IMU Attitude Estimation

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***Abstract*—In this project attitudes are estimated for a given IMU dataset. The orientations are found using three methods: from only accelerometer measurements, from only gyroscope measurements, and through a complementary filter. The resulting estimates are plotted and compared against the ground truth data from Vicon motion capture system.**

I. Introduction

The aim of the project is to implement three methods to estimate the three dimensional orientation/attitude from the data collected from a six degree of freedom Inertial Measurement Unit (6-DoF IMU) sensor i.e., readings from a 3-axis gyroscope and a 3-axis accelerometer. The raw acceleration measurements are corrected and converted to SI units using the bias and scale parameters given. The gyroscope bias is estimated from the average of the initial gyroscope readings and is then used to convert the raw sensor data to SI units. Then attitudes need to be estimated from only accelerometer data, only gyroscope data, and a complementary filter. The estimates from only gyroscope suffer from drift due to error accumulation overtime as a result of numerical integration. Accelerometer estimates are affected by vibration and other external forces that causes translation. To get better estimates a complementary filter is implemented that combines both of the above estimates. All the results are then compared with the ground truth data from Vicon motion capture system.

II. IMU and Vicon data pre-processing

In this section the raw sensor data from accelerometer and gyroscope are converted into physical values with corresponding SI units.

A. Accelerometer

From the IMU data the first three values in each measurement represent the accelerometer readings given as $\mathbf{a} = [a_x, a_y, a_z]^T$. To convert them to SI units (m/s^2) the following equation is used:

$$\tilde{a_i} = (a_i * s_i + b_{i,a}) * 9.81 \tag{1}$$

Here i is the sample number of the data, s_i is the scale for each axis, and $b_{i,a}$ is the accelerometer bias for each axis.

B. Gyroscope

From the IMU data the last three values in each measurement represent the gyroscope readings and are given as $\boldsymbol{\omega} = [\omega_z, \omega_x, \omega_y]^T$. To convert them to SI units (rad/s) the following equation is used:

$$\tilde{\omega_i} = \frac{3300}{1023} \times \frac{\pi}{180} \times 0.3 \times (\omega - b_{i,g}) \tag{2}$$

Here $b_{i,g}$ is the gyroscope bias for each axis and is obtained by taking the average of the first 200 readings of the gyroscope.

$$b_{i,g} = \frac{1}{200} \sum_{k=1}^{200} \omega_k \tag{3}$$

C. Vicon data

The Vicon capture system measured the rotation matrix at every instance. The ZYX Rotation matrix is converted to roll, pitch, and yaw angles to for comparing them with the estimates. Consider a single instance of ZYX rotation matrix R as shown below:

$$R = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \tag{4}$$

The Euler angles are then obtained as:

$$roll(\phi) = \arctan \frac{r_{32}}{r_{33}} \tag{5}$$

$$pitch(\theta) = \arctan \frac{-r_{31}}{\sqrt{r_{32}^2 + r_{33}^2}} \tag{6}$$

$$yaw(\psi) = \arctan \frac{r_{21}}{r_{11}} \tag{7}$$

III. Attitude from accelerometer

Attitude estimates from the accelerometer are obtained from the projection of the acceleration vector with onto the IMU body axis which are known from the gravity vector that is pointing downwards (-Z direction). The angles are given by the following formulas:

$$roll(\phi) = \arctan \frac{a_y}{\sqrt{a_x^2 + a_z^2}} \tag{8}$$

$$pitch(\theta) = \arctan \frac{-a_x}{\sqrt{a_y^2 + a_z^2}} \tag{9}$$

The estimates of yaw from this method are not perfect due to symmetrical nature of Z-axis with gravity vector. But since IMU is not perfectly vertical we can estimate yaw from the following formula:

$$yaw(\psi) = \arctan \frac{\sqrt{a_x^2 + a_y^2}}{a_z} \tag{10}$$

IV. ATTITUDE FROM GYROSCOPE

From the gyroscope we get the body angular velocities and the attitude estimates are obtained through the numerical integration. Before doing the integration the body angular velocities are converted to Euler angle rates. At every time step during the numerical integration the conversion is done using the following formula:

$$\begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix}_{t_i} = \begin{pmatrix} 1 & \sin\phi \tan\theta & \cos\phi \tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi / \cos\theta & \cos\phi / \cos\theta \end{pmatrix}_{t_i} \times \begin{pmatrix} \omega_x \\ \omega_y \\ \omega_z \end{pmatrix}_{t_i} \tag{11}$$

