ANDROID SENSOR FUSION TUTORIAL

While working on my master thesis, I've made some experiences with sensors in Android devices and I thought I'd share them with other Android developers stumbling over my blog. In my work I was developing a head tracking component for a prototype system. Since it had to adapt audio output to the orientation of the users head, it required to respond quickly and be accurate at the same time.

I used my Samsung Galaxy S2 and decided to use its gyroscope in conjunction with the accelerometer and the magnetic field sensor in order to measure the user's head rotations both, quickly and accurately. To acheive this I implemented a complementary filter to get rid of the gyro drift and the signal noise of the accelerometer and magnetometer. The following tutorial describes in detail how it's done.

There are already several tutorials on how to get sensor data from the Android API, so I'll skip the details on android sensor basics and focus on the sensor fusion algorithm. The Android API Reference is also a very helpful entry point regarding the acquisition of sensor data. This tutorial is based on the Android API version 10 (platform 2.3.3), by the way.

This article is divided into two parts. The first part covers the theoretical background of a complementary filter for sensor signals as described by Shane Colton here. The second part describes the implementation in the Java programming laguage. Everybody who thinks the theory is boring and wants to start programing right away can skip directly to the second part. The first part is interesting for people who develop on other platforms than Android, iOS for example, and want to get better results out of the sensors of their devices.

Update (March 22, 2012):
I've created a small Android project which contains the whole runnable code from this tutorial. You can download it here:
SensorFusion1.zip

Update (April 4, 2012):
Added a small bugfix in the examples GUI code.

Update (July 9, 2012):
Added a bugfix regarding angle transitions between 179° <–> -179°. Special thanks to **J.W. Alexandar Qiu** who pointed it out and published the soultion!

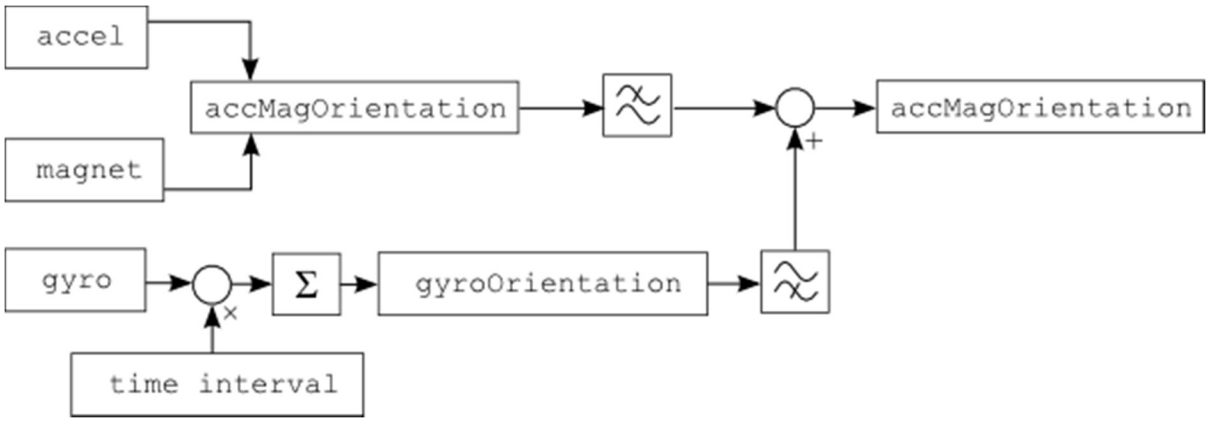
Update (September 25, 2012):
Published the code under the MIT-License (license note added in code), which allows you to do with it pretty much everything you want. No need to ask me first 

SENSOR FUSION VIA COMPLEMENTARY FILTER

Before we start programming, I want to explain briefly how our sensor fusion approach works. The common way to get the attitude of an Android device is to use the*SensorManager.getOrientation()* method to get the three orientation angles. These two angles are based on the accelerometer and magenotmeter output. In simple terms, the acceletometer provides the gravitiy vector (the vector pointing towards the centre of the earth) and the magnetometer works as a compass. The Information from both sensors suffice to calculate the device's orientation. However both sensor outputs are inacurate, expecially the output from the magnetic field sensor which includes a lot of noise.

