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Design of an MPU9250-based Attitude Data Measurement System

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Abstract

Abstract—Attitude solving plays a crucial role in various fields, as it enables accurate determination of an object's orientation and helps optimize system performance. By providing precise attitude information, the MPU9250 nine-axis sensor contributes to the design of balance bikes, aerial mice, and other applications. The project utilizes the STM32F767 microcontroller to interface with the MPU9250 sensor, enabling the acquisition of raw data. The Digital Motion Processor (DMP) and Motion Process Library (MPL) library are employed to perform attitude solving, allowing for real-time estimation of the object's Euler angles. The results from the proposed method demonstrate accuracy, providing a reliable and cost-effective solution for precise attitude resolution. This research enhances operational efficiency, optimizes system performance, and reduces computational complexity. Future efforts will focus on mitigating errors arising from environmental factors.

System Modeling & Hardware Design

Rotate counterclockwise around the Z/Y/X-axis to obtain the yaw angle ψ, pitch angle θ, roll angle φ respectively, as depicted in Fig.1. The rotation matrices Rx(φ), Ry(θ), and Rz(ψ) are employed to compute the rotation of the 3 axes, as well as the Euler angles. Multiplying these rotation matrices together can get the attitude transformation matrix from carrier coordinate system *b* to navigation coordinate system *n*.

Quaternions, higher-order complex numbers in a four dimensional space, are utilized to represent the rotation of *b* to *n*. By performing quaternion multiplication, the vector r^b in the carrier coordinate system and the vector r^n in the navigation coordinate system can be obtained. Objects rotate following a consistent order to reach a specific position, thus anticipating consistency in the attitude matrix represented by various methods. As shown in Fig.2, the Euler angles can be obtained from the quaternions.

The MPU9250 features an integrated 3-axis gyroscope, accelerometer, and magnetometer. These sensors communicate with the microcontroller via the IIC interface, achieving a maximum transfer rate of 400 kHz/s. The gyroscope excels at capturing swift rotations, while the accelerometer precisely detects a wide range of motion intensities. The magnetometer employs a sensitive Hall-type sensor to acquire magnetic field data. The DMP's role is to offload the microcontroller by managing sensor synchronization and attitude sensing. MPL further simplifies attitude solving by reducing computational demands on the operating system and streamlining development.

The STM32's integration of a double precision hardware floating point unit and DSP instructions ensures ample data processing power for attitude solving. The chosen processor, STM32F767, features an ARM Cortex-M7 core with a high pipeline level of six. This enhances processing speed by executing multiple instructions in a single clock cycle.

MPU9250 using 2 common IOs. The program initializes MPU9250 and related peripherals, utilizing the MPL library to enable DMP functionality. Continuous readings of acceleration sensors, gyroscope, magnetometer, and Euler angles are carried out within the main loop, employing MPL Attitude Decomposition. The obtained Euler angles are displayed on STM32F767's screen, offering real-time attitude data feedback. See Fig. 3 for an illustration of the working process.

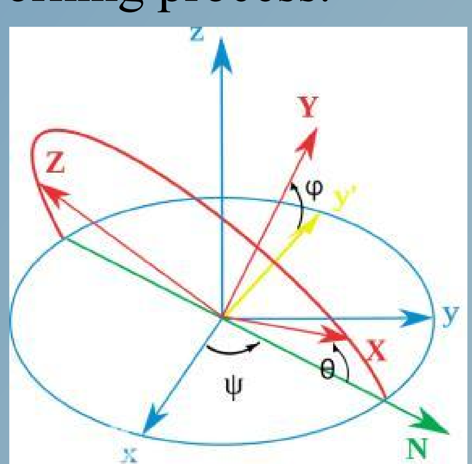

Figure 1. Rotation of the coordinate system to obtain Euler angles

$$\begin{cases} \varphi = \arctan \dfrac{2(q_2 q_3 + q_0 q_1)}{q_0^2 - q_1^2 - q_2^2 - q_3^2} \\ \theta = \arcsin 2(q_0 q_2 - q_1 q_3) \\ \psi = \arctan \dfrac{2(q_0 q_3 + q_1 q_2)}{q_0^2 + q_1^2 - q_2^2 - q_3^2} \end{cases}$$