The Euler rates obtained from the above equation at every time step are then used find the attitude estimates for the next time step through the discrete numerical integration step shown below:

$$\begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix}_{t_{i+1}} = \begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix}_{t_i} + \begin{pmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix}_{t_i} \times (t_{i+1} - t_i) \tag{12}$$

During the integration for the initial step the initial value of the estimate is obtained by taking the average of the first 200 estimates from the Vicon ground truth attitude as shown below:

$$\begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix}_{t_0} = \frac{1}{200} \sum_{k=1}^{200} x_{vicon} \tag{13}$$

V. ATTITUDE USING COMPLEMENTARY FILTER

The attitude estimates from accelerometer and the gyroscope each have complementary issues. The accelerometer estimates are prone to noise and the gyroscope estimates suffer from drift in the long term. These two estimates are combined using low and high pass filters respectively to reduce the error from individual estimates. First the raw sensor data obtained from the accelerometer is sent through a low pass filter by using the following equation to get new sensor values by combining the present sensor value with previous value:

$$\hat{a_{t+1}} = (1-n) \times a_{t+1} + n \times \hat{a_t} \tag{14}$$

And similarly the sensor data of gyroscope is sent through high pass filter using the following equation:

$$\hat{\omega_{t+1}} = (1-n)\hat{\omega_t} + (1-n)(\omega_{t+1} - \omega_t) \tag{15}$$

Here n is taken as 0.8 and the variable $\hat{x}$ represents filtered value. Then the filtered values are used to obtain the orientation estimates which are fused using the following equation to get the new estimates:

$$\begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix}_{comp} = \begin{pmatrix} 1-\alpha & 0 & 0 \\ 0 & 1-\beta & 0 \\ 0 & 0 & 1-\gamma \end{pmatrix} \times \begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix}_{gyro} + \begin{pmatrix} \alpha & 0 & 0 \\ 0 & \beta & 0 \\ 0 & 0 & \gamma \end{pmatrix} \times \begin{pmatrix} \phi \\ \theta \\ \psi \end{pmatrix}_{acc} \tag{16}$$

Here the parameters α, β, and γ are chosen to be $0.8, 0.8$, and 0.9 respectively.

VI. RESULTS

The resulting plots for the training data is shown in figures 1, 2, 3, 4, 5, and 6 below.

VII. CONCLUSION

After looking at the plots for different training data it can be seen that the individual estimates from the gyroscope suffer with drift in the long term due to the numerical integration. The estimates from accelerometer are prone to noises and sudden movements. The complementary filter reduces the error from the sensors to some extent. The performance of the all the filters are better for roll and pitch compared to yaw. The link for the 'rotplot' videos are here: link1, link2. Due to time constraint only two videos were made for first and second training data.

REFERENCES

[1] Nitin J. Sanket, *Orienation Tracking based Panorama Stitching using Unscented Kalman Filter*.

[2] Beard, R.W. (2008). Quadrotor Dynamics and Control Rev 0.1.

