Journal of Technical Education Science No.36 (06/2016)
Ho Chi Minh City University of Technology and Education

AN ADVANCED QUADCOPTER WITH PID CONTROLLER USING BOTH GYROSCOPES AND ACCELEROMETERS

NGHIÊN CỨU THIẾT KẾ ROBOT BAY TỰ ĐỘNG TRÁNH VẬT CẢN CÓ BỐN CÁNH CÂN BẰNG

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Received 23/12/2015, Peer reviewed 27/01/2016, Accepted for publication 16/5/2016

ABSTRACT

This project focus on design a quadcopter and development an algorithm so that help it can navigate and self-balance in both indoor and outdoor enviroment, which can be used as a framework for applications such as data collection, ground surveillance, etc. The proposed algorithm allows the quadcopter can fly from its current location to the given location in space. Assuming that there are obstacles in front of the quadcopter, it has to recognize and avoid these obstacles. The developed quadcopter consists of four rotors mounted on four brushless motors to allow lifting and propelling the quadcopter. Arduino platform was used for programming. There are two PID controllers have been applied to control the quadcopter's self-balance and obstacle avoidance. The PID1 uses input values from an IMU sensor which returns values regarding angles and angular velocities of the quadcopter's frame and a GPS module to control the self-balance of the quadcopter. The PID2 uses input values from 5 ultrasonic sensors, four sensors are mounted around and the fifth is mounted under bottom of the quadcopter's frame to control the obstacle avoidance.

Keywords: *quadcopter; navigation; self-balance; obstacle avoidance; PID controller.*

TÓM TẮT

Dự án nghiên cứu này tập trung vào thiết kế và chế tạo một robot bay bốn cánh, đồng thời phát triển một thuật toán nhằm giúp cho robot có thể di chuyển và tự cân bằng trong không gian, có thể được sử dụng như là một công cụ nền tảng cho các ứng dụng ví dụ như thu thập dữ liệu, giám sát mặt đất,..Thuật toán được đề xuất bởi nhóm tác giả cho phép robot có thể bay từ vị trí hiện tại của chính nó đến một vị trí mong muốn khác được xác định trước trong không gian. Robot được thiết kế và chế tạo trong dự án này bao gồm bốn cánh quạt được gắn trên trục của bốn động cơ không chổi than (brushless motor) nhằm cho phép việc nâng và đẩy robot trong không gian. Nền tảng Arduino đã được sử dụng cho việc lập trình. Có hai bộ điều khiển PID đã được áp dụng để điều khiển việc di chuyển tự động, tự cân bằng và tự nhận biết và tránh vật cản của robot máy bay; Bộ cảm biến IMU và một mô đun định vị tọa độ toàn cầu GPS để kiểm soát quá trình điều hướng và tự cân bằng của robot máy bay. Bộ PID2 nhận các giá trị ngõ vào từ năm cảm biến siêu âm, bốn cái được gắn xung quanh và cái thứ năm còn lại được gắn ở phía dưới bộ của robot để kiểm soát việc tránh vật cản.

Từ khóa: *máy bay 4 động cơ điện; chuyển động robot; tự cân bằng; tránh vật cản; bộ điều khiển PID.*

1. INTRODUCTION

Quadcopter is a flying vehicle using four rapidly spinning rotors, are usually brushless motors, to lift and propel it-self. These rotors are usually arranged and spaced equally at four corners of the quadcopter's square body. By using four independent rotors, the quadcopter can alleviate the swashplate mechanism which is important for a helicopter while still keep the same level of control and degrees of freedom [1]. Basically, quadcopter is controlled by adjusting the angular velocities of the rotors which are spun by electric motors. Quadcopter is a typical design for small unmanned aerial vehicles (UAV) because of the simple structure. Quadcopters are used in surveillance, search and rescue, construction inspections and several other applications [1]. There are two main advantages of quadcopter in comparison to helicopter. First, the simple mechanical structure, quadcopter's rotors do not require complex mechanical linkages for actuation. Second, the use of four rotors ensures that individual rotors are smaller in diameter than the equivalent main rotor on a helicopter, relative to the airframe size. Especially, due to small size, it is easy for quadcopter's rotors are protected by frames enclosing the rotors, so quadcopters can work in indoor environment with obstacle-dense [3].

