Applications of Inertial Navigation Systems in Medical Engineering

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ABSTRACT

Inertial navigation systems are of the most important and practical systems in determining the velocity, position and attitude of the vehicles and different equipment. In these systems, three accelerometers and three gyroscopes are used to measure linear accelerations and angular velocities of vehicles, respectively. By using the output of these sensors and special inertial algorithms in different frames, parameters of vehicle such as position, velocity and attitude can be calculated. These systems are used in medical equipment including, but not limited to MRI devices, intelligent patient beds, surgical robots and angiography equipment. In this paper, inertial navigation systems, inertial sensors such as accelerometers, gyroscopes and inertial navigation algorithm are introduced. Afterwards, different applicable samples of inertial navigation system in medical equipment are described. According to the study carried out in this paper, it is presented and proved that applying inertial navigation in medical equipment is granted with precise and fast positioning as well as attitude determination. Moreover, as this technique of utilizing inertial navigation is applied to medical devices, a high efficiency system in terms of specifying the position and attitude will be achieved.

Keywords

Inertial Navigation System, Position, Velocity, Roll, Pitch, Yaw, Accelerometer, Gyroscope

Introduction

Nowadays, inertial navigation systems are widely used in industrial, military, commercial, agricultural and in particular medical engineering applications. The position, velocity and attitude of medical equipment can be achieved using inertial navigation systems. This inertial navigation system can be applied to medical devices and equipment such as advanced surgical robots, intelligent patient beds, MRI devices, CT scan and angiography device, to name a few. Accordingly, the subject of applying inertial navigation system (INS) in medical engineering equipment and related devices is widely considered.

In this paper, at first inertial navigation systems are introduced and then the attitude of device, Euler angles and inertial sensors will be studied. The discussion of inertial navigation algorithm and its specific relationships are proposed in the next section. Then, the applications of inertial navigation systems in medical engineering and a few examples of these applications are described.

The inertial navigation systems and strap down technology have been investigated extensively in [1]. Applications of inertial navigation systems have been mentioned in aerospace industries. For instance, the topic of guidance and control of the guided missiles is studied in [2].

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Applications of inertial navigation systems have been examined in the fields of robotics, vehicles, transportation, intelligent and automatic devices [3-6]. The use of inertial navigation systems in medical engineering and associated equipment is rapidly spreading. For example, designing and manufacturing an automatic wheelchair based on inertial navigation systems for disabled people (who are only able to move their heads has been investigated in [7], where disabled people can choose the direction to go by moving their heads.

In References [8] and [9], the issue of designing inertial navigation systems has been investigated in order to analyze the movement of people for the purpose of medical and rehabilitation problem diagnosis.

Introduction to Inertial Navigation System

Inertial navigation systems are of the most important methods to determine the position, velocity and attitude of vehicles and equipment. Newton's laws are the basis of inertial navigation systems. By measuring the accelerations of devices and taking its integration, the device velocity is obtained. Also, by double integration of these acclerations, the position of device will be calculated. In these systems, various sensors are used among them accelerometers and gyroscopes are the most well-known. The accelerometers and gyroscopes are used to measure linear accelerations and angular velocities of moving devices, respectively. Each device has six degrees of freedom in space, in which three degrees are along three coordinate axes and the other three degrees are around coordinate axes. Therefore, in order to complete the inertial navigation systems, three accelerometers and three gyroscopes are required. Afterwards, by using algorithm and navigation equations and according to the values of linear accelerations and measured angular velocities, the position, velocity and attitude of the device can be calculated.

Introduction to Attitude and Euler Angles

The purpose of determining the device attitude in the inertial navigation is calculation of Euler angles including pitch, yaw and roll angles. Figure 1 shows an endoscope device. Body coordinate system including x, y and z axes are connected to the device (camera of endoscope) and Euler angles including pitch (θ), yaw (ψ) and roll (Φ) angles are shown.

