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Complementary Filter Application for Inertial Measurement Unit

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Abstract: In this work a digital filter application is made in order to combine accelerometer data and gyroscope data which are necessary for inertial measurement unit. Firstly both accelerometer and gyroscope data handled and the specifications of these data are revealed. Then acquiring the roll, pitch and yaw angles explained. After all of these work the necessitate of the accelerometer and gyroscope outputs are utilized. As a result a complementary filter design is decided in order to combine accelerometer and gyroscope data. The advantages and the structure of the complementary filter are handled deeply in the work. Also the results of the filter are available in the work.

Keywords: Inertial Measurement Unit, Complementary Filter.

Ataletsel Ölçüm Birimi için Tamamlayıcı Filtre Uygulaması

Özet: Bu çalışmada, ataletsel ölçümlerin yeterliliği için ivmeölçer ve jiroskop datalarının birleşimi ile elde edilen bilgilerin kullanıldığı bir dijital filtre uygulaması geliştirilmiştir. İlk olarak ivmeölçer ve jiroskop datalarının özellikleri ele alınarak açıklandı. Sonra hareket edinim, eğim ve sapma açıları açıkladı. Bu işlemlerden sonra elde edilen gerekli parametreler ivmeölçer ve jiroskopun çıkışına uygulandı. Sonuç olarak uygulanan filtreler bu ölçüm birimlerinin kombinasyonu ile karar verme işlemini gerçekleştirdi. Bu uygulama ile elde edilen veriler aynı zamanda örnek çalışmalarda denendi.

Anahtar Kelimeler: Ataletsel Ölçüm Birimi, Tamamlayıcı Filtre Uygulaması,

1. Introduction

Inertial measurement unit is a component which evaluates the accelerometer and gyroscope data in order to state linear and angular motions of rigid body. In the IMU an accelerometer handles the linear motions of the rigid body and gyroscope handles the angular motions of rigid body. Inertial measurement unit is generally used to maneuver vehicle including unmanned aerial vehicles, spacecraft, satellites, missiles and submarines [1]. An IMU also helps to GPS when GPS signal lack or poor. Inertial measurement unit is unique for autonomous systems. In order to realize inertial measurement unit a microcontroller is used and the algorithm is handled at high sampling frequency so the less complex calculation the more performance. During the realization of the IMU there are steps should be to care. Firstly accelerometer and gyroscope data should be acquired properly, then the data should passed through proper filter. So the processor should be as fast as realize these steps.

2. Theory

Micro-electromechanical sensor technology is developed in the last decade so the inertial measurement systems widely used in missiles, unmanned vehicles etc. Generally two sensors are used in the IMU these are accelerometer and gyroscope [2]. Gyroscopes for rotations and accelerometer is for linear accelerations. Through to accelerometers both gravity and acceleration generated by vehicle can be measured. For example gyroscopes are used to manage

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the direction of the autonomous vehicle and stabilization of the vehicle. Accelerometers is used for measuring gravity, seismic signals and vibrations.

2.1. Acquiring Accelerometer and Gyroscope Data

Inertial measurement unit realization starts with the acquiring the sensor data and tuning the data in order to use in the calculations. The tuning is named offset and scale operations.

- Offset operation is very easy. When the sensor is stable and horizontal a value different from zero is acquired. Offset operation is for compensation of the value acquired in horizontally stable position. If the value has oscillations then an average value can be taken inorder to compensation.

- Scale operation is depend on the sensor used. Scale is a coefficient that is used for acquiring the proper unit. This coefficient is gotten from sensor datasheet or by experiment. Widely named as sensor coefficient.

- The operations are formulized as below;

$$accelerometerdata = \left(\begin{array}{l} accelerometer_{ADC} \\ -accelerometer_{offset} \end{array}\right) * accelerometer_{scale} \tag{1}$$

$$gyroscopedata = \left(\begin{array}{l} gyroscope_{ADC} \\ -gyroscope_{offset} \end{array}\right) * gyroscope_{scale} \tag{2}$$

2.2. Gyroscopes

The basis of gyroscopical movement is based on saving angular momentum.

- Measures angular acceleration.
- Cannot measure linear acceleration.
- While stable the value acquired should be zero.
- The unit of the produced data is rad/sec.
- The integration of the produced data gives angle.
- Gyroscopes cannot measure the linear acceleration.
- Factor which effects the truth of the measurement is drift rate.

Drift is acquiring small value different from zero, like measuring any acceleration. when the gyroscope is stable. Angle calculation is made by integration of the gyroscope data so the angle will be completely wrong after a time. While the angle calculation is being done with gyroscope the drift rate should be compensated.

