Proceeding of the 2013
RSI/ISM International Conference on Robotics and Mechatronics
February 13-15, 2013, Tehran, Iran

Constructing IMU Based On ADC And Sensors Calibration For Ballbot

[1]Hosein Zabihi Kheibari, [1]Mahdi Akbari, Atefe Sadat Moosavi Nejad

[1]Shahab Danesh Institute of Higher Education

h.zabihi@shahabdanesh.ac.ir

***Abstract*— In this article the Ballbot described as being unlike a statically stable wheeled robot, is shown to be a dynamic stable robot. The stability of such inherently unstable robot is based on accurate angle and position feedback that is obtained from his IMU. We did not use commercial IMU in this Ballbot construction unlike the previous Ballbots, instead an IMU that is suitable for Ballbot mechanism was designed and implemented. Angle feedback produced by IMU must be as accurate as possible, similar to other sections of robot. Because of this reason we must calibrate sensors for best performance. But before sensors calibration, ADC calibration must be done in order to correct errors occurring during conversion of the sensor analog signals to equivalent digital numbers. By a calibrated ADC, sensor calibration is performed. A precise calibration method which is simple to apply is presented. The method does not need accurate equipment and is performed by a plate attached to an ordinary motor. After acquiring calibrated data, the Kalman filter is implemented for data fusion. The Kalman filter output is very accurate and IMU can track abrupt changes in orientation. It is implemented in Ballbot and could provide proper feedback to balance the Ballbot.**

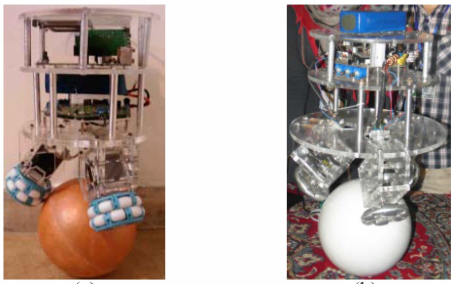
***Keywords:* Ballbot, IMU, ADC, Calibration, accelerometer, gyroscope**

I. INTRODUCTION

Design and construct of dynamically stable robots, is a growing area of research. Statically stable robots have limitations in their construction and action. These robots are not tall and generally have large and heavy bases to ensure low centers of gravity. These robots have limitations in interaction with humans [1].

In 2005 Ballbot robot was made so that it could balance on a ball [2]. In order for Ballbot to remain stable it must have very accurate feedback of his position and body angle so that it can handle himself on the ball and move in any direction. IMU is implemented for measuring such a precise feedback. But IMU consist of sensors which manufactured by MEMS technology. Because of manufacturing limitations and errors during MEMS sensors production, same MEMS sensors have different characteristics [3]. Consequently calibration should be performed to recognize each sensor characteristics.

In this paper, performance of two Ballbot made by our team are described “Fig.1”. These robots unlike the previous versions of Ballbots [2][5], didn’t utilize commercial IMU and an IMU is just designed for our Ballbot. By calibrating ADC before calibrating sensors, calibration procedure and output accuracy were improved. This calibration procedure needs



(a) (b)

Figure1. (a) first Ballbot (b)second Ballbot

simple equipment.

In section II the structure of the robot is explained and its different components are described. In section III the design and construct of IMU are discussed. Two proceeding sections analyzed calibration of ADC in section IV and sensors models and calibration in section V. In the result section, the sensors data fusion has been performed by the Kalman filter and final the results are shown.

II. STRUCTURE OF ROBOT

A one wheel robot is inherently unstable. If we analyze the robot model with Lagrange equations and calculate its transfer functions, we will see pole in right side of S axis [5]. To control this unstable system, we should make all parts highly accurate and decrease construction errors as low as possible. We should eliminate or reduce noises being inserted in the control feedback loop. Also different components should act in a way that control signals perform quickly and accurately. According to this assumption the electronic and mechanic structure of robot is described in the following subsections.

