2.4.1 Inertial Measurement Unit (IMU)

The IMU is a single unit in the electronics module which collects angular velocity and linear acceleration data which is sent to the main processor. The IMU housing actually contains two separate sensors. The first sensor is the accelerometer triad. It generates three analog signals describing the accelerations along each of its axes produced by, and acting on the vehicle. Due to thruster system and physical limitations, the most significant of these sensed accelerations is caused by gravity. The second sensor is the angular rate sensor triad. It also outputs three analog signals. These signals describe the vehicle angular rate about each of the sensor axes. Even though the IMU is not located at the vehicle center of mass, the angular rate measurements are not effected by linear or angular accelerations. The data from these sensors is collected by the IMU 6811 microprocessor through a 12 bit ADC board. The sensor information is then returned to the main processor via a RS422 serial communications interface at a rate of about 200 Hz.
The accelerometer triad, and angular rate sensors within the IMU are mounted such that their sensor coordinate axes are not aligned with those of the vehicle. This is due to the fact that the two sensors in the IMU are mounted in two different orientations in the housing, along with the fact that the axes of the IMU are not aligned with the vehicle axes.
The Figure 2-15 shows two pictures of the IMU, and depicts the direction of the axes of each of the two sensors each with respect to the IMU housing.

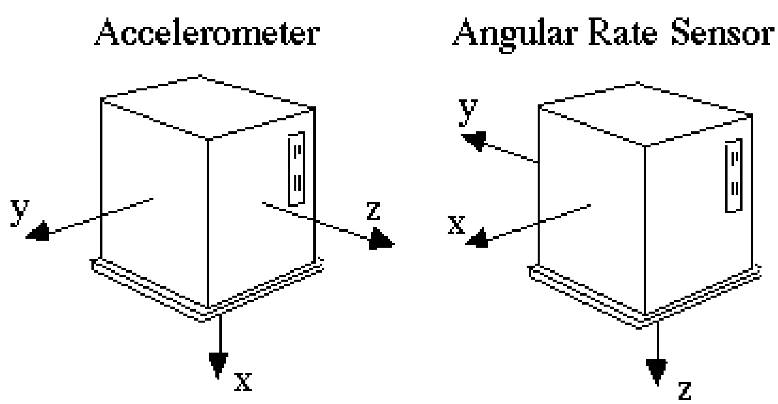

Figure 2-15 Initial IMU sensor coordinate axes

The accelerometer triad was manufactured using a left handed coordinate system. The transformation algorithm first uses (2.1) to align the coordinate axes of the two sensors.

$$\begin{aligned} x_{comp} &= -x \\ y_{comp} &= y \\ z_{comp} &= z \\ \omega_{x_{comp}} &= -\omega_z \\ \omega_{y_{comp}} &= \omega_x \\ \omega_{z_{comp}} &= -\omega_y \end{aligned} \tag{2.1}$$

These simple transformations align the axes of the two sensors so that they appear axes then appear as shown in Figure 2-16.

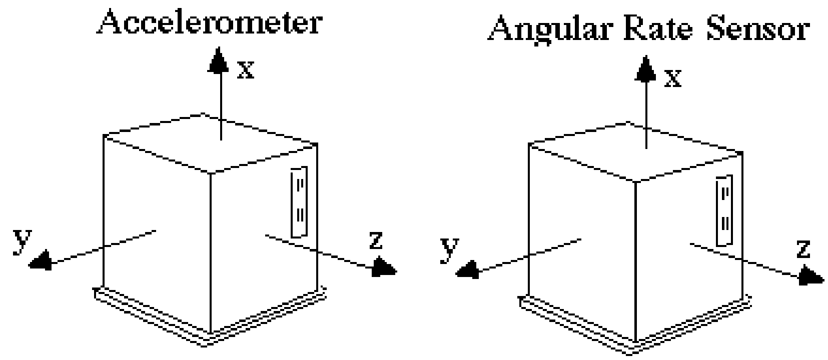

Figure 2-16 Transformed IMU sensor coordinate axes

Notice that the coordinate systems are now aligned and right handed.
Once the sensor axes are aligned with the axes of the IMU, they must be aligned with the vehicle reference frame. The unit is mounted on the wall of the electronics module, and is also rotated 45° with respect to the horizontal. The wall of the electronics module is also angled inward at

$$\tan^{-1}\left(\frac{4}{30}\right) = 7.59 \pm .04^{\circ} = 0.1325 \pm .0007(\text{Radians})$$

from the vehicle axes. This was calculated by using the fact that over the 30 inches from the back to the front of the electronics module the sides move inward 4 inches.
Using this information, along with knowledge of the orientation with which the IMU is mounted to the wall of the EM allows the formation of a direction cosine matrix that is used to convert the measurements from the IMU coordinate frame to the vehicle coordinate frame. Figure 2-17 illustrates the orientation with which the IMU is mounted in the electronics module.