The gyroscope in the device is far more accurate and has a very short response time. Its downside is the dreaded gyro drift. The gyro provides the angular rotation speeds for all three axes. To get the actual orientation those speed values need to be integrated over time. This is done by multiplying the angular speeds with the time interval between the last and the current sensor output. This yields a rotation increment. The sum of all rotation increments yields the absolut orientation of the device. During this process small errors are introduced in each iteration. These small errors add up over time resulting in a constant slow rotation of the calculated orientation, the gyro drift.

To avoid both, gyro drift and noisy orientation, the gyroscope output is applied only for orientation changes in short time intervals, while the magnetometer/acceletometer data is used as support information over long periods of time. This is equivalent to low-pass filtering of the accelerometer and magnetic field sensor signals and high-pass filtering of the gyroscope signals. The overall sensor fusion and filtering looks like this:



So what exactly does high-pass and low-pass filtering of the sensor data mean? The sensors provide their data at (more or less) regular time intervals. Their values can be shown as signals in a graph with the time as the x-axis, similar to an audio signal. The low-pass filtering of the noisy accelerometer/magnetometer signal (*accMagOrientation*in the above figure) are orientation angles averaged over time within a constant time window.

Later in the implementation, this is accomplished by slowly introducing new values from the accelerometer/magnetometer to the absolute orientation:

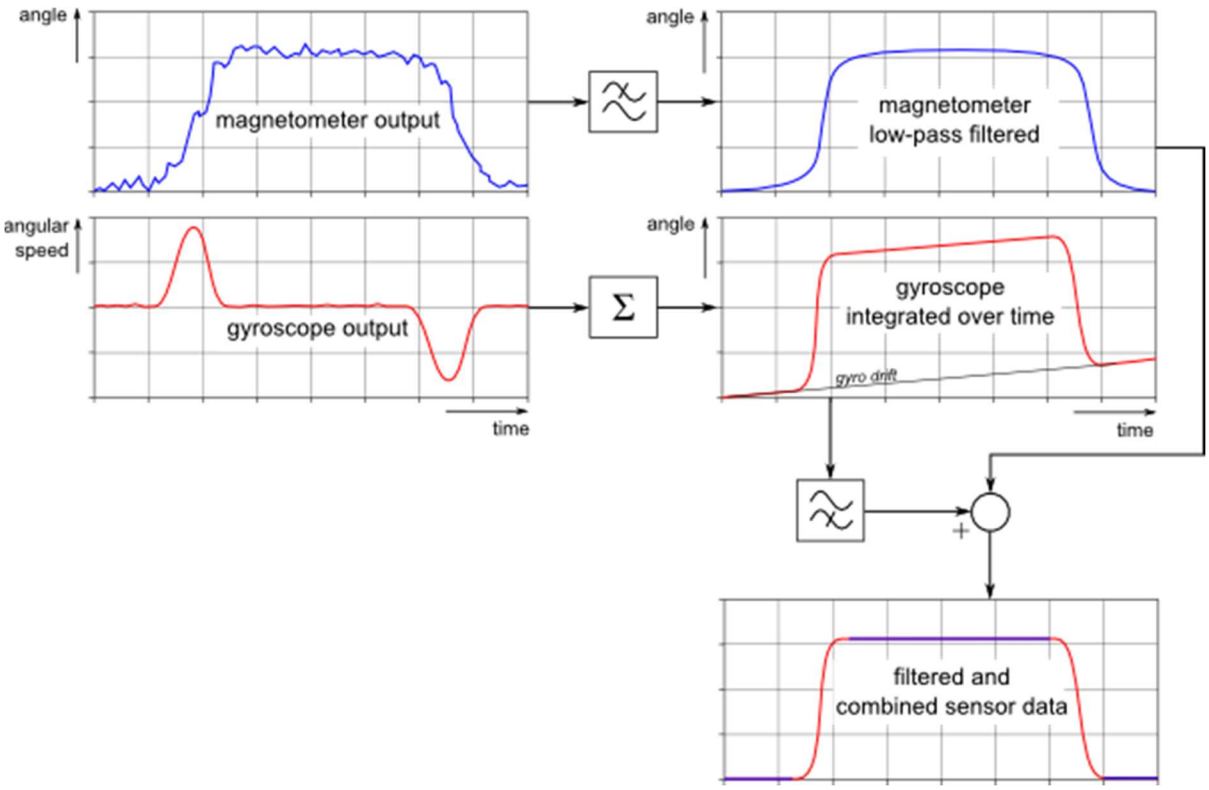
```
// low-pass filtering: every time a new sensor value is available
// it is weighted with a factor and added to the absolute orientation
accMagOrientation = (1 - factor) * accMagOrientation + factor * newAccMagValue;
```