Electronic system

One of the essential parts of the robot's electronic system is the inertial measurement unit (IMU). It is composed of three single axis gyroscopes with the part number ADXRS150, a dual axis accelerometer with the part number ADXL203 and a three axis magnetometer. The sensor output is sampled and processed by ATxmega64A3 processor. Sensors data fusion is done by the Kalman filter, the exact angle of roll, pitch, yaw of robot will be recognized. All these tasks are performed onboard and the data updates with the speed of 455 times per second.

The data is sent as a serial connection to another processor which is responsible for controlling robot.

Detailed feedback which is obtained by the IMU, will be transferred to the main processor ATxmega128A1. PID control loop is implemented on the main processor. Control signals are sent with the speed of 4.4 KHz by PWM signal to three L298 drivers. Simultaneously, accurate feedback is received from the motion of motors by Optical Encoder and measuring the motors consumed current.

In the supply section, power switching is used for optimum consumption. Isolated switching IC is used for each motor to reduce the unwanted impact of motors on supply line,. Other parts include: GPS, wireless communication, display, adjustment volumes and other small parts.

Mechanical system

The body of robot has simple design based on TGU Ballbot [4]. The main part of mechanical system is related to gearbox and robot wheels. Motion mechanism is like the previous Ballbots except CMU Ballbot [1]. In this mechanism, we have three motors with a certain angle on the ball. The previous version of Ballbots utilized dc motor, gearbox or stepper motor for transferring force. But we built a gearbox with timing belt ourselves.

One feature of gear gearbox is its backlash. Backlash is not important in many applications but in Ballbot backlash cause the robot to oscillate on the ball without sending control signals. In order to overcome this issue we construct the timing belt gearbox with very low backlash.

The wheels are important too. The wheels that were used in the first version of our Ballbot had two contact areas that caused inaccurate rotation and unwanted shocks to the robot. With the help of TGU Ballbot team, we built 3 wheels for the second Ballbot.

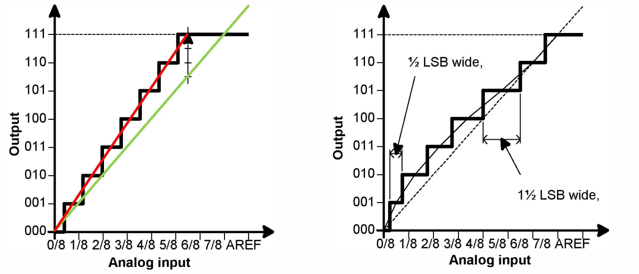
III. Design and Construct an IMU

Obtaining the exact value of three axis rotational angels, play a key role in robot performance. Angle feedback of the robot is estimated by the IMU, if the noise of estimated robot's angle is more than acceptable value, controller will not be able to stabilize robot, therefore we must eliminate errors and noises which may exist in making IMU procedure.

First error is in the data sampling by the microcontroller's ADC which has been described in section IV. Then the gyroscope and accelerometer sensors must be calibrated to send detailed information to microcontroller.

IV. ADC Calibration

The ATxmega64A3 microcontroller ADC is a pipeline ADC and has 12 bit resolution, also its sampling rate is 1Mbps [6]. This convertor has two modes for analog to digital conversion, the first mode is single input conversion and the second mode is differential input conversion. ADC reference voltage can be applied externally or the one volt internal voltage can be used. These options provide different



(a) (b)

Figure2. 3bits ADC (a) with gain error (red line) Correct transfer function (green line) (b) with nonlinearity error

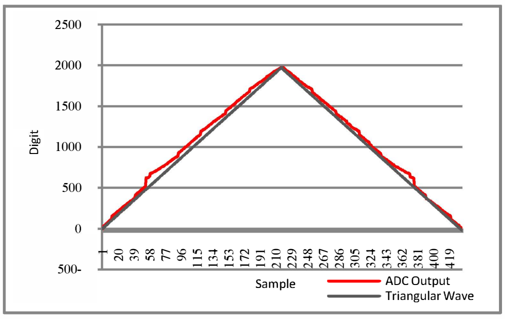
conditions which all have been tested to get the most accurate conversion, in a way that a constant voltage from the resistor voltage divider is applied to the converter input pin, and checking the ADC output in different conditions.