2.3. Accelerometers

- Accelerometers measures linear acceleration at x, y , z axis.
- Cannot measure angular acceleration
- Thanks to accelerometer roll (ϕ) and pitch (θ) angles can be calculated. These calculations are formulized below [3].

$$\phi = \arctan\left(\frac{y}{z} + \pi\right) * 57.295 \qquad (3)$$

$$\theta = \arctan\left(\frac{x}{z} + \pi\right) * 57.295 \qquad (4)$$

- Velocity in x and y axis are calculated by integration of the accelerometer data.

$$\dot{x} = \int_0^t \ddot{x}\,dt \qquad (5)$$

$$\dot{y} = \int_0^t \ddot{y}\,dt \qquad (6)$$

- Factor which effects the truth of the measurement is bias.
- Bias should be compensated by experiment or taking from sensor datasheet.
- Accelerometer measurement suffers from high frequency oscillations so proper filter should be designed for the output of accelerometer.

2.4. Complementary Filter

There are various sensor fusion algorithms in order to combine accelerometer and gyroscope data for inertial measurement unit. Also complementary filter can be designed for fusion of accelerometer and gyroscope data. As known accelerometer data suffer from high frequency vibrations and gyroscope data suffer from drift in time. The high frequency vibrations can be compensated by low pass filter and small drift can be compensated by high pass filter. Complementary Filter structure contains both high pass filter for gyroscope and low pass filter for accelerometer. The filter structure and specifications are explained below.

- Compensates drift and eliminates noise
- Angle calculation is fast and doesn't cause lag.
- Filter doesn't include heavy mathematical calculations so it doesn't effect microprocessor operation.

Complementary filter is theoretically more complex than basic filters, but more easy than Kalman Filter and can be used alternatively for Kalman Filter such applications [4].

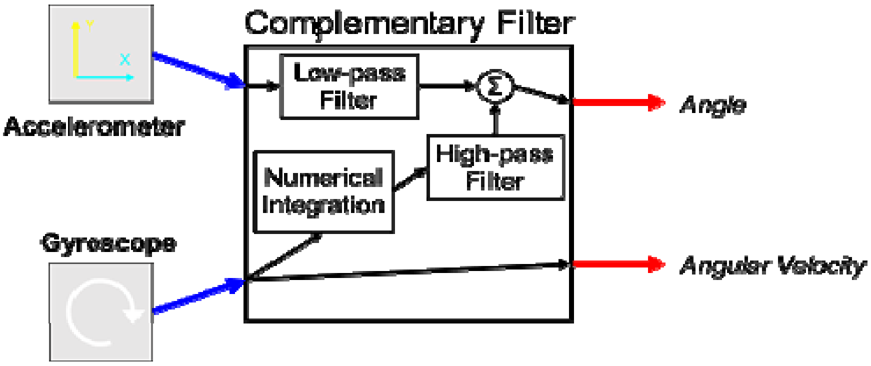

Fig. 1. Complementary Filter Structure

Numerical integration is similar to getting position from integration of velocity. Here the velocity is the gyroscope data and position is angle.

$$position = position + velocity * dt \tag{7}$$

$$angle = angle + gyroscopedata * dt \tag{8}$$

$$angle = \underbrace{a * \underbrace{(angle + gyroscopedata * dt)}_{numerical\ integration}}_{high\ pass\ filter} + \underbrace{((1 - a) * (accelerometer))}_{low\ pass\ filter} \tag{9}$$

Here a is the tuning parameter of the complementary filter and should be between 0-1. Because the total gravity low pass filter and high pass filter should be 1. For example a is tuned to 0.96 the high pass filter's gravity or gyroscope's angle calculation gravity will affect total angle calculation with 0.96 gravity and low pass filter or accelerometer will effect 1-0.096=0.04 gravity.

3. Conclusion

As seen Fig. 2. the gyroscope output suffers from the drift. Drift causes totaly wrong values in time. As known the angle calculation made by gyroscope is made by numerical integration. This mean even there is a small drift due to the numerical integration the angle calculation will totally be wrong in time.