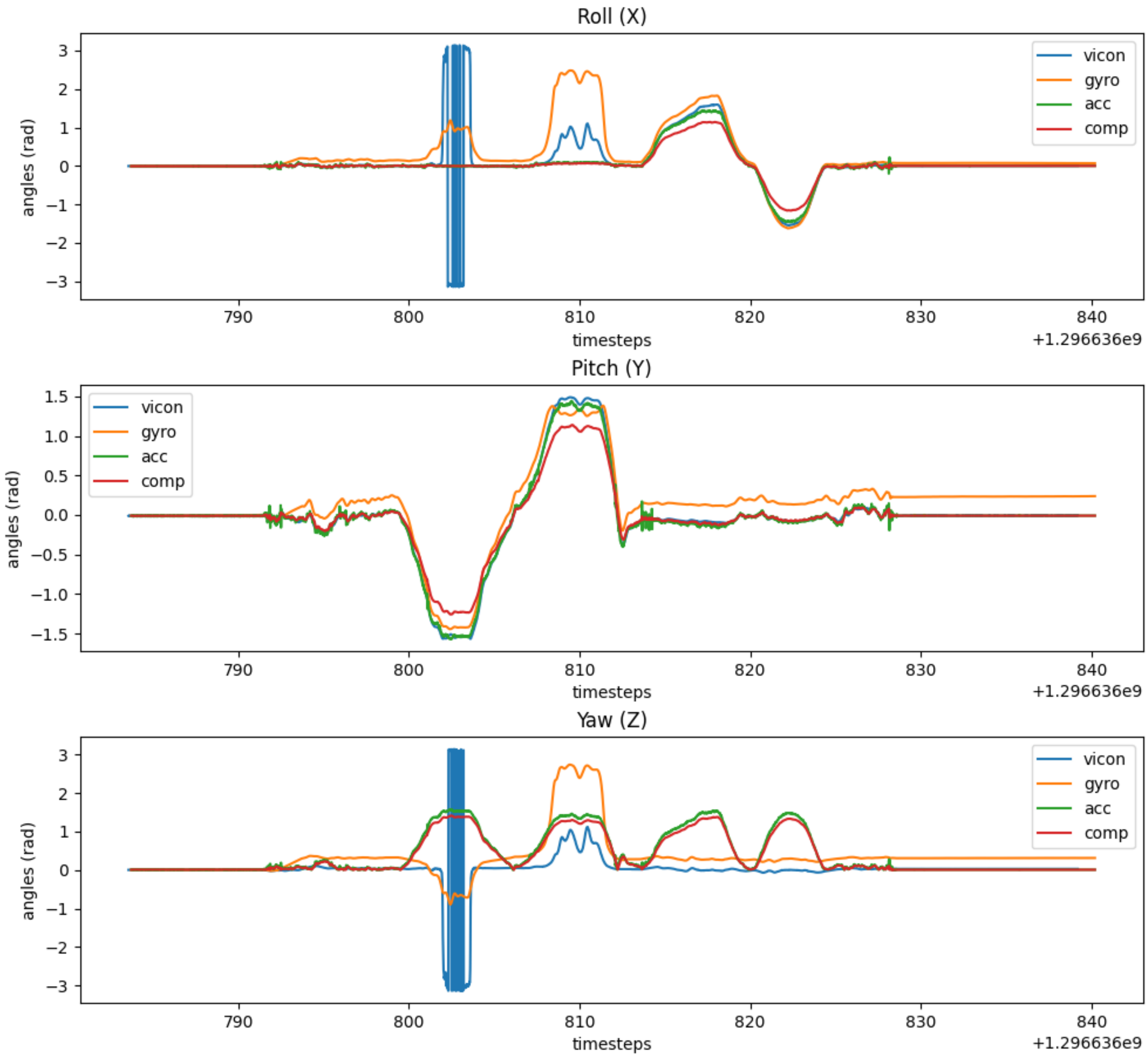

Fig. 1. Euler angle plots for test data 1.

