Measurement of a Vehicle's Dynamic Motion

Combine Angular Rate Sensors with Accelerometers

When testing a vehicle, one often needs to measure the dynamic motions of the vehicle and angle of the vehicle relative to the road. Accelerometers let you measure the forces caused by turning, accelerating or braking, but the measurements won't be accurate unless the vehicle is level relative to the Earth during these maneuvers. If the vehicle tilts forward, for example, you'll get gravity components measured by the accelerometer you use to measure the braking force.

Most tilt sensors sense the direction of gravity as a reference direction. Gravity is a type of acceleration, which is a changing velocity. Braking, accelerating, and turning a vehicle produce accelerations on the vehicle. In a tilt measurement, you want to measure gravitational acceleration only. In a measurement of a vehicle's dynamics, you want to measure motional acceleration only.

A tilt sensor will give inaccurate angle measurements when subjected to motion acceleration. An accelerometer will give inaccurate acceleration measurements when the vehicle tilts.

Angular rate sensors can help correct for the effect of the forward tilt by measuring rotations around the center of gravity of the vehicle. Unfortunately, angular rate sensors have their own drawbacks. Angular rate sensors measure rotation rate, not rotation angle; the rotation angle is found by integrating the measured rotation rate over time. Error in the rotation rate will integrate in larger error over time. You can, however, combine acceleration measurements with angular rate measurements and produce accurate measurements of the dynamic motions of a vehicle. Each measurement technology can compensate for weaknesses in the other. With enough computational power, you can perform accurate measurements of acceleration and angles in real time.

To implement this, you will need to measure acceleration along three orthogonal axes, and rotations around these same axes. To measure the complete dynamic motion of a vehicle, we will instrument the vehicle with a 3-axis accelerometer aligned along the body, and three angular rate sensors aligned with the accelerometer axes. See figure 1. If possible, the sensors should be mounted at the vehicle center of gravity to minimize rotational accelerations affecting the accelerometer measurements.

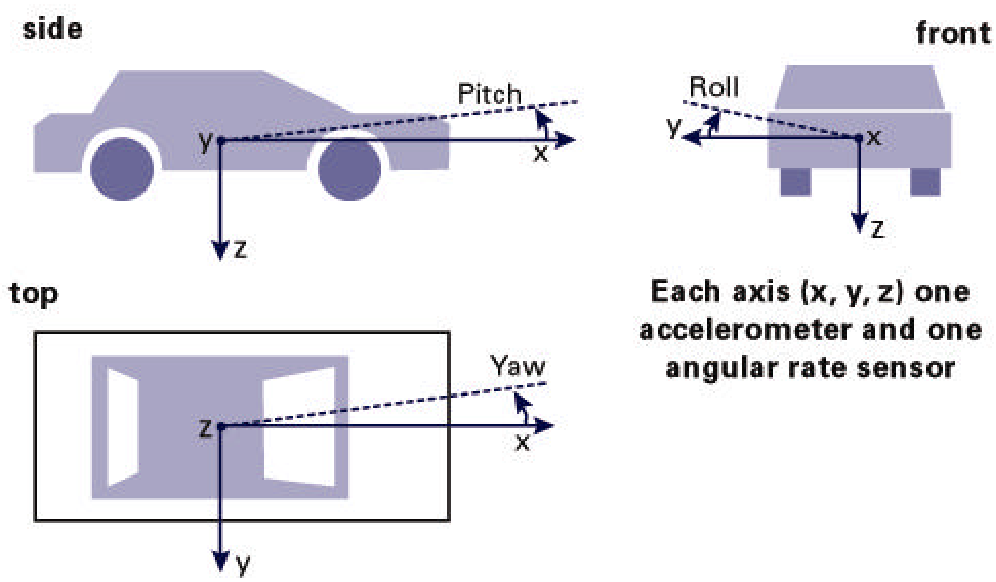

Figure 1. Sensor axes on vehicle

You can use angular rate sensors to measure the rate that a vehicle rotates around a given axis. If you integrate the rate over time, you'll get the angle as a function of time. For example, you can use angular rate sensors to track the vehicle's rotational motion around the x and y axes. You can then integrate the rotational information to calculate the vehicle's pitch and roll as a function of time. Using the calculated pitch and roll, you can subtract the gravity components produced by the tilt from the accelerometer data.

To calculate the actual pitch and roll angles, you must integrate the angular rate signals. As a result, an offset error in angular rate will produce an error in angle, which increases linearly with time. In addition, the random noise in the rate sensors will produce a random-walk effect in the calculated angle. The random walk causes the calculated angle to drift at a rate proportional to the square root of time, even in the absence of rate bias error. These effects will limit the usefulness of all but the most expensive angular rate sensors for measurements longer than a few minutes.

Fortunately, we can take advantage of the rate sensor's accuracy over short time periods and the accelerometer's stability over long time periods to produce angle calculations that are stable over both short and long times. Use the rate sensor to measure angle changes on short time scales. Use the accelerometer like a tilt sensor to calculate the tilt angles, and force the rate sensor derived angles to slowly match the accelerometer angles over a long time scale.

To perform these measurements, you need sensors, data-acquisition equipment, and computational power. Use a 3-axis accelerometer and 3-axis angular-rate sensors. You need 3-axis sensors to measure the complete motion of your vehicle, no matter its orientation. You can also add a temperature sensor and use the data to compensate for temperature effects in the accelerometer and rate sensor outputs. You should then digitize the sensor outputs and feed them to a processor or data logger.