In the early years of the 21st century, there are many researchers proposed control schemes for quadcopter. In 2004, Bouabdallah *et al* presented the results of two model-based control techniques applied to an autonomous four-rotor micro helicopter called quadrotor. [4]. In 2005, Guenard *et al* described an intuitive control strategy for a four rotors vertical take-off and landing (VTOL) remote-controlled vehicle. A nonlinear controller simplifying the vehicle manipulation and insuring quasi-stationary flight conditions is developed. The approach considers that the rotor dynamics are negligible compared to the body dynamics and develops a control law based on saturating the linear dynamics for bounding the vehicle orientation and limiting it to very small values [5]. In 2010, Pounds *et al* developed the X-4 Flyer, a quad-rotor robot using custom-built chassis and avionics with off-the-shelf motors and batteries, to be a highly reliable experimental platform. A linear SISO controller was designed to regulate flyer attitude [6]. Also in 2010, Raffo *et al* presented an integral predictive and nonlinear robust control strategy to solve the path following problem for a quadrotor helicopter. The dynamic motion equations are obtained by the Lagrange-Euler formalism. Simulation results in the presence of aerodynamic disturbances, parametric and structural uncertainties are presented to corroborate the effectiveness and the robustness of the proposed strategy [7]. In 2014, Mueller *et al* presented periodic solutions for a quadrocopter maintaining a height around a position in space despite having lost a single, two opposing, or three propellers. In each case the control strategy consists of the quadrocopter spinning about a primary axis, fixed with respect to the vehicle, and tilting this axis for translational control. A linear, time-invariant description of deviations from the attitude equilibrium is derived, allowing for a convenient cascaded control design. The results for the cases of losing one and two propellers are validated in experiment, while the case of losing three propellers is validated in a nonlinear simulation [8].

Nowadays, together with the development of science and technology, particularly in the field of electronics, microcontrollers, sensors, image processing, etc..., many technologies have been applied for quadcopter making it more helpful, smarter, even it can navigate autonomously in environment, such as: the Volocopter VC200 was introduced in 2013 [9], Raffaello D'Andrea demonstrated his flying quadcopters: robots that think like athletes, solving physical problems with algorithms that help them learn [10], etc…

The article is organized as follows: Section 1 briefly overviews about quadcopter and some of famous researches on this field. Section 2 explains about the background for researching on quadcopter field, introduces some of algorithms to control quadcopter, etc... Section 3 explains the methodology of our research, the use of algorithms such as PID, SLAM to control our proposed quadcopter. Section 4 illustrates experimental results and several discussions according to those achieved results. The conclusions are presented in Section 5. Final section lists the reference papers.

2. BACKGROUND

Basically, the quadcopter's motion is controlled by varying each rotor's rotation speed. The pair of rotors 1 and 3 rotates in a clockwise direction, while the pair of rotors 2 and 4 rotates in a counter-clockwise direction, as shown in Figure 1. This configuration is devised in order to balance the drag created by each of the spinning rotor pairs. By varying the rotation speed of the four rotors, a quadcopter can perform the basic four maneuvers such as roll, pitch, yaw and altitude, as shown in Figure 2. The roll angle is controlled by varying the relative rotation speed of the rotors 1 and 3, meanwhile the pitch angle is controlled by varying the relative rotation speed of the rotors 2 and 4, and the yaw angle is controlled by varying the speeds of clockwise rotating pair and counter-clockwise rotating pair. In order change the altitude of the quadcopter, the relative rotation speed of all four rotors must be changed simultaneously to generate the collective thrust so that can propel the quadcopter up or down.