The high-pass filtering of the integrated gyroscope data is done by replacing the filtered high-frequency component from *accMagOrientation* with the corresponding gyroscope orientation values:

```
1  fusedOrientation =
2       (1 - factor) * newGyroValue;     // high-frequency component
3       + factor * newAccMagValue;       // low-frequency component
```

In fact, this is already our finished comlementary filter.

Assuming that the device is turned 90° in one direction and after a short time turned back to its initial position, the intermediate signals in the filtering process would look something like this:



Notice the gyro drift in the integrated gyroscope signal. It results from the small irregularities in the original angular speed. Those little deviations add up during the integration and cause an additional undesireable slow rotation of the gyroscope based orientation.

IMPLEMENTATION

Now let's get started with the implementation in an actual Android application.

First we need to set up our Android app with the required members, get the *SensorManager* and initiaise our sensor listeners, for example, in the *onCreate* method:

```
public class SensorFusionActivity extends Activity implements SensorEventListener{
    private SensorManager mSensorManager = null;

    // angular speeds from gyro
    private float[] gyro = new float[3];

    // rotation matrix from gyro data
    private float[] gyroMatrix = new float[9];

    // orientation angles from gyro matrix
    private float[] gyroOrientation = new float[3];

    // magnetic field vector
    private float[] magnet = new float[3];

    // accelerometer vector
    private float[] accel = new float[3];

    // orientation angles from accel and magnet
    private float[] accMagOrientation = new float[3];

    // final orientation angles from sensor fusion
    private float[] fusedOrientation = new float[3];

    // accelerometer and magnetometer based rotation matrix
    private float[] rotationMatrix = new float[9];
```

```
25      public void onCreate(Bundle savedInstanceState) {
26          super.onCreate(savedInstanceState);
27          setContentView(R.layout.main);
28
29          gyroOrientation[0] = 0.0f;
30          gyroOrientation[1] = 0.0f;
31          gyroOrientation[2] = 0.0f;
32
33          // initialise gyroMatrix with identity matrix
34          gyroMatrix[0] = 1.0f; gyroMatrix[1] = 0.0f; gyroMatrix[2] = 0.0f;
35          gyroMatrix[3] = 0.0f; gyroMatrix[4] = 1.0f; gyroMatrix[5] = 0.0f;
36          gyroMatrix[6] = 0.0f; gyroMatrix[7] = 0.0f; gyroMatrix[8] = 1.0f;
37
38          // get sensorManager and initialise sensor listeners
39          mSensorManager = (SensorManager) this.getSystemService(SENSOR_SERVICE);
40          initListeners();
41      }
42
43      // ...
44  }
45
46
```

Notice that the application implements the *SensorEventListener* interface. So we'll have to implement the two methods *onAccuracyChanged* and *onSensorChanged*. I'll leave*onAccuracyChanged* empty since it is not necessary for this tutorial. The more important function is *onSensorChanged*. It updates our sensor data continuously.