First of all, micro adjustments were programmed for single input mode; as a result we saw that by applying a constant voltage to the input pin, the output oscillated in the range of 38 LSB. This conversion error and oscillating refers to the internal structure of processor. In the internal structure of the ADC processor, a comparator is used to convert a MSB bit in each clock cycle. When we use the single input mode, the processor will generate the negative input of this internal comparator, but this internal generated voltage is unstable and causes the ADC output conversion get unstable too. To overcome this deficiency we must use differential mode and connect the negative differential input pin to the ground. Therefore the internal voltage would not affect conversion.

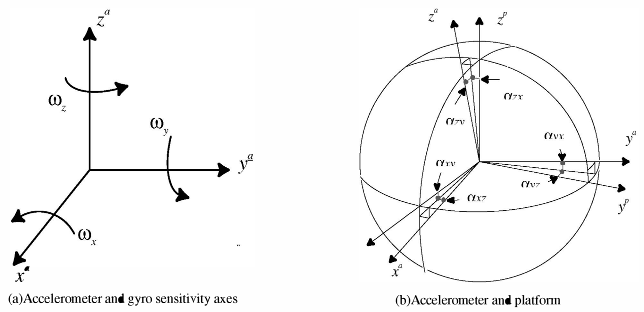
Another issue is the selection of reference voltage, which can be internal or external reference voltage. As it was described in the ATxmega A series datasheet [6], we can use the accurate one volt internal voltage as a reference, but in practice, it appears that this internal voltage is unstable too, and it is better to use an external reference voltage. Finally we got the best output by choosing the external VCC/1.6 voltage as reference voltage and make conversion in differential mode. By this adjustment ADC output was oscillating in the range of 4 LSB by applying a constant voltage to the positive pin of differential input and connecting the negative pin to the ground. Although we made significant improvements, the ADC resolution was reduced to 11-bit due to connecting the negative pin of differential input to the ground and knowing that the positive input never becomes negative. After getting the best output of a static input, we should convert the dynamic input as best as possible.

The transfer function of a 3-bit ADC is shown in “Fig.2”. This real ADC is different from the ideal ADC. In an ideal ADC, each input has a unique output and the ideal ADC has infinite resolution. But in reality ADC has four major errors.[7] The first error is quantization error that is because of limited ADC resolution, to reduce this error we can use high-resolution ADC.

The second error is the offset error that is the non-zero ADC output when zero input has been applied. By measuring this error, 2LSB offset error was recognized.



"Figure 3" ADC conversion result to a 1 Hz 1.9V triangular wave



"Figure 2" The accelerometer sensitivity axes $\{x^a, y^a\}$ and the gyros to measure the angular velocities around accelerator axes [8].

The third error is the gain error. As it is shown in "Fig.2(a)", the slope of ADC function which is in red, is not correct. This error should be corrected after removing offset error. To measure this error we applied a voltage to input pin and then monitor the output. We increase the input voltage up to the reference voltage. Before getting to the reference voltage, if the output reaches to the top (equal to 2^n that n is ADC resolution), the gain error will be smaller than one and all output numbers should multiply to:

$$Gain\ Error = \frac{Vin}{Vref} \tag{1}$$

Vin is input voltage of pin when the output has reached to the top. But if the input voltage reaches the reference voltage and the output does not reach to the top, the gain error will be bigger than one and all output numbers should multiply to:

$$Gain\ Error = \frac{2^n}{digit} = \frac{Top}{digit} \tag{2}$$

$digit$ is the output ADC number when the input voltage reaches to the reference input and n is ADC resolution.

