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A novel method of attitude measurement for floated inertial platform using optical sensors

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ABSTRACT

This paper presents a novel method to measure the attitude of the vehicle navigated by the floated inertial platform. Due to the non-contact characteristic between the sphere and the shell, eight optical sensors are mounted in the suspension pads and used to measure the rotation of the shell relative to the static sphere. The measurement is the arc derived from the rotational shell sweeping over the optical sensor. During a single rotation of the shell, a quarternion is formed by the rotational axis and angle derived from the outputs of the optical sensors. Based on this quarternion, iterating the recursion formula of the quarternion can calculate the quarternion from the initial moment to the arbitrary moment, which is used to compute the attitude angles of the shell according to the specified rotation sequence. Based on this method, a corresponding approach is proposed to identify the real measurement coordinate frame of the optical sensor. The simulation results denote that the actual measurement coordinate frame can be identified with high accuracy and faster maneuvers produce faster convergence of the estimate. The availability and precision of this attitude measurement method are demonstrated in the cases of the shell rotating in a simple sequence and a complex one.

1. Introduction

The floated inertial platform [1,2] is a new inertial navigation platform used as the navigation system of aerial, land or submarine vehicle. Thus, this platform can measure the position, velocity and attitude of the vehicle. For example, the Advanced Inertial Reference Sphere (AIRS) [3] is the third-generation floated inertial platform, which is applied to MX missile. This platform, as shown in Fig. 1, is composed of the sphere, the shell and the fluid. The shell consists of two semispherical shells and an insulated ring (Fig. 2) and contains the sphere and the fluid filling the space between the sphere and shell. These semispherical shells are utilized to supply DC power to the sphere, and the insulated ring is used to seal the fluid and prevent the semispherical shells, as the electrodes of the DC power, to touch each other.

The sphere is supported in the shell omnidirectionally by the hydrostatic supporting system [4,5] and it is separated with the shell by the fluid film between the suspension pad and the shell. The sphere remains stable in the inertial space under the control of the torquers [6]. Thus, it is used to construct the navigation coordinate frame. The acceleration of the vehicle in this navigation frame can be directly measured by the accelerometers installed in the sphere. The shell is fixed in the vehicle and rotates with the vehicle. Thus, the attitude of the vehicle is calculated by measuring the shell rotation relative to the sphere. More details about the structure and working principle of the floated inertial platform can be found in Refs. [4,5].

The attitude measurement of the vehicle is emphasized in this paper. Since the shell is fixed in the vehicle, the attitude of the vehicle can be expressed by the pitch, yaw and roll angles of the shell relative to the sphere stabilized in the inertial space.

At present, the attitude of the vehicle is measured by some inertial sensors which usually consist of 3-axis gyroscopes. The theory of the attitude measurement using gyroscopes is clear, available and proven in practice. Generally, the 3-axis gyroscopes and 3-axis accelerometers constitute an inertial navigation system, which can measure the attitude, position and velocity. Based on the installation of the inertial sensors, the inertial navigation system is usually classified as strapdown and platform. For the strapdown inertial navigation system, the attitude can be calculated by integrating the quarternion or direction cosine matrix with the output of the gyroscopes [7,8]. However, there are some common defects impacting the accuracy of the attitude estimation, such as error accumulation, vehicle vibration, etc.

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Nomenclature

$\mathbf{P_i}$	origin of the measurement coordinate frame
α	azimuth angle of the point $\mathbf{P_i}$ in the sphere coordinate frame
β	elevation angle of the point $\mathbf{P_i}$ in the sphere coordinate frame
r	distance from the center $\mathbf{C}$ of the sphere to the point $\mathbf{P_i}$
$M_X(\cdot)$	rotation matrix around X axis
$M_Z(\cdot)$	rotation matrix around Z axis
$\boldsymbol{M_{C2PTi}}$	transfer matrix from the sphere coordinate frame to the transfer coordinate frame
$\boldsymbol{M_{PT2PEi}}$	transfer matrix from the transfer coordinate frame to the measurement coordinate frame
$\boldsymbol{M_{C2PEi}}$	transfer matrix from the sphere coordinate frame to the measurement coordinate frame
$\boldsymbol{\eta_c^n}$	rotating axis of the shell in the sphere coordinate frame from $n-1$ to n
ϕ^n	rotating angle of the shell from $n-1$ to n
$(P_iEX_i^n, P_iEY_i^n)$	measured value of the optical sensor at moment n
$l_i^{\Delta n}$	length of the measured arc
$\boldsymbol{v_i^n}$	linear velocity of the rotating shell
$\boldsymbol{v_{ci}^n}$	linear velocity of the rotating shell in the sphere coordinate frame
$\boldsymbol{\omega_c^n}$	angular velocity of the rotating shell in the sphere coordinate frame
$\boldsymbol{R_{c0i}}$	vector from the center $\mathbf{C}$ of the sphere to the origin $\boldsymbol{P_i}$
$\boldsymbol{\zeta_c^n}$	measuring noise
Δt	measurement period
R_i^n	radius of the measured arc
q_{shell}^n, q_{shell}^{n-1-n}	rotation quarternion of the shell during the time from $n-1$ to n
q_{shell}^{0-n}	rotation quarternion of the shell during the time from 0 to n
$\boldsymbol{\eta_s^n}$	rotating axis of the shell in the shell coordinate frame from $n-1$ to n
α	azimuth angle of the origin of the measurement coordinate frame
β	elevation angle of the origin of the measurement coordinate frame
γ	deflection angle of the origin of the measurement coordinate frame
$X_{1i}, X_{2i}, \cdots, X_{6i}$	new estimated parameters
φ, $\dot{\varphi}$	angle and angular speed of the inner gimbal
θ, $\dot{\theta}$	angle and angular speed of the middle gimbal
ψ, $\dot{\psi}$	angle and angular speed of the outer gimbal
σ	standard deviation of the Gauss distribution