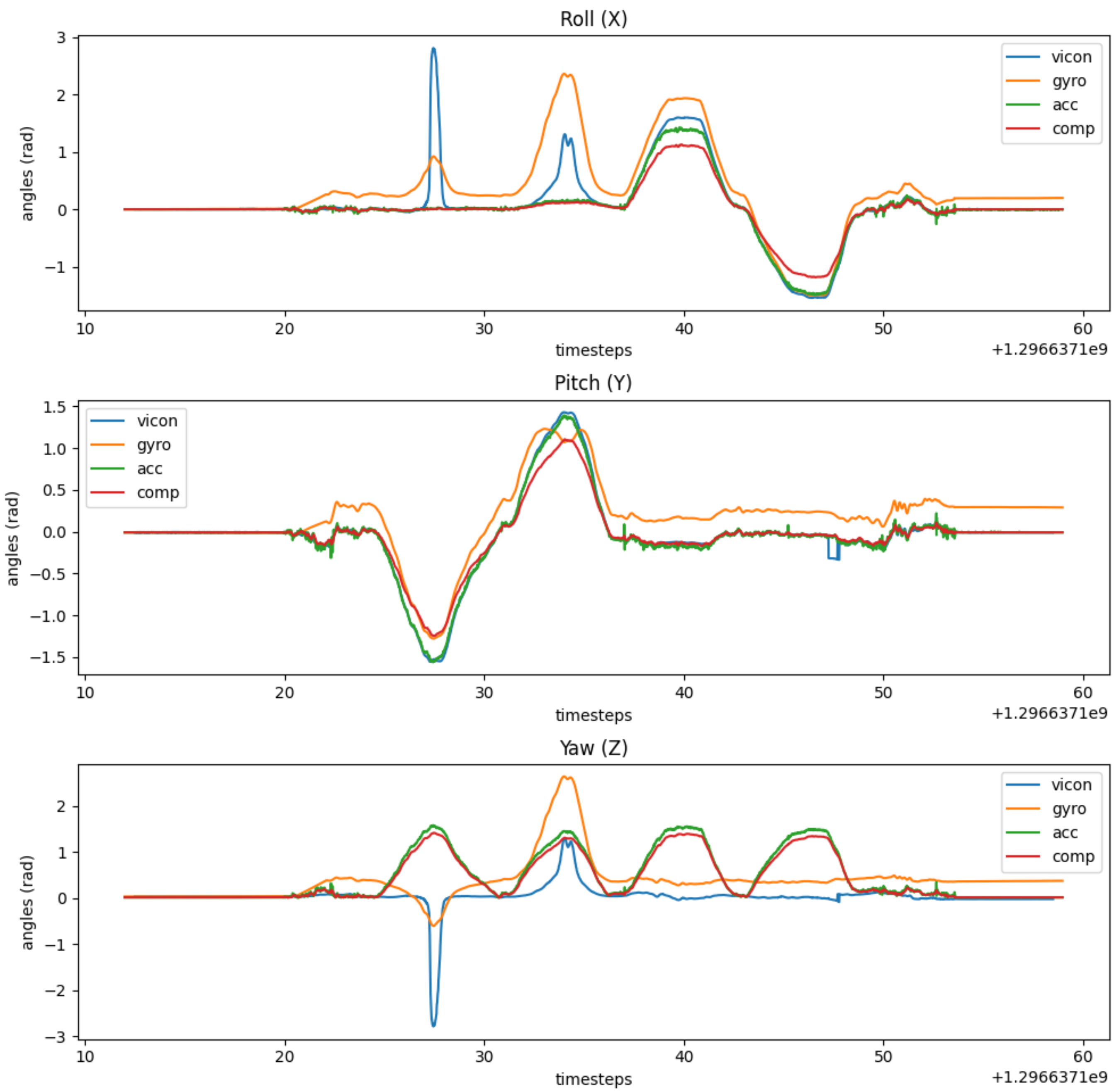

Fig. 2. Euler angle plots for test data 2.