The fourth ADC error is its nonlinear behavior. This error occurs when the ADC steps vary in different parts of transfer function and it causes deviation in its transfer function "Fig.2 (b)" This error is not important in many applications but in making IMU it is very important. To test that, a triangular signal with a 1 Hz frequency and 1.93 V peak voltage have been applied to the input by a signal generator. This signal was sampled 455 times and corresponding output values were obtained and plotted in "Fig.3" In this experiment, the error was increasing up to 50 LSB in some areas. To remove this error, we make a look up table and place the calibration value in it. By using the look up table and applying the same triangular signal, ADC output becomes exactly equal to the triangle wave.

V. Sensor Calibration

We made sure that the input signal was converting to the equivalent correct digit after accurate ADC calibration. Then we tried to calibrate input signals.

Two axis accelerator has been used in the designed IMU, because Ballbot never has 180 degree rotation about to X or Y axis and has no need for using a accelerometer in Z direction. The IMU is placed on top of robot and accelerometer axes $\{x^a, y^a\}$ place parallel to top plate of robot. Three gyroscopes installed in a way to measure angular velocity of accelerometer axes "Fig.4 (a)". But in reality the sensor sensitivity axes are not orthogonal and there are axis misalignments "Fig.4 (b)". By concerning axis misalignment error from the orthogonal set of platform coordinate axis, the specific force in accelerometer coordinate can be transformed into specific force estimates in platform coordinate as [8]

$$s^p = \mathrm{T}_a^p\, s^a \qquad \mathrm{T}_a^p = \begin{bmatrix} 1 & -\alpha_{yz} & \alpha_{zy} \\ \alpha_{xz} & 1 & -\alpha_{zx} \\ -\alpha_{xy} & \alpha_{yx} & 1 \end{bmatrix} \tag{3}$$

Where s^p and s^a denote the specific force in platform and accelerometer coordinate, respectively. Here α_{ij} is the rotation of the i-th accelerometer sensitivity axis around the j-th platform axis. If we define accelerometer coordinate as platform coordinate, the angles $\{\alpha_{xz}, \alpha_{xy}, \alpha_{yx}\}$ will become zero. Because we didn't use z axis in IMU $\{\alpha_{zy}, \alpha_{zx}\}$ angles became zero too. The only not zero angle is a_{yz} and it's equal to accelerometer y and x axis deflection of 90 degree. Whereas the x- and y-accelerometers are mounted into the same MEMS sensor, the misalignment between them is too small to measure. Hence we neglect it and assume the accelerometer coordinate is the same as platform coordinate.

Now we should calibrate gyroscopes about accelerometer coordinate. That is, three rotations are required to make the sensitivity axes of gyros orthogonal to each other. The result of orthogonal gyroscopes coordinate should convert to accelerometer coordinate by three rotations. The relation reads

$$\omega^p = T_g^p\, \omega^g \qquad T_g^p = \begin{bmatrix} 1 & -\gamma_{yz} & \gamma_{zy} \\ \gamma_{xz} & 1 & -\gamma_{zx} \\ -\gamma_{xy} & \gamma_{yx} & 1 \end{bmatrix} \tag{4}$$

978-1-4673-5811-8/13/$31.00 ©2013 IEEE

Proceeding of the 2013
RSI/ISM International Conference on Robotics and Mechatronics
February 13-15, 2013, Tehran, Iran

TABLE 1 accelerometer and gyroscope specifications

Sensor Type	Raw Sensor Data Conversion Values	
	0 Offset [lsb]	*Sensitivity[lsb/(°/s)]*
Accelerometer	2500	1000
Gyroscopes	2500	12.5

We will present a simple and applicable way to find these angles but we need to analyze accelerator and gyroscopes output before that.