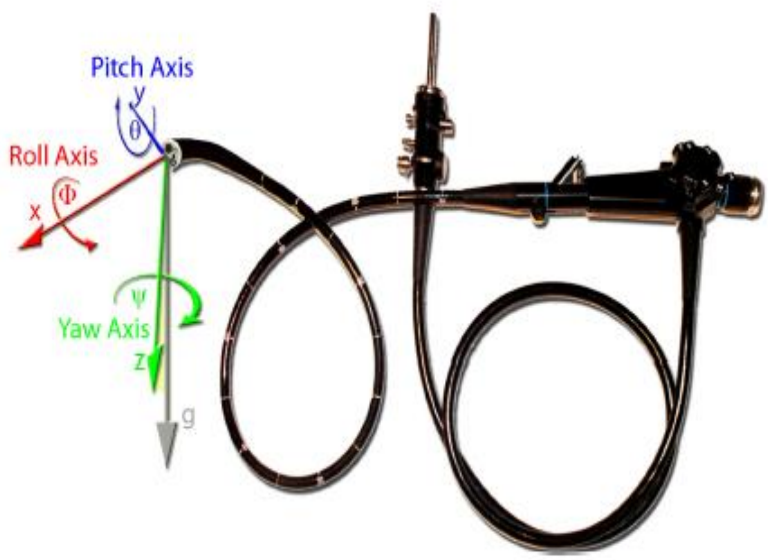

Figure 1: Euler angles and body freme which are connected to an endoscope camera [10]

Three orthogonal gyroscopes can measure angular velocities of device (known as p, q and r) around the axes of body coordinate system. In order to calculate Euler angles and attitude of device, a matrix called rotation matrix is used. This matrix is calculated by outputs of gyroscopes. Details of this calculation are presented in Inertial Navigation Algorithm and Related Equations section.

Inertial Sensors

Inertial sensors are one of the important parts of any inertial navigation system. Accelerometers and gyroscopes are the most basic sensors that measure linear accelerations and angular velocities, respectively. Nowadays, there are various types of accelerometers and gyroscopes among which MEMS and NEMS Sensors are widely used. These sensors come with advantages such as low cost, small size, low weight and convenient connection to electronic circuits. Some examples of MEMS accelerometers and gyroscopes are shown in Figures 2, 3 and 4.

Inertial Navigation Algorithm and Related Equations

In this section, the inertial navigation algorithm and its equations are described. According to the block diagram in Figure 5, three orthogonal accelerometers measure the linear accelerations of device in the body coordinate frame connected to the device, and three

Figure 2: ADXRS300 Gyroscope

Figure 3: ADXL321 Accelerometer

Figure 4: G750T MEMS Gyro System

orthogonal gyroscopes measure the angular velocities of device (called p, q, and r). The parameters known as quaternions are calculated by using these angular velocoties. Relationship between quaternions and the output signals of gyroscopes is as follows [11].

$$\dot{\vec{q}}=\frac{1}{2}\Omega_q\vec{q},\ \Omega_q=\begin{bmatrix}0 & -p & -q & -r\\ p & 0 & r & -q\\ q & -r & 0 & p\\ r & q & -p & 0\end{bmatrix},\vec{q}=[q_0\ q_1\ q_2\ q_3]^T \qquad (1)$$

Where $\vec{q}$ quaternion vector and Ωq is skew matrix of angular velocities. In order to extract the atuitudes and angles, a matrix called rotation matrix, C_b^e can be used. This matrix is a rotational matrix from body frame to ECEF frame (Earth Centered Earth Fixed) and is cal-

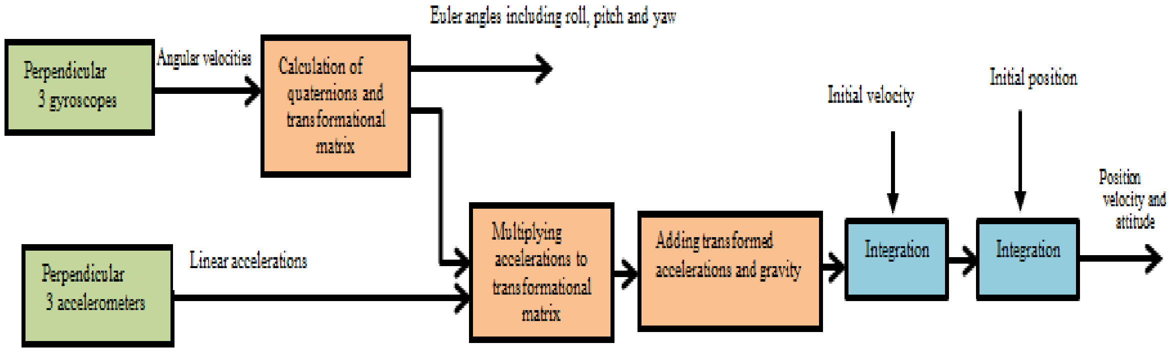

Figure 5: INS algorithm in order to determine position, velocity and attitude of vehicle.

