Attitude Estimation by Compensating Gravity Direction

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Abstract— In attitude estimation, accelerometer signals are generally used to reset integration of angular rate signals. However, linear acceleration of the object causes the measurement of gravity direction by accelerometers distorted drastically. This paper presents the attitude estimation system for the humanoid robot CREST Θ where the accelerometer outputs were used to correct quaternion integration errors.

Key Words: Attitude Estimation, Inertial Navigation System

1. Introduction

A sensor system with gyros and accelerometers is generally used for attitude estimation. Angular velocity signals can be integrated to yield orientation while accelerometers can provide gravity direction. However, gyro signals are uncertain. Integration results in unreliable estimates. In contrast, accelerometer signals need not be integrated since they provide direct values of tilt angles. Unfortunately, outputs of accelerometers are the compound of gravity and acceleration of the object when accelerated. Therefore the inclination information is not correct. There have been many methods proposed during the past ten years. In [1], the data were fused simply by a low-pass and a high-pass filter. The Kalman filter is employed in many works [2]-[5]. In all mentioned works, accelerometer outputs were used regardless of the effect of acceleration. This would not give good results for high maneuver systems such as humanoid robots. This paper presents the attitude estimation system for the humanoid robot CREST Θ. The accelerometer outputs were used to correct integration error based on its reliability at each instant.

2. Description of the Sensor System

The sensor system as shown in Fig[1] consists of two bi-axial gyroscopes placed perpendicularly to measure angular rates in three orthogonal axes and a tri-axial accelerometer. Sensor signals are converted to digital signals and processed by a small programmable board before being sent to the main computer of the robot through a serial port. This enables ultra high speed data transmission without loading the main computer.

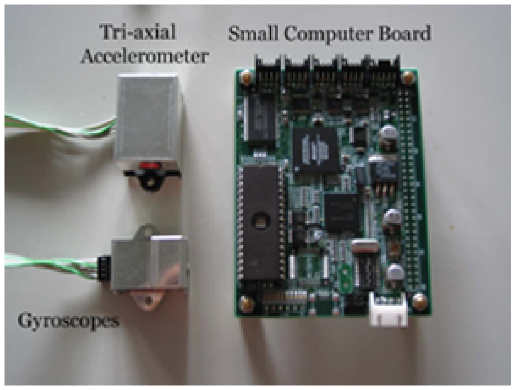

Fig.1 Sensor and Processing Board

3. Attitude Calculation

3·1 Quaternion representation

Although the euler-angle representation gives more visualization of object orientation than does the quaternion representation, it has the singularity problem at some orientations. To avoid the problem, the quaternion representation should be used in estimation step. Euler angles can be constructed whenever needed after the rotation matrix has been established. Rotation of a rigid body around a unit vector $\vec{K} = [k_x, k_{,y}, k_z]$ for angle θ can be represented by a quaternion vector defined by

$$\vec{q} = [s, \vec{v}]; \tag{1}$$

where $|\vec{q}| = 1$ and
$s{=}cos(\frac{\theta}{2})$ $v_x{=}k_x sin(\frac{\theta}{2})$ $v_y{=}k_y sin(\frac{\theta}{2})$ $v_z{=}k_z sin(\frac{\theta}{2})$

A corresponding rotation matrix can be computed by

$$\begin{bmatrix} s^2+v_x^2-v_y^2-v_z^2 & 2(v_xv_y-v_zs) & 2(v_xv_z+v_ys) \\ 2(v_xv_y+v_zs) & s^2+v_y^2-v_x^2-v_z^2 & 2(v_yv_z-v_xs) \\ 2(v_xv_z-v_ys) & 2(v_yv_z+v_xs) & s^2+v_z^2-v_y^2-v_x^2 \end{bmatrix} \tag{2}$$

The first derivative of quaternion is related to angular velocity with respect to body frames $\vec{\omega}^b$ by

$$\dot{\vec{q}} = \frac{1}{2}\vec{q} \oplus \vec{\omega}^b = \frac{1}{2}\begin{bmatrix} -\vec{v}^T\vec{\omega}^b \\ s\vec{\omega}^b + \vec{v}\times\vec{\omega}^b \end{bmatrix} \tag{3}$$

3·2 Algorithm

Estimation is performed by the following steps.