The MEMS sensors output a voltage proportional to the physical quantities sensed by the sensors, acceleration and angular rates, respectively. Table1. This scaling can be found in each sensor datasheet, but a range for that is determined and the exact scaling isn't mentioned. In [9] these parameters were examined however some obtained parameters were not even in that range. This is due to manufacturing errors and limitations that cause different characteristic for two same sensors. Moreover, there is initial null voltage in sensors which is the output voltage of sensors in the absence of physical force. To calculate imposed forces you have to subtract null voltage from sensors output voltage. Although null voltage is given by manufactures data sheet, it differs from what you measure in reality. The MEMS sensors output is nonlinear. For the sensors used in our application the nonlinearities are in the order of 0.1% and so maybe neglected.

By defining k_a and k_g as the output scale factor of acceleration and gyroscopes, respectively, we have:

$$k_a = \mathrm{diag}\left(k_{x_a}, k_{y_a}, k_{z_a}\right) \qquad b_a = [\,b_{x_a}\; b_{x_a}\; b_{x_a}]^T \tag{5}$$

$$k_g = \mathrm{diag}\left(k_{x_g}, k_{y_g}, k_{z_g}\right) \qquad b_g = [\,b_{x_g}\; b_{x_g}\; b_{x_g}]^T \tag{6}$$

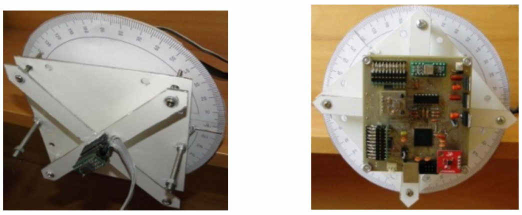
The measured output of the accelerometer and gyroscopes can be modeled as [10]

$$\tilde{s}^p = k_a (T_a^p)^{-1}\, s^p + b_a + v_a \tag{7}$$

$$\tilde{\omega}^g = k_g\, \omega^g + b_g + v_g \tag{8}$$

Where v_a and v_g are accelerometer and gyro measurement noise, respectively. There are ways to find these parameters and calibrate sensors. In [9] and [10] a turn table and mechanical platform are used. In [11] a calibration procedure using an optical tracking system is studied. In [12] and [13] a Kalman filter is designed with precise maneuvers to calibrate low-cost IMU sensors. But accurate equipment is needed in most of the way. The cost of constructing a mechanical platform many times can exceed the cost of developing the IMU. Performing Kalman filter for estimating parameters which is presented in [13] and [12] needs huge amount of processing. Some cases [13] neglected the misalignment error. We presented a simple and applicable approach which needs an ordinary motor with a rotational plate. “Fig.5” This method could be performed with cheep equipment.

We should consider gyroscope output voltage in stationary condition for finding null voltage of gyroscopes. Associated



(a) (b)

“Figure 5” simple plate attached to motor

ADC output for what described in section 3-1 is oscillating between 4 digits. So we averaged from 500 samples to estimate gyroscopes null voltage accurately.

Accelerometer null voltage is attained by imposing zero g to accelerator sensitivity axis. Placing an accelerator in this situation should be done with accurate equipment which is not possible in many low cost applications. The approach we performed is measuring output voltages for correspondent ± 1 g input. Meaning that we obtain the maximum and minimum voltage of sensor output in stationary condition and Null voltage will be

$$b_a = \frac{\mathrm{digit}_{+1g} - \mathrm{digit}_{-1g}}{2} \tag{9}$$

Where digit_{+1g} *and* digit_{-1g} are ADC output corresponding to imposing $\pm 1\,g$ input. But the digit_{+1g} and digit_{-1g} are attained when the sensitivity axes are perfectly orthogonal to earth. We use a calibration plate for this purpose “Fig.5”. There is a degree plate install to the motor body. A simple plate attached to a motor output shaft. On this plate a movable cross plate is attached which accelerometer place at the center of that. By the two calibration screws placed at the corners of cross plate. We can change the accelerometer axes angle according to the earth by 0.1accuracy. After placing the accelerometer we monitor ADC output and start to twist calibration screw to reach maximum output. The sensor gets to its maximum output in each angle when its sensitivity axes are exactly perpendicular to the earth. By reaching to maximum output in a fixed angle you can be sure that accelerator sensitivity axes became perpendicular to the earth. After that, by rotating the motor slowly to a revolution and save ADC output, you get a sin signal which its positive and negative peak would be digit_{+1g} anddigit_{-1g}, respectively. By acquiring these two digits k_a is equal to

$$k_a = \frac{\left(\mathrm{digit}_{+1g} - \mathrm{digit}_{-1g}\right)\frac{Vref}{2^n}}{2} \tag{10}$$

Where Vref and n are ADC reference and ADC resolution, respectively.