Figure 2. The formula for Euler's angle

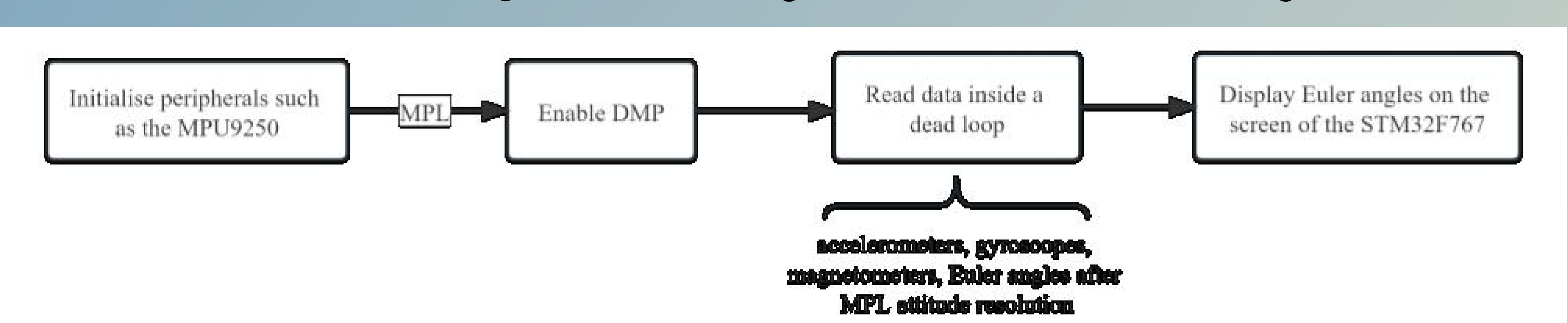

Figure 3. Flow of the system to achieve the function

Methods

The MPU9250 communicates with the STM32F767 via IIC, requiring the initialization of the connected SDA and SCL data lines. This initialization is contained within the *IIC_Init* function.

Next, the full scale range (FSR) of the gyroscope and accelerometer sensors is configured by accessing their respective configuration registers. For the gyro, typically set to ±2000°/s. With the gyroscope's 16-bit resolution, sensitivity is 65536/4000=16.4 LSB/(°/s). For the accel, often set to ±2g. Sensitivity is calculated as 65536/4=16384 LSB/g.

The gyroscope sampling frequency is calculated using: Sampling frequency = Gyroscope output frequency / (1 + SMPLRT_DIV). Typically, the gyroscope's bandwidth is set at half of its sampling rate. For example, if aiming for a 50Hz sampling rate, a 25Hz bandwidth is appropriate.

The gyro data output registers consist of six registers (0x43 to 0x48) containing x/y/z-axis values. Reading these registers provides access to gyro data. For the x-axis, the high 8-bit register (0x43) and the low 8-bit register (0x44) are read. Similar steps apply for the other axes. The same method is used to acquire x/y/z-axis values for the acceleration and magnetometer sensors.

MPU9250 comes with an embedded MPL, facilitating seamless integration with the DMP. This allows direct conversion of raw sensor data into quaternion output, making calculations of Euler angles straightforward.

The DMP initialization starts by connecting the MPU9250 sensor to the IIC interface. Then, *mpu_init* initializes the MPL and assigns the result to a variable *res*. The subsequent process involves quaternion output calculation, fusion, vector compass calibration, and detection of magnetic interference, etc. Start the MPL and store the result in *res*. Configure the selected sensors for fusion, set up the FIFO for gyroscope and accelerometer data, and define default and magnetometer sampling rates. Retrieve and use sensor parameters to configure sampling rates and orientation. Load DMP firmware and align device orientation with the gyroscope's.

After successful code compilation and downloading, real-time pitch, roll, and yaw angles of the MPU9250 are displayed on the screen. Manipulating the board physically reveals dynamic angle changes, promptly reflected on the screen. For real-world angle measurement, a protractor is employed, and the screen's displayed values are compared to gauge system accuracy.

Results: Placing the development board on a nearly horizontal tabletop and rotating it horizontally, it was observed that the pitch angle jumps between 0.4° and 1.1°, while the roll angle fluctuates between -0.4° and 0.3°. These fluctuations can be attributed to computational inaccuracies and the non horizontal nature of the tabletop. The development board plane is conceptualized as a rectangular shape, where the origin of the coordinate system is located at the top-left corner. The x-axis is aligned with the left side edge, the y-axis corresponds to the upper side edge, and the z-axis is perpendicular to the plane, originating from the origin and extending in a direction normal to the surface. Rotation of the development board in a counterclockwise direction around the z/y/x-axis leads to a decline in the yaw/pitch/roll angle. Upon reaching a specific angle, the yaw angle reaches 0°, indicating that the attitude of the development board aligns with its initial position within the coordinate system. The measurement of rotational angles demonstrates a strong correlation with the data displayed on the screen, which can be attributed to the high sensitivity of the MPU9250 sensor and the comprehensive nature of the implemented code.

Conclusion

This paper's attitude measurement system combines STM32F767's robust control capabilities with MPU9250's advanced sensor processing. The gyroscope attains a 1kHz output frequency, yielding ±0.1° attitude angle accuracy. Real-time display of attitude data is enabled, ensuring precise object motion estimation. This holds significance across diverse scenarios like aviation, vehicle control, and industrial automation. Attitude data aids control and decision-making, benefiting personnel in control centers and enhancing applications in intelligent wearables and structural monitoring.