culated as follows [11].

$$C_b^e = \begin{bmatrix} (q_0^2+q_1^2-q_2^2-q_3^2) & 2(q_1q_2-q_0q_3) & 2(q_1q_3+q_0q_2) \\ 2(q_1q_2+q_0q_3) & (q_0^2-q_1^2+q_2^2-q_3^2) & 2(q_2q_3-q_0q_1) \\ 2(q_1q_3-q_0q_2) & 2(q_2q_3+q_0q_1) & (q_0^2-q_1^2-q_2^2+q_3^2) \end{bmatrix} \quad (2)$$

Where q_i (i = 0, 1, 2, 3) are elemets of quaternion vector. By using rotational matrix, it is possible to determine the attitude of device, roll, pitch and yaw angles. The equations for this purpose are followed [11].

$$\psi = \tan^{-1}\left(\frac{c_{21}}{c_{11}}\right),\ \theta = -\sin^{-1}(c_{31}),\ \varphi = \tan^{-1}\left(\frac{c_{32}}{c_{33}}\right) \quad (3)$$

Figure 5. INS algorithm in order to determine position, velocity and attitude of vehicle

In equations (3), c_{ij} entries are located on row i and column j. The accelerometers are connected to devices in order to measure the linear accelerations in body coordinate frame. According to (4), by rotating the matrix, it is possible to transfer linear accelerations from body coordinate frame to the desired coordinate frame such as ECEF and NED (North - East - Down) frames. In this equation, $({}^b a_x \ {}^b a_y \ {}^b a_z)^T$ is the vector of linear acceleration in the body frame and $({}^e a_x \ {}^e a_y \ {}^e a_z)^T$ is the vector of linear acceleration in the ECEF coordinate frame.

$$\begin{pmatrix} {}^e a_x \\ {}^e a_y \\ {}^e a_z \end{pmatrix} = C_b^e \begin{pmatrix} {}^b a_x \\ {}^b a_y \\ {}^b a_z \end{pmatrix} \quad (4)$$

The total accelerations of device are obtained through adding transferred accelerations and ground gravitational acceleration. The ground gravitational acceleration is constant and is equal to $(0 \quad 0 \quad 9.81)^T$ or last vector in equation (5), the total acceleration of device in the ECEF frame is given by equation (5) [11].

$$\begin{pmatrix} {}^e A_x \\ {}^e A_y \\ {}^e A_z \end{pmatrix} = \begin{pmatrix} {}^e a_x \\ {}^e a_y \\ {}^e a_z \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ 9.81 \end{pmatrix} \quad (5)$$

By integration of (5), the velocity of device in any time can be calculated. Considering the initial velocity of device as well as the initial position of device, the position of the device is calculated by double integrating(5). Recently, due to extensive use of inertial navigation systems, the inertial measurement units (IMU) and attitude heading reference system (AHRS) have been constructed by a number of companies including Microstrain and Xsens. 3DM-GX3-35 and MTI-G systems are the samples of products of these companies. These systems are shown in Figures 6 and 7, respectively.