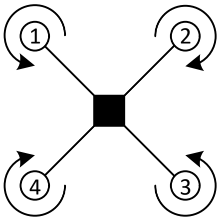

***Figure 1**. Configuration of a typical quadcopter, consists of a frame and four rotors at four corners.*

There are many control techniques for quadcopter have been proposed by many researchers in the world so far. In 2002, Altug *et al* [11] presented control methods for an autonomous four-rotor helicopter using visual feedback as the primary sensor. In 2004, Bouabdallah *et al* has been applied the classical approach PID and the morden technique LQ to control the quadcopter [4], and Castillo *et al* [12] presented a controller design and its implementation on a mini rotorcraft having four rotors. The proposed controller is based on Lyapunov analysis using a nested saturation algorithm, meanwhile Dunfied *et al* designed and developed an intelligent controller based on neural networks for a hoverable flying robot to be capable of achieving vertical taken off and landing and to be able to sustain a specified attitude is presented [13].

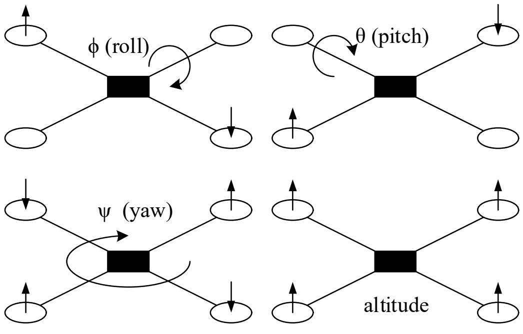

***Figure 2**. The basic four maneuvers: roll, pitch, yaw and altitude for quadcopter's motion.*

3. METHODOLOGY

3.1 Quadcopter model

In order to model a quadcopter, firstly, a frame of reference must be determined. In fact, the quadcopter's moving is in three direction x, y and z in 3-D space. Normally, the center of gravity or physical center of the quadcopter is used as the reference point for all of calculations, the x and y axis are fixed as shown in Figure 3, meanwhile the z-axis as being orthogonal to the x-axis and y-axis. In this figure, F_1, F_2, F_3 and F_4 denote the torque and thrusts generated by four rotors respectively, meanwhile *m.g* is the effect of gravity and *L* represents the distance from the centre of quadcopter to the motor axis, *L* is the same for all four rotors, and *m* denotes the mass of the quadcopter. The angles around the x, y and z axis are called Euler angles, roll (ϕ), pitch (θ) and yaw (ψ), respectively. These angles and coordinate systems have described fully the position and orientation of the quadcopter.

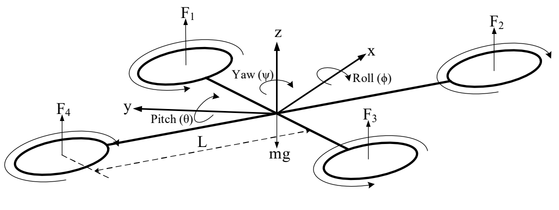

***Figure 3**. Description of a quadcopter's frame and its relative parameters.*

3.2 Reference frames

There are two reference frames to describe the quadcopter's navigation, as shown in Figure 4, one is the ground frame {E} and another is the quadcopter frame {B}. {E} is an earth-fixed coordinate system with the origin located on the ground. By convention, the x-axis points towards the north, the y-axis points towards the east, and the z-axis points towards the center of the earth. Meanwhile, {B} is a body-fixed coordinate system with the origin fixed at the center of mass of the quadcopter frame.

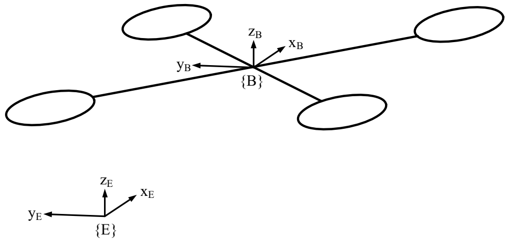

***Figure 4**. The quadcopter frame and the ground frame.*

3.3 Kinematic and Dynamic

The frame {B} relates to the frame {E} by a position vector *x* and a rotation matrix ${}^{E}_{B}R$. The linear position of quadcopter is given by

$$x=\begin{bmatrix}p_x\\ p_y\\ p_z\end{bmatrix}\in\{E\} \tag{1}$$

Therefore, the linear velocity of the quadcopter is defined by

$$\upsilon=\dot{x}=\begin{bmatrix}\dot{p}_x & \dot{p}_y & \dot{p}_z\end{bmatrix}^T \tag{2}$$