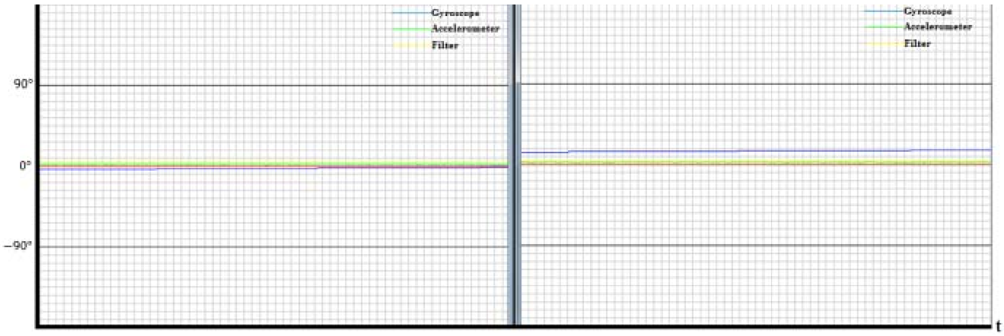

Fig. 2. Drift

As seen in the figure when the gyroscope and accelerometer at horizontal position and stable all the outputs should be zero. Accelerometer output and filter output measure the angle zero but at the beginning gyroscope measures also the angle zero and by the reason of drift in time the angle value goes far away from zero. In order to compensate these negativity belong to gyroscope a high pass filter should be designed for the output of gyroscope.

As mentioned before accelerometer can only measure linear accelerations and thanks to accelerations in x, y, z axis relative angles in x, y, z axis can be measured. Accelerometer also has a negativity about angle calculation. This negativity is that accelerometer can not distinguish linear accelerations and angular changes. Complementary filter eliminates this negativity and accelerometer distinguish the linear accelerations and angular changes.

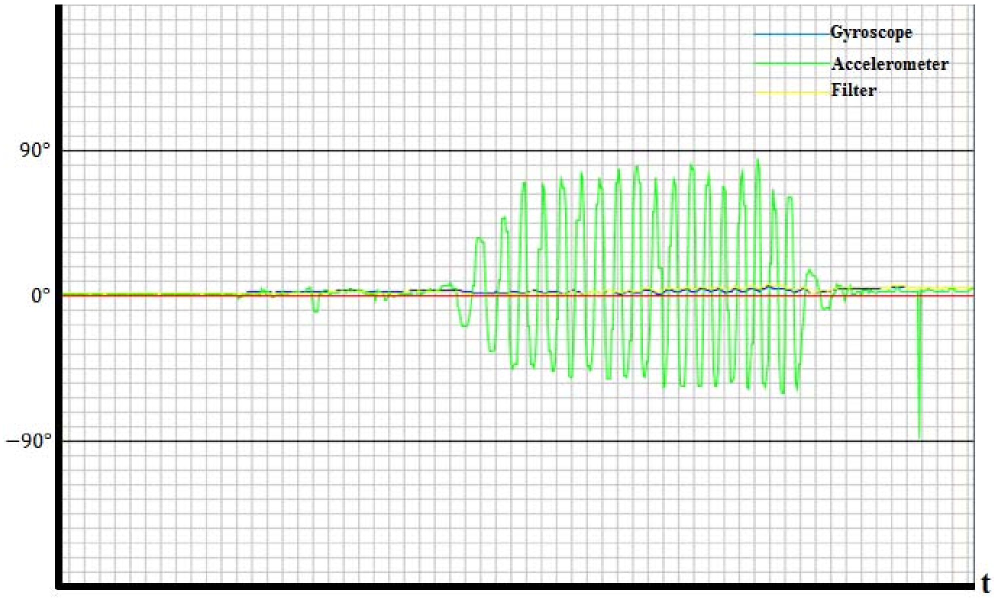

Fig. 3. Accelerometer Output Due to Linear Acceleration

As seen in Fig. 3. when accelerometer is horizontal, linear acceleration is applied like vibration. Despite there is not angular change, due to vibration in horizontal position accelerometer can not distinguish linear accelerations and cause angular change. As seen in figure gyroscope output and complementary filter output are not affected by the linear vibrations and they always measure the angle value zero.

Another negativity belong to accelerometer that accelerometer data suffer from high frequency angular oscillations.