Should you want to perform the calculations after acquiring the data, you can use a PC. If, however, you'd like real-time results you need a digital signal processor (DSP) as part of your data-acquisition equipment. You can then send the calculated angle data, the calculated angles, and the corrected accelerations and rate information to a computer over a digital link. If you send a binary data packet, you should be able to achieve a data transfer rate of over 200 Hz with a serial RS-232 line at 38.4K baud. This will be significantly faster than the bandwidth of the angular rate sensors.

Place the sensors as close to the vehicle center of motion as possible. Otherwise, rotational motions will cause the accelerometers to measure centrifugal accelerations. Remember, you use the accelerometers to measure the linear accelerations of the center of gravity of the vehicle. You should minimize coupling the rotational motion into the accelerometer measurements.

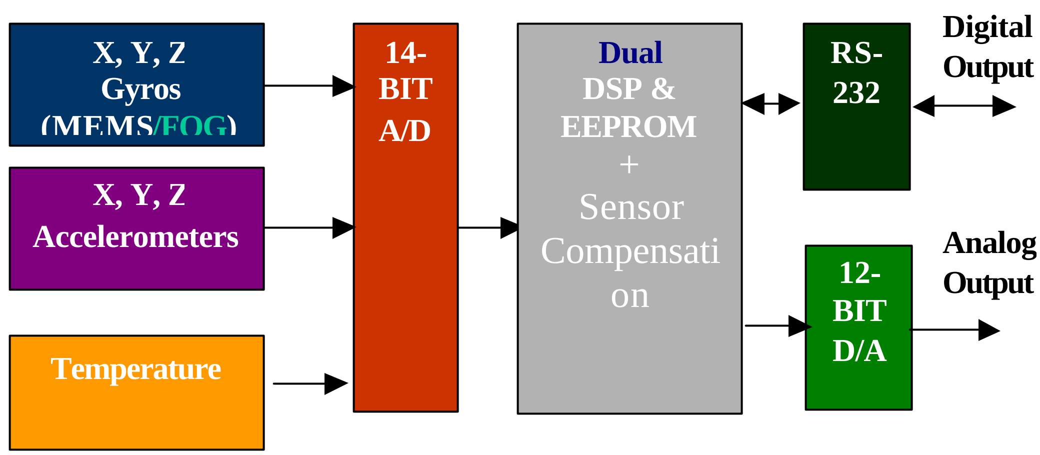

Figure 2. Hardware Configuration

Figure 3 shows the algorithm for one axis. Integrate the rate sensor output in real time to find a raw angle. Use the accelerometer to measure the direction of gravity and infer a tilt angle. For example, if you measure 0.1 G acceleration in the x-axis, this implies a tilt of arcsine (0.1) = 5.7°. To avoid vibration and shock from producing a false indication of the gravitational tilt angle, use a low pass filter with a cutoff of 100 Hz or less. The filter can be as simple as a single-pole RC filter.

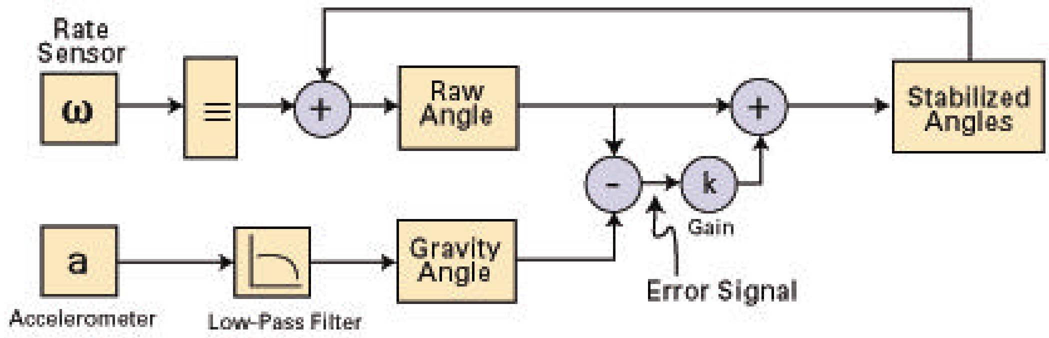

Figure 3. Stabilized Angle Calculation.

Calculate the difference between the two angles. That difference is your error signal that you can use to correct the angle calculation. I've defined a gain parameter, k, that controls how much of the error signal you use to correct the rate sensor angles. Finally, sum the raw angle from the rate sensor with the error signal. The output of this process is a calculated angle, dominated on short time scales by the rate sensor information, but corrected on long time scales by the accelerometer data. The time scale is set by the value of k.

The gain parameter k is similar to the erection rate in an analog vertical gyro. The value of k sets the time constant at which the rate sensor angle calculation is stabilized by the gravity angle calculation. You should choose a time constant that is longer than your expected maneuvers in testing. Take this value and divide by your measurement rate. This is the value for k to use. For example, if you want a time constant of 5 seconds, and you are measuring your accelerometers and rate sensors at 200 Hz, then you would use a value of 5/200 = 0.025 for k.

Once you have stabilized tilt angles, you can use these data to correct your raw accelerometer data, which will let you find the true acceleration along all axes. Remember, if you are tilted, some of gravity's acceleration will be measured on your x and y accelerometer axes. One way to do this is to create a rotation matrix, using the measured pitch and roll, that will rotate the measured acceleration vector (x, y and z axis measurements aligned with the vehicle) to the equivalent vector level with respect to earth. In the level system, gravity is completely vertical, so the level x and y axes measure pure motional acceleration, not gravity.

The end result is a complete description of the motion of your vehicle, including angular rates; stabilized tilt angles; and corrected linear accelerations. The system described can be implemented in real time using solid state sensors. This makes for a reliable, inexpensive system for vehicle motion testing.