Figure 6: MTI-G Inertial Measurement Unit (Xsens Copmany)

Figure 7: 3DM-GX3-35 Attitude Heading Reference System (MicroStrain Company)

Applications of Inertial Navigation System in Medical Engineering

Applications of inertial navigation system in medical engineering and its related sciences are widely developed, and still the research is in progress in these areas. Since for most of devices in medical engineering determining the velocity, position and attitude including Euler angles are essential, the inertial navigation systems are inseparable parts of these devices. In this part of the paper, some examples of INS's applications are mentioned in medical engineering. Figure 8 shows synthetic gloves that have the ability to recognize and simulate the hand gestures that can be used for assisting robots to help disabled patients. In this project, an inertial measurement unit including accelerometers and gyroscopes measure accelerations and angular velocities of artificial hand. The main part of this project is Arduino microcontroller. Inertial navigation algorithms are programmed in Arduino microcontroller in

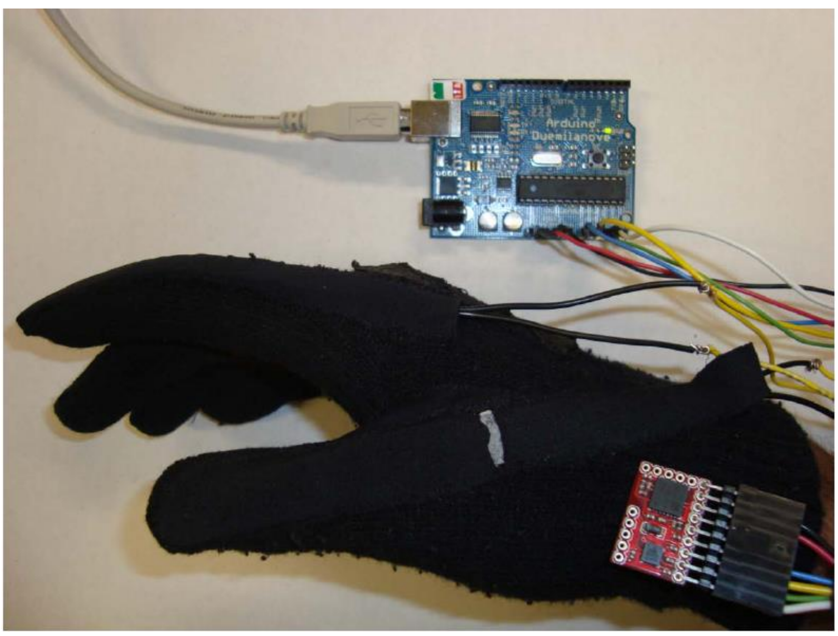

Figure 8: Hand gestures recognition gloves with inertial navigation system [12].

order to determine the parameters of inertial navigation such as position, velocity and attitude.

In Figure 9, another example of application of inertial navigation systems in medical engineering for people with severe physical disabilities is shown. Some patients with spinal cord injury are only able to move their heads. Figure 9 shows a controllable wheelchair for these patients. In this project, some accelerometers have been installed on a hat which is installed on the patient's head to detect the left, right, back and front motions of patient. These commands are transmitted by accelerometers to a servo motor wich can control the motions of wheelchair.

As another example, an endoscopic system for imaging the internal organs of the human body is shown in Figure 10. In this system, one accelerometer and two gyroscopes are used for guidance, navigation and control of endoscopic device.

