 0.56 (dial memory) without compensator and of 0.22 (dial memory) with compensator.
4. The SAI resemble the original altitude indicator concerning the front view which interfaces the instrument and user in a helicopter simulator cockpit.

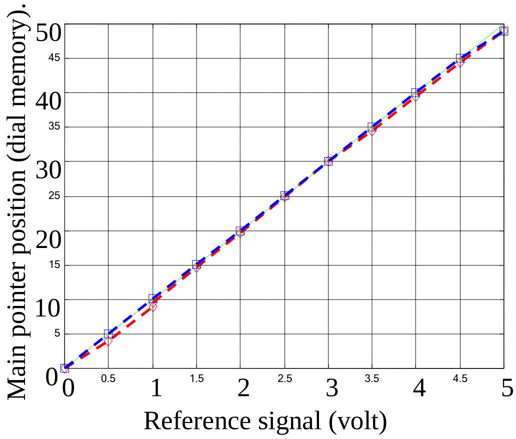


Figure 11. Main pointer experimental result.

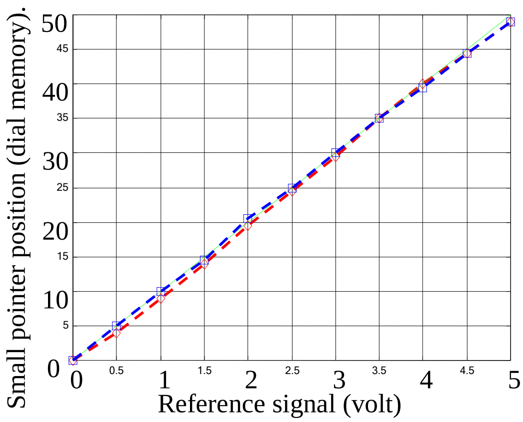


Figure 12. Small pointer experimental result.

5. Reference

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