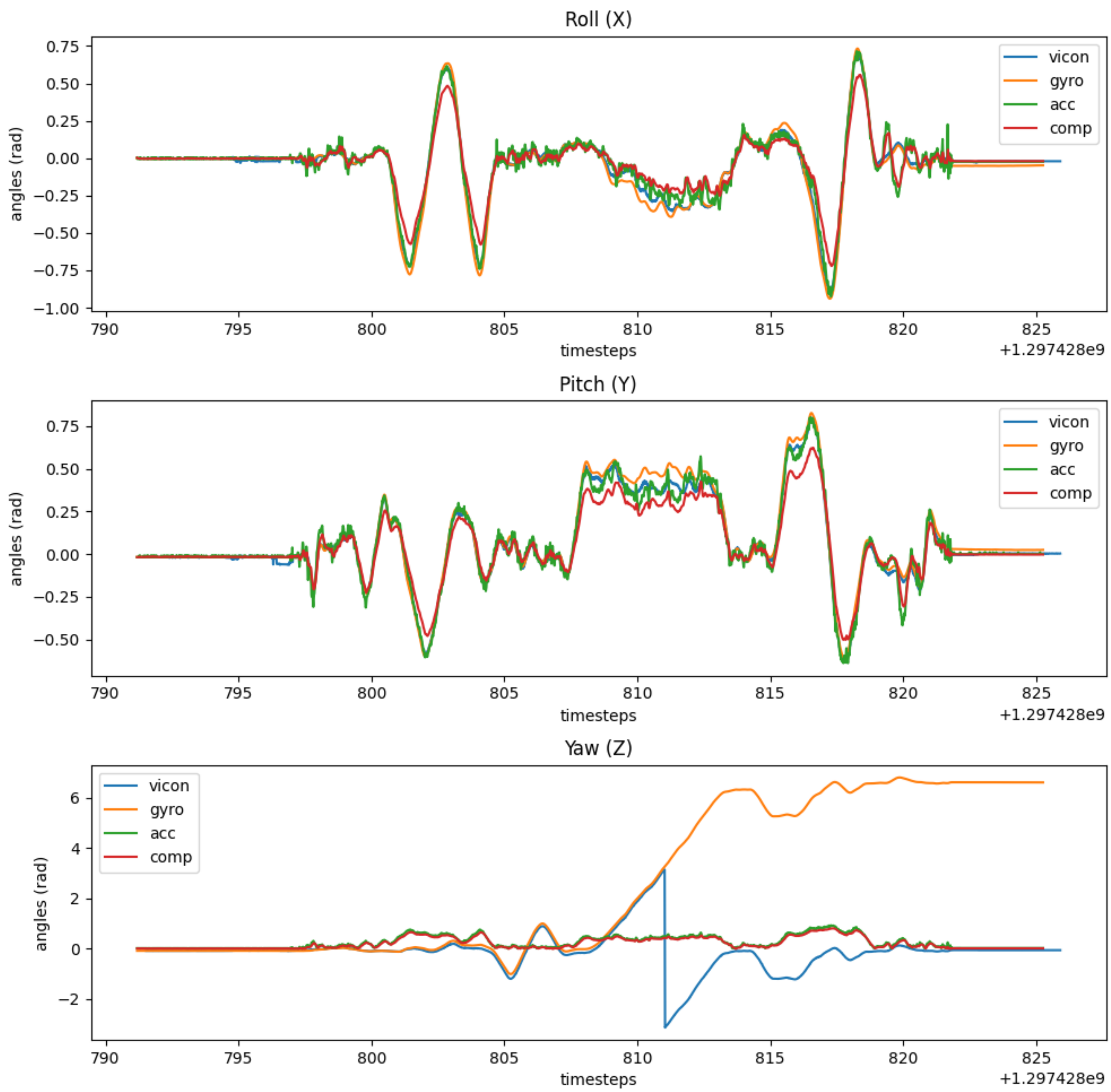

Fig. 3. Euler angle plots for test data 3.