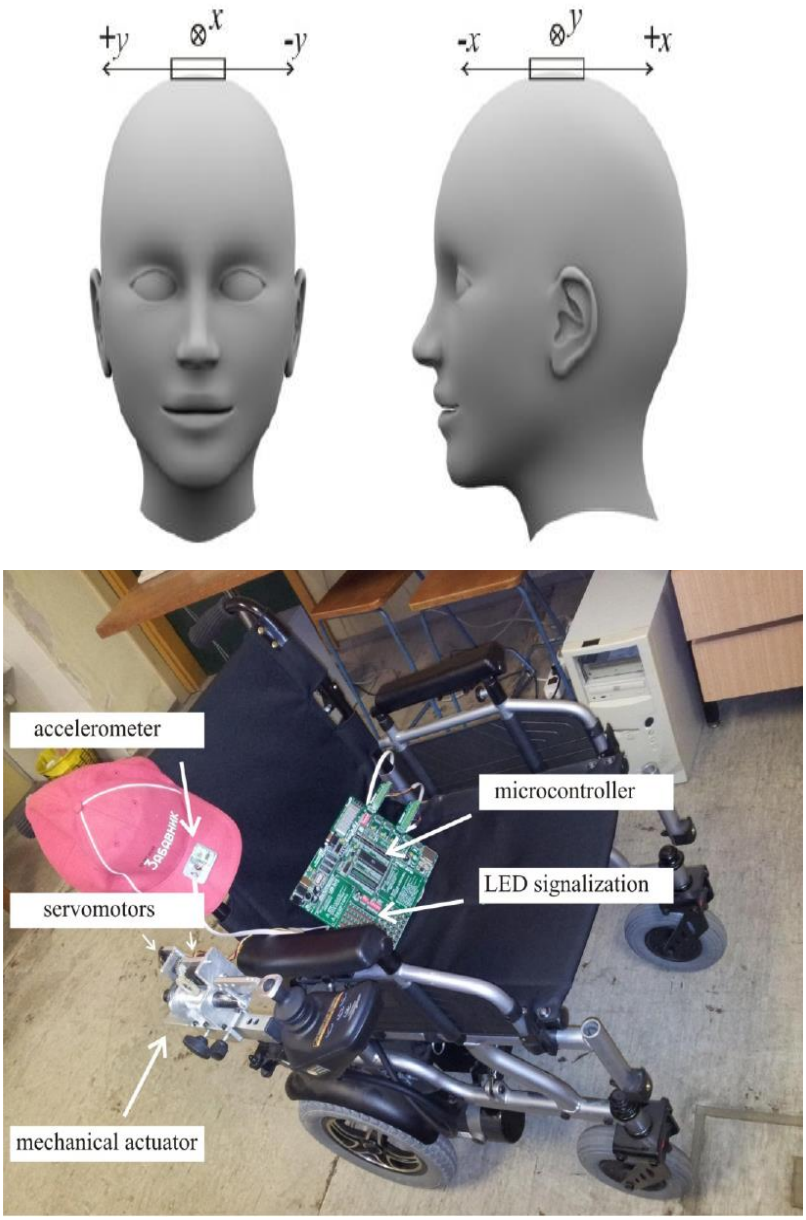

Figure 9: Controllable automatic wheelchair by head movements of spinal cord disabled

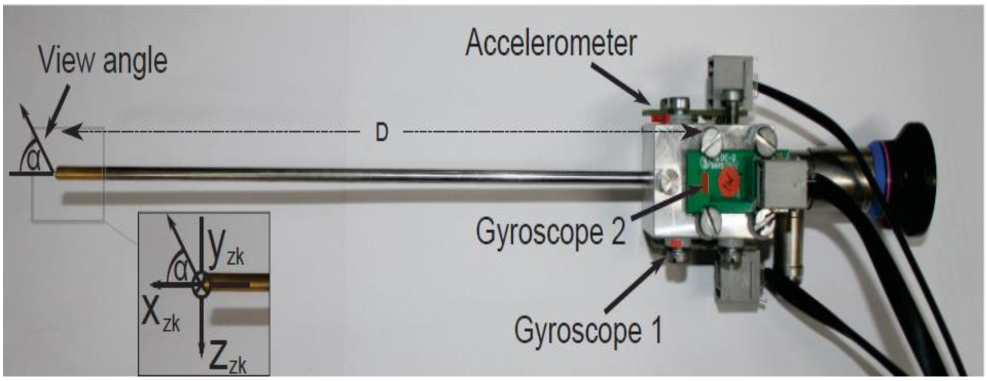

Figure 10: Inertial sensors and their applications in endoscope device.

Inertial navigation systems also can be used in other applications of medical engineering such as surgical robots and intelligent patient beds. It is predicted that due to the development and advancement of technology, the applications of inertial navigation systems in medical engineering will be increased.

Conclusion

In this paper, inertial navigation systems and the conventional sensors such as accelerometers and gyroscopes are introduced. Then, algorithm of inertial navigation and related equations are explained. In the following of this paper, some applications of inertial navigation system in biomedical engineering and a number of industrial samples in this field are mentioned. According to the application samples described in this study, it is apparent that applying inertial navigation system to medical/biomedical engineering is vital for todays' need, and is extensively followd by the industry to manufacture devices and equipment that are not only cheap and light, but also have high degree of precision and performance, with high efficiency.

Conflict of Interest

None

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