The initialisation of the sensor listeners happens in the *initListeners()* method:

```
?
1   public void initListeners(){
```

```
        mSensorManager.registerListener(this,
            mSensorManager.getDefaultSensor(Sensor.TYPE_ACCELEROMETER),
            SensorManager.SENSOR_DELAY_FASTEST);

        mSensorManager.registerListener(this,
            mSensorManager.getDefaultSensor(Sensor.TYPE_GYROSCOPE),
            SensorManager.SENSOR_DELAY_FASTEST);

        mSensorManager.registerListener(this,
            mSensorManager.getDefaultSensor(Sensor.TYPE_MAGNETIC_FIELD),
            SensorManager.SENSOR_DELAY_FASTEST);
    }

```

After the listeners are initialised, the *onSensorChanged()* method is called automatically whenever new sensor data is available. The data is then copied or processed, respectively.

```
public void onSensorChanged(SensorEvent event) {
    switch(event.sensor.getType()) {
    case Sensor.TYPE_ACCELEROMETER:
        // copy new accelerometer data into accel array
        // then calculate new orientation
        System.arraycopy(event.values, 0, accel, 0, 3);
        calculateAccMagOrientation();
        break;

    case Sensor.TYPE_GYROSCOPE:
        // process gyro data
        gyroFunction(event);
        break;

```

```
14        case Sensor.TYPE_MAGNETIC_FIELD:
15            // copy new magnetometer data into magnet array
16            System.arraycopy(event.values, 0, magnet, 0, 3);
17            break;
18        }
19    }
20
```

The Android API provides us with very handy functions to get the absolute orientation from the accelerometer and magnetometer. This is all we need to do to get the accelerometer/magnetometer based orientaion:

```
1  public void calculateAccMagOrientation() {
2      if(SensorManager.getRotationMatrix(rotationMatrix, null, accel, magnet)) {
3          SensorManager.getOrientation(rotationMatrix, accMagOrientation);
4      }
5  }
```

As described above, the gyroscope data requires some additional processing. The Android reference page shows (see Sensor.TYPE_GYROSCOPE). I have simply reused the proposed code and added some parameters to it so it looks like this:

```
1   public static final float EPSILON = 0.000000001f;
2
3   private void getRotationVectorFromGyro(float[] gyroValues,
4                                          float[] deltaRotationVector,
5                                          float timeFactor)
6   {
7       float[] normValues = new float[3];
8
9       // Calculate the angular speed of the sample
        float omegaMagnitude =
```

```
10          (float)Math.sqrt(gyroValues[0] * gyroValues[0] +
11          gyroValues[1] * gyroValues[1] +
12          gyroValues[2] * gyroValues[2]);
13
14      // Normalize the rotation vector if it's big enough to get the axis
15      if(omegaMagnitude > EPSILON) {
16          normValues[0] = gyroValues[0] / omegaMagnitude;
17          normValues[1] = gyroValues[1] / omegaMagnitude;
18          normValues[2] = gyroValues[2] / omegaMagnitude;
19      }
20
21      // Integrate around this axis with the angular speed by the timestep
22      // in order to get a delta rotation from this sample over the timestep
23      // We will convert this axis-angle representation of the delta rotation
24      // into a quaternion before turning it into the rotation matrix.
25      float thetaOverTwo = omegaMagnitude * timeFactor;
26      float sinThetaOverTwo = (float)Math.sin(thetaOverTwo);
27      float cosThetaOverTwo = (float)Math.cos(thetaOverTwo);
28      deltaRotationVector[0] = sinThetaOverTwo * normValues[0];
29      deltaRotationVector[1] = sinThetaOverTwo * normValues[1];
30      deltaRotationVector[2] = sinThetaOverTwo * normValues[2];
31      deltaRotationVector[3] = cosThetaOverTwo;
32  }
33
```