Meanwhile, the orientation is represented by Euler angles, as the angular position:

$$\xi=\begin{bmatrix}\psi\\ \theta\\ \phi\end{bmatrix}=\begin{bmatrix}\text{yaw}(\psi)\\ pitch(\theta)\\ roll(\phi)\end{bmatrix} \tag{3}$$

so the angular velocities are defined by $\dot{\xi}$ as follows

$$\dot{\xi} = \begin{bmatrix}\dot{\psi} & \dot{\theta} & \dot{\phi}\end{bmatrix}^{T} \tag{4}$$

Because the angular velocity ω of the quadcopter is a vector pointing along the axis of rotation, meanwhile the angular velocities $\dot{\xi}$ are just the time derivative of yaw, pitch, and roll. Therefore, $\dot{\xi}$ can be converted into the ω by the following relation:

$$\varpi = \begin{bmatrix}1 & 0 & -s_{\theta}\\ 0 & c_{\phi} & c_{\theta}s_{\phi}\\ 0 & -s_{\phi} & c_{\theta}c_{\phi}\end{bmatrix}\cdot\dot{\xi} \tag{5}$$

Accordingly, the rotation matrix from the quadcopter frame to the ground frame is

$$\begin{aligned}{}_{B}^{E}R &= Rot(z,\psi)\cdot Rot(y,\theta)\cdot Rot(x,\phi)\\ &= \begin{bmatrix}c_{\psi}c_{\theta} & c_{\psi}s_{\phi}s_{\theta}-c_{\phi}s_{\psi} & s_{\phi}s_{\psi}+c_{\phi}c_{\psi}s_{\theta}\\ c_{\theta}s_{\psi} & c_{\phi}c_{\psi}+s_{\phi}s_{\theta}s_{\psi} & c_{\phi}s_{\psi}s_{\theta}-c_{\psi}s_{\phi}\\ -s_{\theta} & c_{\theta}s_{\phi} & c_{\phi}c_{\theta}\end{bmatrix}\end{aligned} \tag{6}$$

where the following shorthand notations for trigonometric functions are used: $c_{\alpha} = \cos(\alpha)$, $s_{\alpha} = \sin(\alpha)$, and

$$\begin{aligned}Rot(z,\psi) &= \begin{bmatrix}c_{\psi} & -s_{\psi} & 0\\ s_{\psi} & c_{\psi} & 0\\ 0 & 0 & 1\end{bmatrix}\\ Rot(y,\theta) &= \begin{bmatrix}c_{\theta} & 0 & s_{\theta}\\ 0 & 1 & 0\\ -s_{\theta} & 0 & c_{\theta}\end{bmatrix}\\ Rot(x,\phi) &= \begin{bmatrix}1 & 0 & 0\\ 0 & c_{\phi} & -s_{\phi}\\ 0 & s_{\phi} & c_{\phi}\end{bmatrix}\end{aligned} \tag{7}$$

Force, in the direction of the rotor axis, and torque, around the rotor axis, at each rotor are created by the angular velocity and acceleration as given by

$$F_i = k\omega_i^2 \tag{8}$$

$$M_i = b\omega_i^2 + I_M\dot{\omega}_i \tag{9}$$

where

- F_i denotes force at rotor i^{th} in the direction of the rotor axis and created by the angular velocity ω_i,
- M denotes torque at rotor i^{th} around the rotor axis and created by the angular velocity ω_i and acceleration $\dot{\omega}_i$,
- k denotes the lift constant,
- b denotes the drag constant, and
- I_M denotes the inertia moment of the rotor.