To calculate the correct k_g, we placed the gyroscope on the plate and rotated the motor with known angular velocity which was obtained from motor encoder. By twisting the screw and repeating the procedure we reached biggest digit with a fixed angular velocity. In that position gyro sensitivity axes is exactly parallel to motor rotational axes and in that situation k_g can be calculated by

$$k_g = \frac{(digit - b_k)\frac{Vref}{2^n}}{\dot{\omega}_m} \quad (11)$$

Where Vref and n are ADC reference and ADC resolution, respectively. $Digit$ is the biggest number attained from ADC output by rotating with a fixed angular velocity of motor $\dot{\omega}_m$. We calculate k_g by this procedure for 3 gyroscopes.

After finding the correct parameters(k_a, k_g, b_a, b_g), we fix IMU on the plate "Fig.5 (b)". By adjusting calibration IMU screws, we fix IMU in a way that the angles calculated from calibrated accelerometer be the same as degree plate. In this situation IMU coordinate which is acceleration coordinate is same as motor coordinate plate.

We rotate the motor and store the 3 gyroscopes output and correspondent motor angular velocity at each sampling time. By knowing angular velocity which motor had at each sampling time, we can calculate:

$$\gamma_{xy} = \frac{\left(\mathrm{digit}_{g_x}(t) - b_{g_x}\right)\left(\frac{Vref}{2^n}\right)}{\left(k_{g_x}.\omega_m(t)\right)} \quad (12)$$

Where $\mathrm{digit}_{g_x}(t)$ is the ADC output voltage at time t from gyro measuring x angular velocity axes, and $\omega_m(t)$ is motor angular speed at time t. with the same way:

$$\gamma_{yx} = \frac{\left(\mathrm{digit}_{g_y}(t) - b_{g_y}\right)\left(\frac{Vref}{2^n}\right)}{\left(k_{g_y}.\omega_m(t)\right)} \quad (13)$$

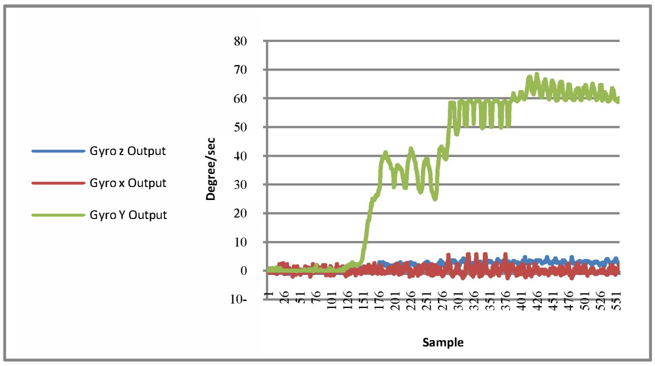
Rotation output is shown in "Fig.6". We can calculate the other four parameters by rotating IMU around y and x axes.