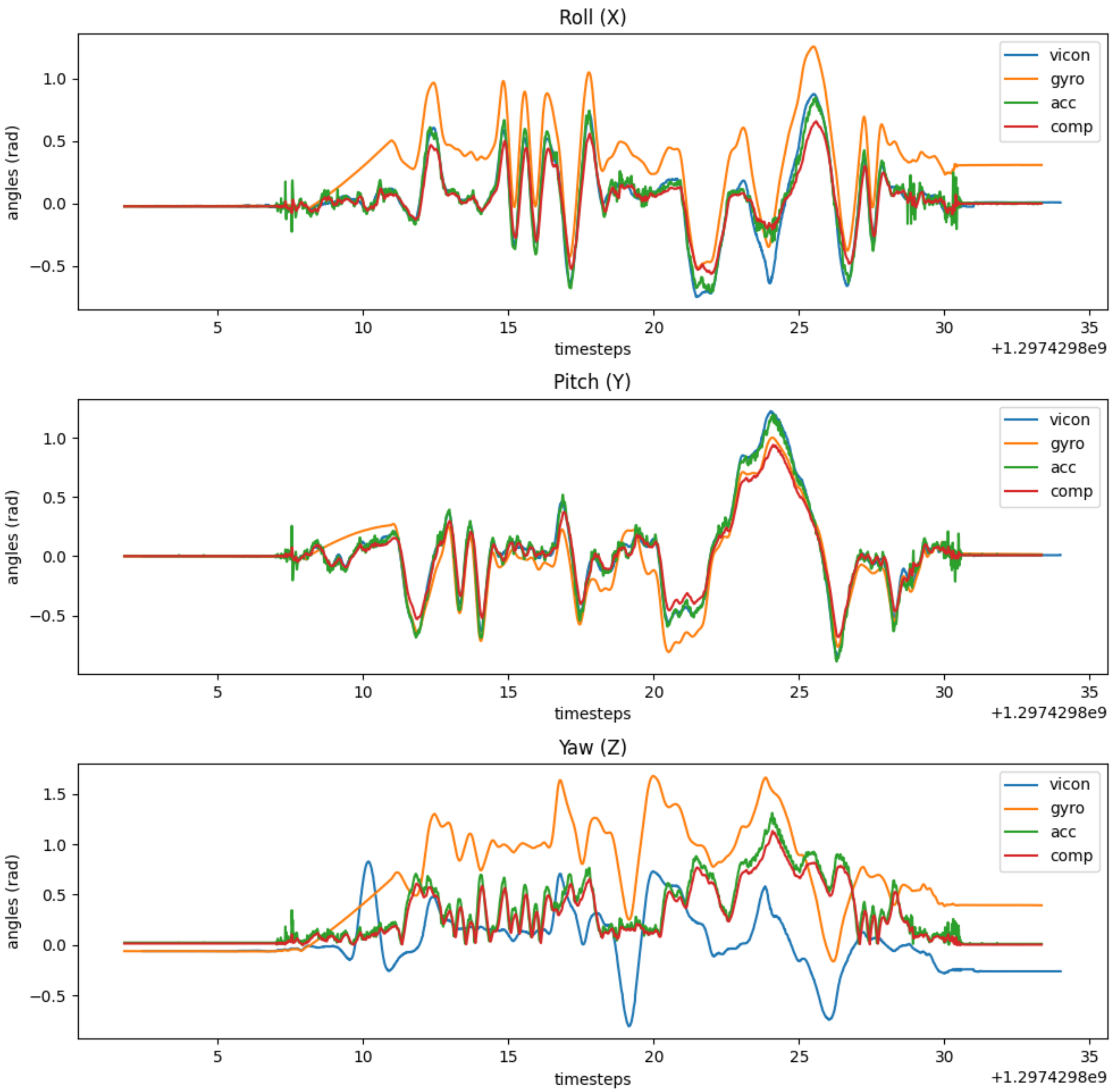

Fig. 4. Euler angle plots for test data 4.