Due to the quadcopter consists of four rotors, therefore the thrust of the quadcopter in the direction of the body z-axis is calculated by

$$F = F_1 + F_2 + F_3 + F_4 \tag{10}$$

Normally, the effect of acceleration $\dot{\omega}_i$ is insignificant, so it can be skipped in calculations. Therefore, the total torque is given by

$$\begin{aligned}M &= M_1 + M_2 + M_3 + M_4\\ &= L.\sum_{i=1}^{4} F_i\end{aligned} \tag{11}$$

The conditions so that the quadcopter can hovering are

1. *Equilibrium of forces:*

$$F = -mg \tag{12}$$

2. *Equilibrium of directions (direction of forces must be parallel to direction of gravity vector):*

$$F_1 \| F_2 \| F_3 \| F_4 \| g \tag{13}$$

3. *Equilibrium of torques:*

$$M = 0 \tag{14}$$

4. *Equilibrium of angular velocities:*

$$(\varpi_1 + \omega_3) - (\varpi_2 + \omega_4) = 0 \tag{15}$$

In order the quadcopter goes up or down, just impose the condition 1 as no equilibrium, mean $F \neq -mg$ by increasing/decreasing the angular velocities ω_i, and remain conditions 2 and 3 as follows:

$$\begin{cases} F > -mg \Rightarrow go\ up \\ F < -mg \Rightarrow go\ down \end{cases} \tag{16}$$

For yaw rotation (*around the body z-axis*), remain condition 1, 2, and 3 while impose no equilibrium for angular velocities, mean $(\varpi_1 + \omega_3) - (\varpi_2 + \omega_4) \neq 0$. Therefore, the angular velocity of yaw rotation is calculated by

$$\dot{\psi} = k_Y((\varpi_1 + \omega_3) - (\varpi_2 + \omega_4)) \tag{17}$$

where k_Y denotes the constant to increase/decrease the angular velocity of yaw rotation. Thence, the yaw angle is given by

$$\psi = \int \dot{\psi} dt \tag{18}$$

For roll rotation (*around the body x-axis*), impose no equilibrium for torques, means $M \neq 0$, by unbalancing rotor velocities as $(\varpi_1 + \omega_4) - (\varpi_2 + \omega_3) \neq 0$. Therefrom, the angular velocity of roll rotation is given by

$$\dot{\phi} = k_R((\varpi_1 + \omega_4) - (\varpi_2 + \omega_3)) \tag{19}$$

where k_R denotes the constant to increase/decrease the angular velocity of roll rotation. Thence, the roll angle is given by

$$\phi = \int \dot{\phi} dt \tag{20}$$

Due to unbalancing rotor velocities, leading to no equilibrium of directions, that means forces F_i not parallel to g, as shown in Figure 5.

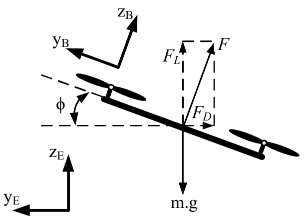

Figure 5. *Roll rotation*

In roll rotation case, the total thrust $F = \sum_{i=1}^{4} F_i$ is decomposed in lift force, F_L, and drag force, F_D, as follows:

$$\begin{cases} F_L = F \cdot \cos\phi \\ F_D = F \cdot \sin\phi \end{cases} \tag{21}$$

For pitch rotation (*around the body y-axis*), impose no equilibrium for torques, mean $M \neq 0$, by unbalancing rotor velocities as $(\varpi_1 + \omega_2) - (\varpi_3 + \omega_4) \neq 0$. Therefrom, the angular velocity of pitch rotation is given by

$$\dot{\theta} = k_P((\varpi_1 + \omega_2) - (\varpi_3 + \omega_4)) \tag{22}$$

where k_P denotes the constant to increase/decrease the angular velocity of pitch rotation. Thence, the pitch angle is given by

$$\theta = \int \dot{\theta} dt \tag{23}$$

Similarly, unbalancing rotor velocities, leads to no equilibrium of directions.

3.4 Equations of Movement

The angular velocities of roll, pitch and yaw rotation from Eqs. (15), (18) and (24), respectively as follows

$$\begin{cases} \dot{\phi} = k_R((\varpi_1 + \omega_4) - (\varpi_2 + \omega_3)) \\ \dot{\theta} = k_P((\varpi_1 + \omega_2) - (\varpi_3 + \omega_4)) \\ \dot{\psi} = k_Y((\varpi_1 + \omega_3) - (\varpi_2 + \omega_4)) \end{cases} \tag{25}$$

and total thrust, T, of the quadcopter is

$$T = k\sqrt{F} = k(\omega_1 + \omega_2 + \omega_3 + \omega_4) \tag{26}$$

Assuming a common factor of proportionality $k_R = k_P = k_Y = k$, the matrix of equations of quadcopter movement is