The above function creates a rotation vector which is similar to a quaternion. It expresses the rotation interval of the device between the last and the current gyroscope measurement. The rotation speed is multiplied with the time interval — here it's the parameter *timeFactor* — which passed since the last measurement. this function is then called in the actual *gyroFunction()* for gyro sensor data processing. This is where the gyroscope rotation intervals are added to the absolute gyro based orientation. But since

we have rotation matrices instead of angles this can’t be done by simply adding the rotation intervals. We need to apply the rotation intervals by mytrix multiplication:

```
?
1   private static final float NS2S = 1.0f / 1000000000.0f;
2   private float timestamp;
3   private boolean initState = true;
4
5   public void gyroFunction(SensorEvent event) {
6       // don't start until first accelerometer/magnetometer orientation has been acquire
7       if (accMagOrientation == null)
8           return;
9
10      // initialisation of the gyroscope based rotation matrix
11      if(initState) {
12          float[] initMatrix = new float[9];
13          initMatrix = getRotationMatrixFromOrientation(accMagOrientation);
14          float[] test = new float[3];
15          SensorManager.getOrientation(initMatrix, test);
16          gyroMatrix = matrixMultiplication(gyroMatrix, initMatrix);
17          initState = false;
18      }
19
20      // copy the new gyro values into the gyro array
21      // convert the raw gyro data into a rotation vector
22      float[] deltaVector = new float[4];
23      if(timestamp != 0) {
24          final float dT = (event.timestamp - timestamp) * NS2S;
25      System.arraycopy(event.values, 0, gyro, 0, 3);
        getRotationVectorFromGyro(gyro, deltaVector, dT / 2.0f);
        }
```

```
26        // measurement done, save current time for next interval
27        timestamp = event.timestamp;
28
29        // convert rotation vector into rotation matrix
30        float[] deltaMatrix = new float[9];
31        SensorManager.getRotationMatrixFromVector(deltaMatrix, deltaVector);
32
33        // apply the new rotation interval on the gyroscope based rotation matrix
34        gyroMatrix = matrixMultiplication(gyroMatrix, deltaMatrix);
35
36        // get the gyroscope based orientation from the rotation matrix
37        SensorManager.getOrientation(gyroMatrix, gyroOrientation);
38    }
39
40
41
```

The gyroscope data is not processed until orientation angles from the accelerometer and magnetometer is available (in the member variable *accMagOrientation*). This data is required as the initial orientation for the gyroscope data. Otherwise, our orientation matrix will contain undefined values. The device's current orientation and the calcuated gyro rotation vector are transformed into a rotation matrix.

The *gyroMatrix* is the total orientation calculated from all hitherto processed gyroscope measurements. The *deltaMatrix* holds the last rotation interval which needs to be applied to the *gyroMatrix* in the next step. This is done by multiplying *gyroMatrix* with *deltaMatrix*. This is equivalent to the Rotation of *gyroMatrix* about *deltaMatrix*. The*matrixMultiplication* method is described further below. Do not swap the two parameters of the matrix multiplication, since matrix multiplications are not commutative.

The rotation vector can be converted into a matrix by calling the conversion function *getRotationMatrixFromVector* from the *SensoManager.* In order to convert orientation angles into a rotation matrix, I've written my own conversion function:

?

```
1  private float[] getRotationMatrixFromOrientation(float[] o) {
2      float[] xM = new float[9];
3      float[] yM = new float[9];
4      float[] zM = new float[9];
5
6      float sinX = (float)Math.sin(o[1]);
7      float cosX = (float)Math.cos(o[1]);
8      float sinY = (float)Math.sin(o[2]);
9      float cosY = (float)Math.cos(o[2]);
10     float sinZ = (float)Math.sin(o[0]);
11     float cosZ = (float)Math.cos(o[0]);
12
13     // rotation about x-axis (pitch)
14     xM[0] = 1.0f; xM[1] = 0.0f; xM[2] = 0.0f;
15     xM[3] = 0.0f; xM[4] = cosX; xM[5] = sinX;
16     xM[6] = 0.0f; xM[7] = -sinX; xM[8] = cosX;
17
18     // rotation about y-axis (roll)
19     yM[0] = cosY; yM[1] = 0.0f; yM[2] = sinY;
20     yM[3] = 0.0f; yM[4] = 1.0f; yM[5] = 0.0f;
21     yM[6] = -sinY; yM[7] = 0.0f; yM[8] = cosY;
22
23     // rotation about z-axis (azimuth)
24     zM[0] = cosZ; zM[1] = sinZ; zM[2] = 0.0f;
25     zM[3] = -sinZ; zM[4] = cosZ; zM[5] = 0.0f;
26     zM[6] = 0.0f; zM[7] = 0.0f; zM[8] = 1.0f;
27
28     // rotation order is y, x, z (roll, pitch, azimuth)
     float[] resultMatrix = matrixMultiplication(xM, yM);
     resultMatrix = matrixMultiplication(zM, resultMatrix);
     return resultMatrix;
```

```
}
```

I have to admit, this function is not optimal and can be improved in terms of performance, but for this tutorial it will do the trick. It basically creates a rotation matrix for every axis and multiplies the matrices in the correct order (y, x, z in our case).