Subscript

i	number of the optical sensor

Superscript

n	moment

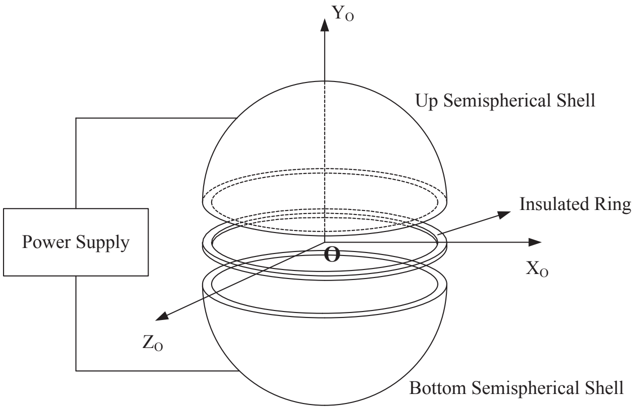

Fig. 2. Schematic diagram of shell.

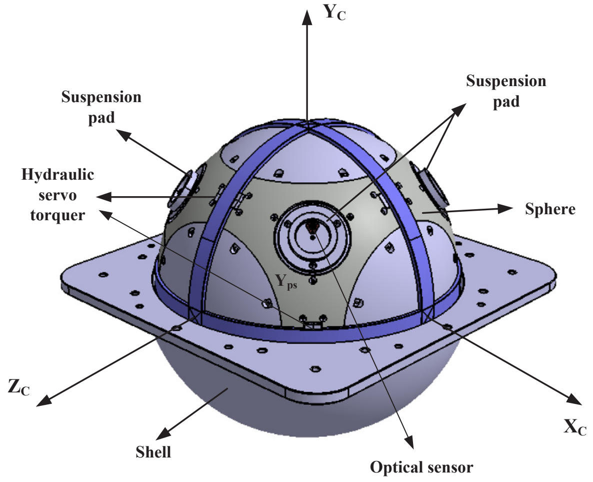

Fig. 1. Geometrical configuration of floated inertial platform.

In order to improve the accuracy, many researchers proposed the method integrating other sensors, such as magnetometer, vision sensor, Global Positioning System (GPS), etc. Kiani [9] extended a hyper least square (HyperLS) to ellipsoid fitting with different variances along the sensitive axes of any 3D-field sensor, like Three-axis magnetometers (TAMs), accelerometers, etc. The TAMs of a LEO maneuvering spacecraft, calibrated by this strict ellipsoid, are utilized for real time attitude determination via nonlinear colored noise filters of extended Kalman filter, simplex unscented Kalman filter (SUKF) and cubature Kalman filter. In [10], a miniaturized and cost-effective Inertial Measurement Units (IMU) and a True Air Speed (TAS) sensor are utilized to construct a sensor fusion configuration. The fusion of TAS sensor suppresses the time growing error of the gyroscope so that the aircraft attitude estimation is more accurate. In [11] and [12], the position and attitude of the target spacecraft relative to the chief spacecraft are determined using the extended Kalman filter (EKF) to fuse the measurements of the vision sensors and IMU. In addition, there are many literatures investigating the integration of gyros and the GPS. Crassidis [13] derived a sigma-point Kalman filter for integrating the GPS measurements with the inertial measurements from the gyros to determine the attitude of a moving vehicle. The performance was better than a standard extended Kalman filter approach. Literature [14] presents a novel approach of employing an extended Kalman Filter (EKF) to fuse the measurements of a GPS receiver and a three-axis accelerometer to estimate the vehicle attitude and the installation angles of sensor unit with respect to the vehicle. This method releases the requirement of known the road tilt angle, which compensates for different installation angles. To improve the accuracy of the yaw angle estimation, Wu [15] proposed a cascaded Kalman filter to deal with the yaw angle separated with the aid of the GPS-measured course angle. The above publications mainly present the approach of the vehicle attitude estimation with gyros integrating other sensors. The key idea of these approaches is the modified Kalman filter technique [16–20] applied for fusing the measurements of the gyros