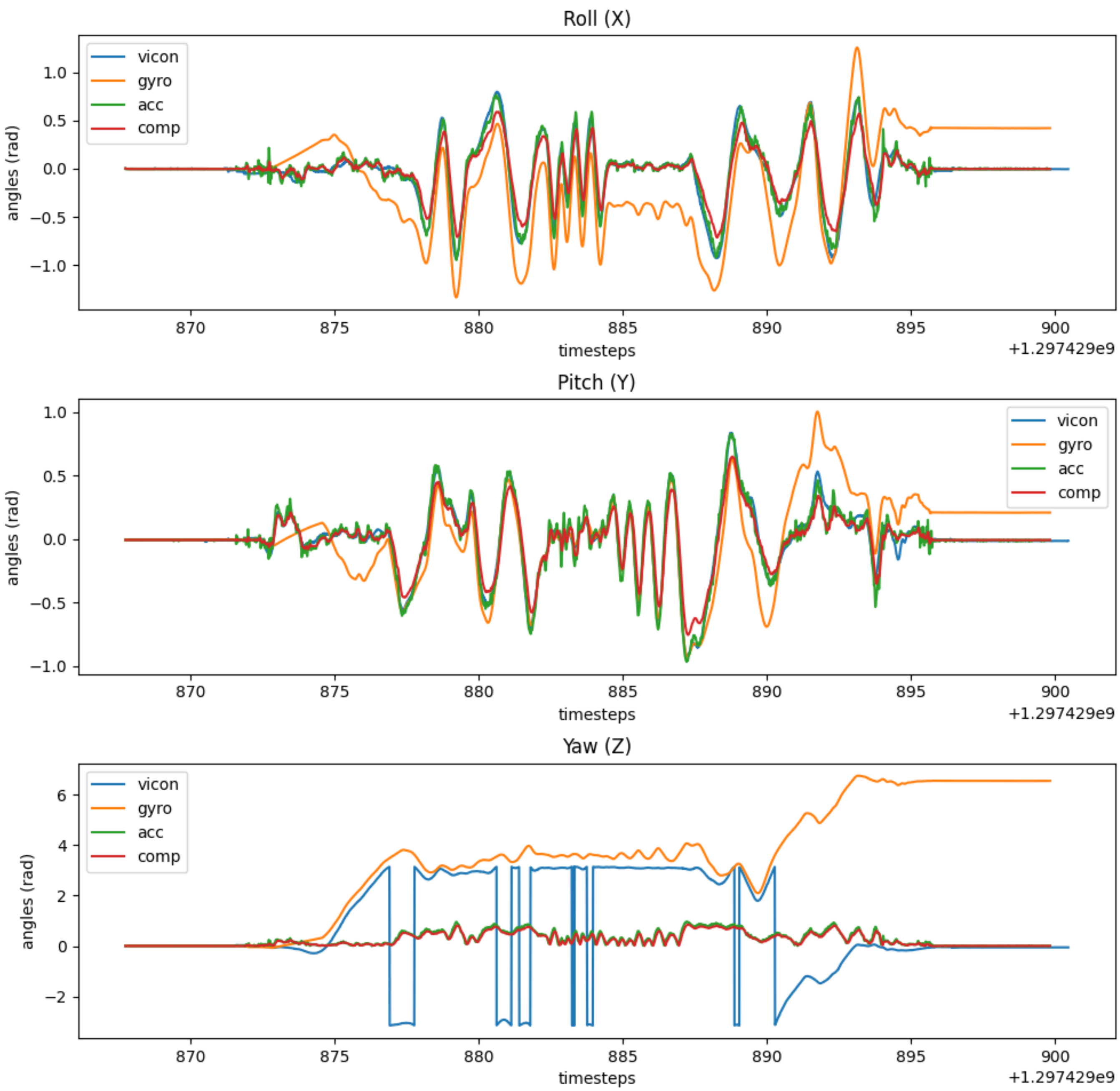

Fig. 5. Euler angle plots for test data 5.