This is the function for the matrix multiplication:

```
?

private float[] matrixMultiplication(float[] A, float[] B) {
    float[] result = new float[9];

    result[0] = A[0] * B[0] + A[1] * B[3] + A[2] * B[6];
    result[1] = A[0] * B[1] + A[1] * B[4] + A[2] * B[7];
    result[2] = A[0] * B[2] + A[1] * B[5] + A[2] * B[8];

    result[3] = A[3] * B[0] + A[4] * B[3] + A[5] * B[6];
    result[4] = A[3] * B[1] + A[4] * B[4] + A[5] * B[7];
    result[5] = A[3] * B[2] + A[4] * B[5] + A[5] * B[8];

    result[6] = A[6] * B[0] + A[7] * B[3] + A[8] * B[6];
    result[7] = A[6] * B[1] + A[7] * B[4] + A[8] * B[7];
    result[8] = A[6] * B[2] + A[7] * B[5] + A[8] * B[8];

    return result;
}
```

Last but not least we can implement the complementary filter. To have more control over its output, we execute the filtering in a separate timed thread. The quality of the sensor signal strongly depends on the sampling frequency, that is, how often the filter method is called per

second. That's why we put all the calculations in a *TimerTask* and define later the time interval between each call.

```
class calculateFusedOrientationTask extends TimerTask {
    public void run() {
        float oneMinusCoeff = 1.0f - FILTER_COEFFICIENT;
        fusedOrientation[0] =
            FILTER_COEFFICIENT * gyroOrientation[0]
            + oneMinusCoeff * accMagOrientation[0];

        fusedOrientation[1] =
            FILTER_COEFFICIENT * gyroOrientation[1]
            + oneMinusCoeff * accMagOrientation[1];

        fusedOrientation[2] =
            FILTER_COEFFICIENT * gyroOrientation[2]
            + oneMinusCoeff * accMagOrientation[2];

        // overwrite gyro matrix and orientation with fused orientation
        // to comensate gyro drift
        gyroMatrix = getRotationMatrixFromOrientation(fusedOrientation);
        System.arraycopy(fusedOrientation, 0, gyroOrientation, 0, 3);
    }
}
```

If you've read the first part of the tutorial, this should look somehow familiar to you. However, there is one important modification. We overwrite the gyro based orientation and rotation matrix in each filter pass. This replaces the gyro orientation with the “improved” sensor data and eliminates the gyro drift.

Of course, the second important factor for the signal quality is the *FILTER_COEFFICIENT*. I've determined this value heuristically by rotating a 3D-model of my smartphone using the sensor from my actual device. A value of 0.98 with a sampling rate of 33Hz (this yields a time period of 30ms) worked quite well for me. You can increase the sampling rate to get a better time resolution, but then you have to adjust the *FILTER_COEFFICIENT* to improve the signal quality.

So these are the final additions to our sensor fusion code:

```
public static final int TIME_CONSTANT = 30;
public static final float FILTER_COEFFICIENT = 0.98f;
private Timer fuseTimer = new Timer();
public void onCreate(Bundle savedInstanceState) {

    // ...

    // wait for one second until gyroscope and magnetometer/accelerometer
    // data is initialised then scedule the complementary filter task
    fuseTimer.scheduleAtFixedRate(new calculateFusedOrientationTask(),
                                  1000, TIME_CONSTANT);
}
```

I hope this tutorial is a sufficient explanation on custom Android based sensor fusion. If you find any mistakes I've made or have any questions, don't hesitate, please let me know.