VI. RESULT

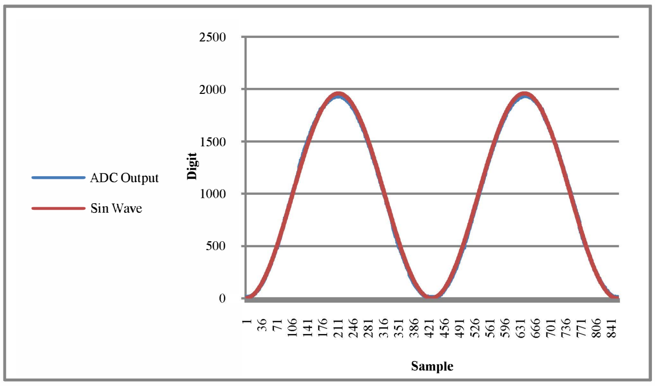
The Atxmega64A3 we examined had 2 LSB offset error and 1.013 gain error. The nonlinearity error is compensated by a look up table. For testing the calibrated ADC we applied a sine wave with 1 Hz frequency and 1.9 V peak-to-peaks voltage to the ADC input. Applied Signal and the ADC corrected output is shown in "Fig.7". It can be seen that the analog input signal is converted to equivalent digital form with acceptable precision and there is no effect of ADC errors in conversion.

We applied the Sensor calibration method by a calibrated ADC and you can see the sensor calibration parameter in "Table.2"

These values are very different from the datasheet values; it is good to say the mentioned calibration method was tested on a gyroscope sensor by a not calibrated ADC. We rotated the gyroscope on the plate with determined speed and



"Figure 7" Gyroscopes output from rotating IMU around the z coordinate when IMU coordinate is the same as rotational plate coordinate



"Figure7" Calibrated ADC output to a 1hz 1.9v sine wave

Table2. Calibrated sensors specification

Sensor Type	Raw Sensor Data Conversion Values	
	0 Offset [lsb]	*Sensitivity [lsb/(°/s)]*
Accelerometer	2378.8	930.24
Accelerometer	2393.06	922.64
Gyroscope x	2079.7	9.05
Gyroscope y	2149	12.12
Gyroscope z	2249.5	9.01

Table3. T_a^p Parameter

Parameter	*Misalignment[°]*	*Parameter*	*Misalignment[°]*
γ_{yz}	1.35	γ_{zx}	0.91
γ_{zy}	2.73	γ_{xy}	4.71
γ_{xz}	0.89	γ_{yx}	0.18

the amount of k_g is Calculated from (11) then rotated the gyroscope with the same speed but in the opposite direction and the amount of kg is calculated again, but because there were errors in the ADC, k_g obtained different in two directions and two $k_g$had ratio of about ¾. Once again, it confirms that the ADC calibration should perform before sensor calibration.

In the final stage of calibration, we performed three orthogonal rotations on the rotational plate and calculated the

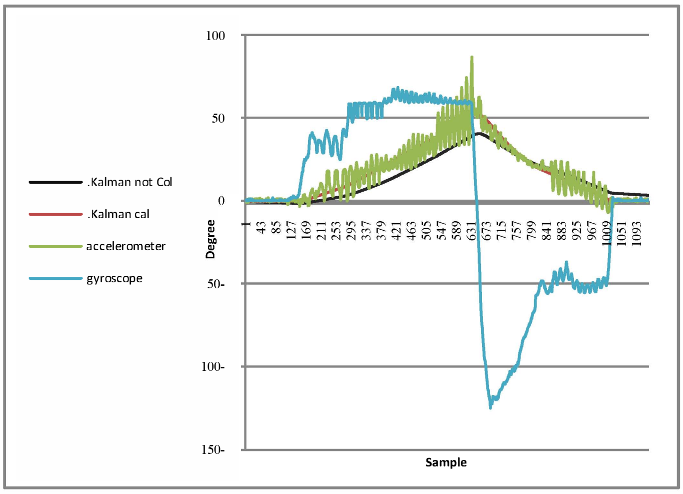
978-1-4673-5811-8/13/$31.00 ©2013 IEEE

Proceeding of the 2013
RSI/ISM International Conference on Robotics and Mechatronics
February 13-15, 2013, Tehran, Iran