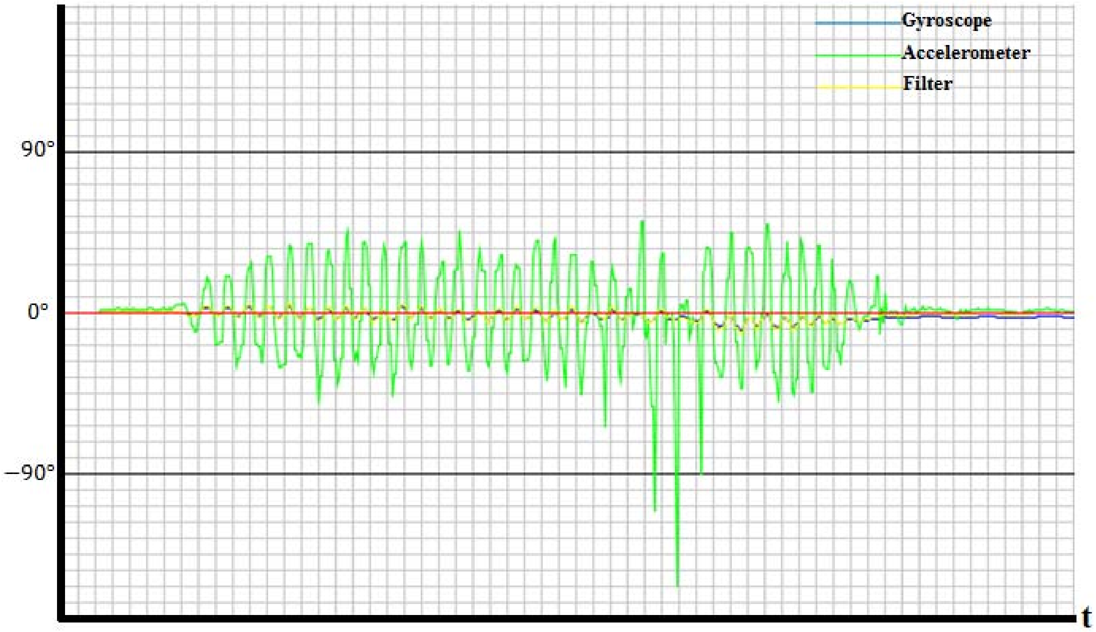

Fig. 4. Accelerometer Output Due to High Frequency Angular Oscillation

As seen in Fig. 4. High frequency angular oscillations are affecting the accelerometer data in order to compensate this negativity low pass filter is designed and high frequency oscillations are filtered.

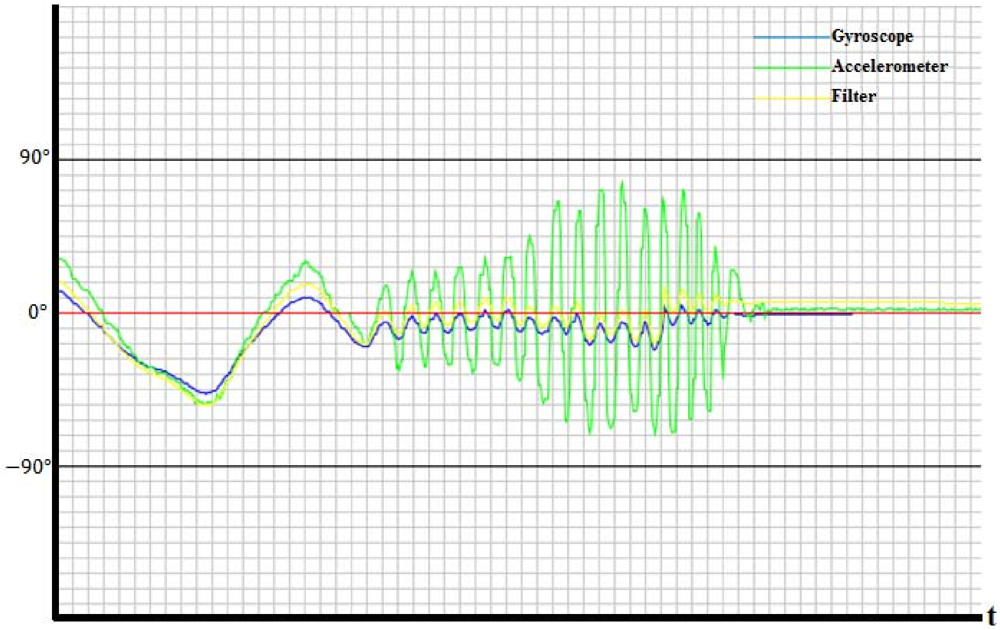

Fig. 5. Filter Output

If summarize, an inertial measurement unit comprise of basically one accelerometer for linear motions an done gyroscope for angular motions. The work is about how to get roll pitch and yaw angles efficiently. While getting these angles both accelerometer and gyroscope data are used. Gyroscope data suffer from drift and accelerometer data suffer from linear and angular oscillations. In order to compensate drift high pass filter designed and in order to compensate accelerometer output high pass filter designed. The complementary filter is combination of these filters by a tuning parameter explained before. As seen in fig. 5. Complementary filter is successful enough to compensate both accelerometer and gyroscope negativities. The filter is not affected by drift as seen in fig. 2. and also not affected by linear and angular vibrations as seen in fig. 5. Filter is as successful as gyroscope at measuring angle. Superior side of the filter is not affected by vibrations and drift.

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