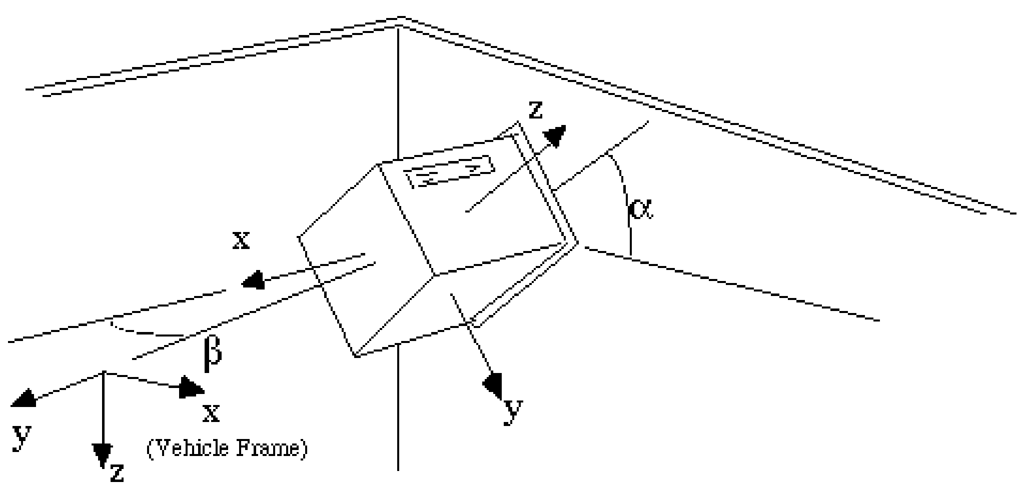

Figure 2-17 Transformed IMU coordinate axes compared to vehicle coordinate axes

Following is the order of transformations:
1) Rotate alpha + 90° about the x-axis to align the IMU z-axis with the Vehicle z-axis.

$$\mathbf{T}_1 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \tag{2.2}$$

2) Rotate beta + 90° about the z-axis to align IMU and vehicle coordinate frames.

$$\mathbf{T}_2 = \begin{bmatrix} \cos\beta & -\sin\beta & 0 \\ \sin\beta & \cos\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.3}$$

So the complete transformation from IMU to vehicle coordinates is given by

$$\mathbf{T} = \mathbf{T}_2\mathbf{T}_1 \tag{2.4}$$

$$\mathbf{T} = \begin{bmatrix} -\sin\beta & \cos\beta\sin\alpha & \cos\alpha\cos\beta \\ \cos\beta & \sin\alpha\sin\beta & \cos\alpha\sin\beta \\ 0 & \cos\alpha & -\sin\alpha \end{bmatrix}. \tag{2.5}$$

Inserting numerical values for the angles ([alpha] = 45°, [beta] = 7.5946°), produces:

$$\mathbf{T} = \begin{bmatrix} -0.132162 & 0.700904 & 0.700904 \\ 0.991228 & 0.0934528 & 0.0934528 \\ 0 & 0.707107 & -0.707107 \end{bmatrix} \tag{2.6}$$

In order to transform the sensor data from the individual sensor frames into the vehicle frame, first use the simple sign/axis transformations shown in (2.1), then pre-multiply the modified sensor data by the transformation matrix given in (2.6). It would also be possible to combine the initial transformations from (2.1) into the transformation in (2.6), however since the initial axes are different for each of the two sensors in the IMU, there would be a different transformation matrix for each sensor. In interest of simplicity, the software first aligns the sensor axes using (2.1), and then uses the transformation matrix from (2.6) to transform the data of the accelerometer and angular rate sensors from IMU to vehicle coordinates.