1. When the robot is not in motion, use the accelerometer outputs to calculate the initial quaternion $\vec{q}_{s,0}$. The quaternion at time step i is designated by $\vec{q}_{s,i}$. Subscript s denotes *sensor* coordinates.
2. Transform the accelerometer outputs from sensor coordinates s to world coordinates w.

$$^{w}\vec{a}_i = {}^{w}_{s}R_i {}^{s}\vec{a}_i \tag{4}$$

3. Calculate the correction angular velocity $\Delta\vec{\omega}_i$.

$$\Delta\vec{\omega}_i = \frac{^{w}\vec{a}_i \times {}^{w}\vec{g}}{\|^{w}\vec{g}\|^2} \tag{5}$$

4. Calculate the quaternion rate.

$$\dot{\vec{q}}_{s,i} = \frac{1}{2}\vec{q}_{s,i} \oplus (\vec{\omega}^{s}_{i} + {}^{w}_{s}R^{T}_{i} K \Delta\vec{\omega}_i) \tag{6}$$

The correction gain K is defined as a function of $\|^{s}\vec{a}_i\|$ in order to compensate for reliability of the predicted gravity direction.
5. Update the quaternion vector

$$\vec{q}_{s,i+1} = \vec{q}_{s,i} + \dot{\vec{q}}_{s,i} * T_s \tag{7}$$

Where T_s is the sampling time.
6. Unitize the quaternion vector.

$$\vec{q}_{s,i+1} = \vec{q}_{s,i+1}/\|\vec{q}_{s,i+1}\| \tag{8}$$

7. Repeat from step 2.

4. Experimental results

To investigate the effect of gravity direction compensation, sensor signals were sampled over a period of time when the robot was stationary. The estimation of x-axis euler angle with/without gravity direction compensation is shown in Figure [2]. It can be seen that without the compensation the estimates unacceptably diverged.

Another experiment was conducted to examine effectiveness of the algorithm. To analyse quantitatively, a turn table was used. The turn table is driven with a 36000-step-per-round-precision stepping motor so that its posititon and speed can be controlled precisely. The initial position of the sensor units was -60 deg. After a period of time, the turn table rotated with angular rate of 30 deg/sec in positive direction to +60 deg pos. and stoped for a while and rotated again at the same speed to +180 deg pos. before it proceeded the same pattern of rotation in negative direction to the original position of -60 deg. The results are shown in Fig[3]. Unlike the stationary case, both results seemed to track the rotation neatly. The drift problem was not severe in this case because the object was continuously moving. This could let the error be canceled over in some levels. However, since the error in integration will accumulate, long term stability can not be achieved without error correction. There was a significant error between estimated values and those indicated by the turn table. This is due to misalignment of the sensors. In addition, that the support of the turn table is not perfectly horizontal could amplify the misalignment errors.

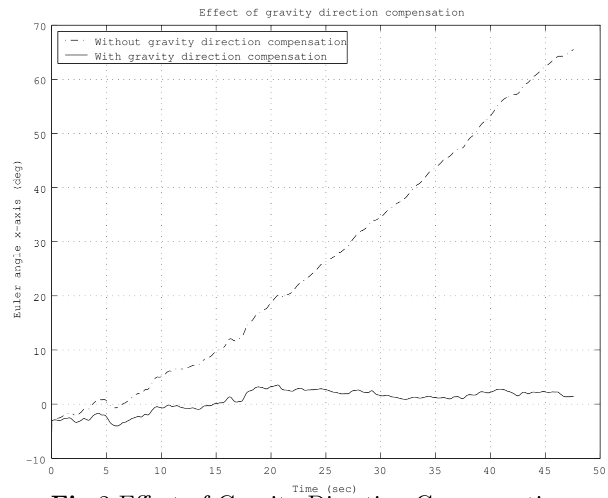

Fig.2 Effect of Gravity Direction Compensation

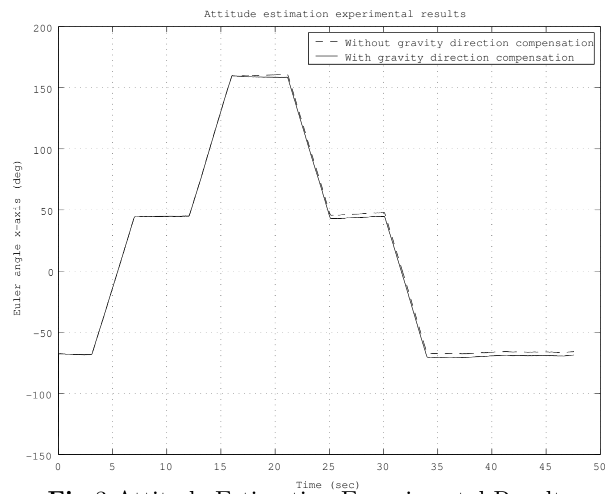

Fig.3 Attitude Estimation Experimental Results

5. Conclusions

In this paper, the attitude estimation system for the humanoid robot CREST Θ is described. The concept of gravity direction compensation was employed to reset the integration error.

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