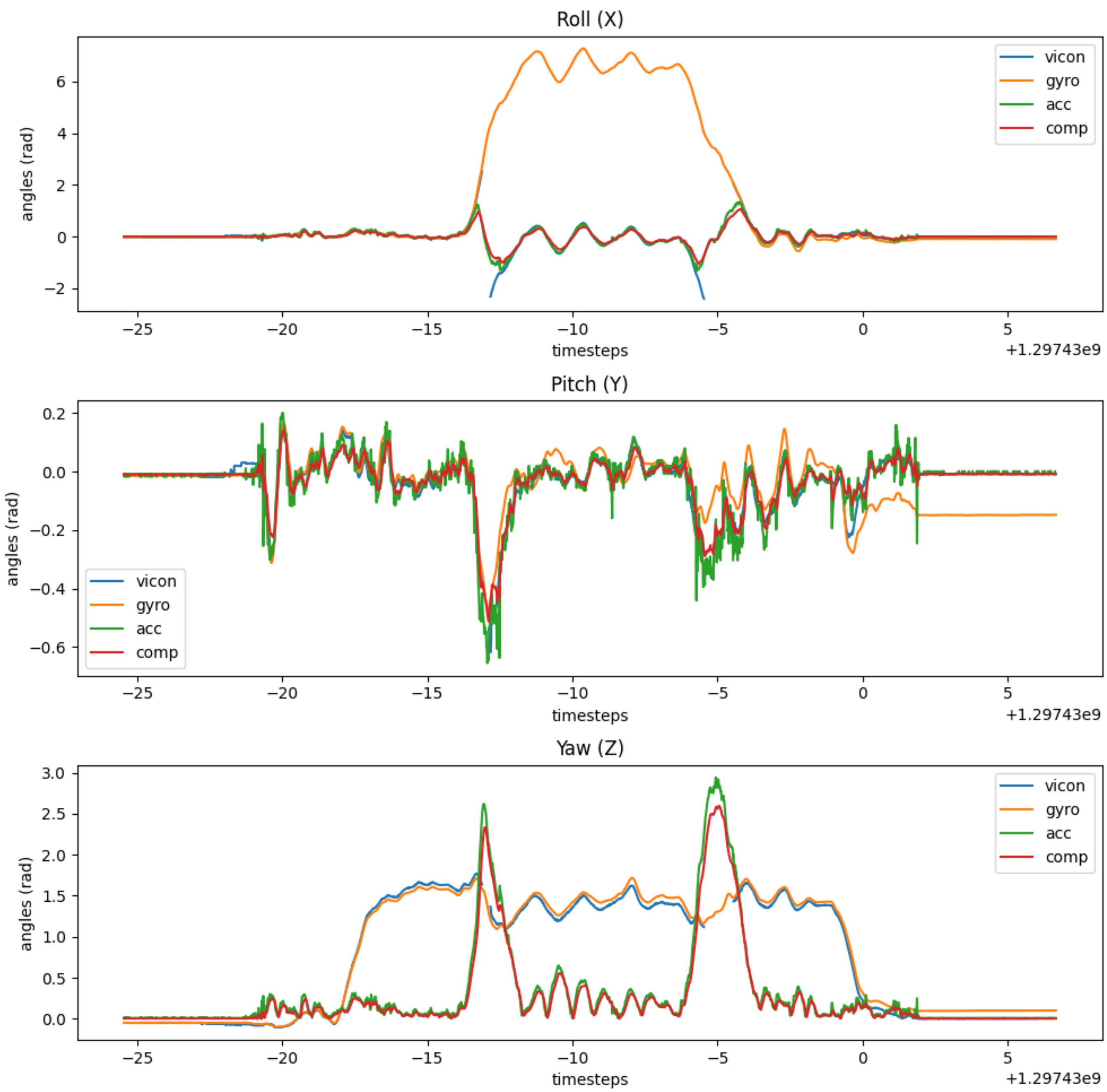

Fig. 6. Euler angle plots for test data 6.