T_a^p parameters by described method. "Table3". With this method there is no need to be concerned about proper and orthogonal components installation because the installation errors can be corrected. When we were sure of having removed errors, we combined the sensor data by the Kalman filter [14]. Kalman filter parameters were adjusted by trial and error, for best performance on the robot. In a test we rotated the IMU by motor from zero degree angles to 52 degree angle and rotate inversely from 52 degree angle to zero degree angles with an angular velocity of 60 degree per second. "Fig.8". The movement acceleration noises that influence the accelerometer, were ineffective on the Kalman filter output. Furthermore, Kalman filter has removed the drift of gyroscope signal. As it is clear, the IMU is able to track the abrupt and oscillating moves. This is due to the accurate calibration is done. For comparison we show the output of a similar Kalman filter that use not calibrated data in the figure:

I. CONCLUSION

A MEMS sensor based inertial measurement unit has been constructed in-house, intended to be used in Ballbot. In order to provide an accurate feedback for such an unstable robot, a deeply ADC calibration must be performed before calibrating IMU. By an accurate calibrated ADC, IMU calibration is performed which requires simple and ordinary equipment. A Kalman filter made the data fusion and output a reliable angle estimation which were proper to use in lot's of applications. The calibrated IMU has been attached to our Ballbot and it could maintain his balance perfectly. With this performance our second Ballbot won the first place in IranOpen Robotics 2012 Competition at demo league.



"Figure 8" Calibrated and not Calibrated Kalman output of rotation from 0 degree to 52 degree and vice versa at the 60 Degree per second angular velocity

II. REFERENCES

[1] T. Lauwers, "A dynamically stable single-wheeled mobile robot with inverse mouse-ball drive", Robotics and Automation, ICRA 2006, pp. 2884 – 2889.

[2] T. Lauwers, G. Kantor, and R. Hollis, "One is enough" In Proc. Int'l. Symp. for Robotics Research, San Francisco, October 12-15 Foundation for Robotics Research.

[3] G. Dissanayake, "The aiding of a low-cost strapdown inertial measurement unit using vehicle model constraints for land vehicle applications", Robotics and Automation, IEEE Transactions on, Oct 2001, vol. 17 , Issue: 5, pp. 731 - 747

[4] M. Kumagai "Development of a robot balancing on a ball", Control, Automation and Systems, ICCAS 2011, pp. 433 - 438

[5] P. Fankhauser, C. Gwerder, "3D Modeling and Control Design for a Ballbot" 2010

[6] XMEGA A Manual, 2010 Atmel Corporation.

[7] R.H. Walden, "Analog-to-Digital Converter Survey and Analysis" Selected Areas in Communications, IEEE Journal 1999, vol.17 , Issue. 4 , pp.539 – 550.

[8] *I. Skog, P. Handel*. "Calibration of a MEMS Inertial Measurement Unit". XVII IMEKO WORLD CONGRESS 2006.

[9] M. Gaffney, "An automated calibration tool for high performance wireless inertial measurement in professional sports".sensors, 2011 IEEE, pp. 262 – 265.

[10] R M. Rogers, "Applied Mathematics In integrated Navigation Systems", Second Edition 2011. AIAA Education Series.

[11] A. Kim and M.F Golnaraghi, "Initial calibration of an inertial measurement unit using an optical position tracking system", in *Proc. PLANS 2004, IEEE Position Location and Navigation Symposium*,

[12] E. Foxlin and L. Naimark, "Miniaturization, calibration & accuracy evaluation of a hybrid self-tracker," in Mixed and Augmented Reality, 2003. Proceedings. The Second IEEE and ACM International Symposium on. IEEE, 2003, pp. 151–160.

[13] A. Amirsadr, J. Kim, L. Petersson and J. Trumpf. "Practical Considerations in Precise Calibration of a Low-cost MEMS IMU for Road-Mapping Applications" 2010

[14] S. Godha, "Performance evaluation of low cost MEMS-based IMU integrated with GPS for land vehicle navigation application," Master's thesis, Department of Geomatics Engineering, University of Calgary, Calgary, Canada, 2006.

978-1-4673-5811-8/13/$31.00 ©2013 IEEE