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \\ T \end{bmatrix} = K \cdot \begin{bmatrix} \varpi_1 \\ \varpi_2 \\ \varpi_3 \\ \varpi_4 \end{bmatrix} \tag{27}$$

where

$$K=\begin{bmatrix} k & -k & -k & k \\ k & k & -k & -k \\ k & -k & k & -k \\ k & k & k & k \end{bmatrix} \tag{28}$$

The Eq. (22) gives the angular velocities of the quadcopter, given by the velocity of rotors. However, to control the quadcopter, angular velocities ω_i must be set in order to impose a certain rotation rate of axis in the body frame by the following equation:

$$\begin{bmatrix} \varpi_1 \\ \varpi_2 \\ \varpi_3 \\ \varpi_4 \end{bmatrix} = K^{-1} \cdot \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \\ T \end{bmatrix} \tag{29}$$

The simple control model to set values of angular velocities ω_i and the diagram of motor/propeller driving are shown in Figure 6 and Figure 7.

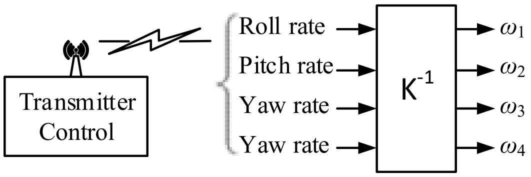

***Figure 6**. Directly controlling roll, pitch, yaw rates, and total thrust.*

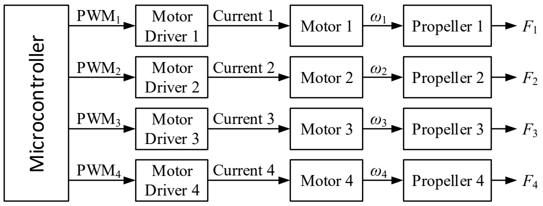

***Figure 7**. The motor/propeller driving diagram.*

3.5 The PID controller

In general, drivers, motors and propellers are chosen to be of the same type for the four arms. The signal to control motor/propeller is PWM from the output ports of the microcontroller. However, in fact, these drivers, motors and propellers are certainly not the same. Therefore, although the same PWM signals applied to these driver/motor/propeller chains but thrust forces created on each rotors will be different. Especially, the center of gravity (COG) is not easy to place at the center of the quadcopter body.

To solve the problem of controlling for driver/motor/propeller, a PID controller has been designed and applied to the quadcopter control as shown in Figure 8.

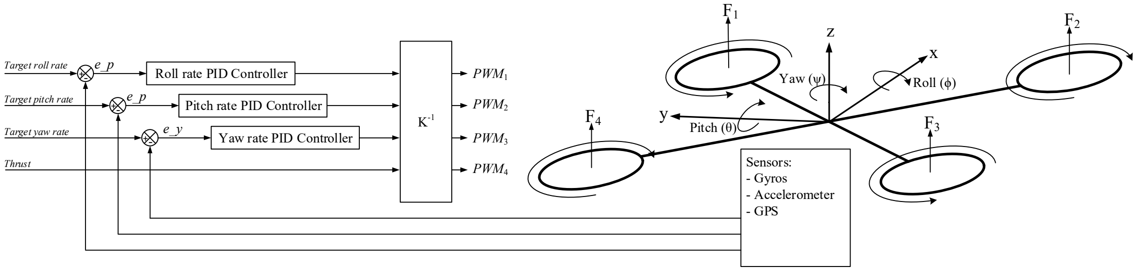

***Figure 8**. The PID controler used to control the quadcopter movement.*

The PID controller is designed as follows:

$$C(t)=K_P e(t)+K_I\int_0^t e(t)dt+K_D\frac{de(t)}{dt} \tag{30}$$

By disreting C(t), at k^{th} sampling C(k) is

$$C(k)=K_P e(k)+K_I\sum_0^k e(j)\Delta T+K_D\frac{e(k)-e(k-1)}{\Delta T} \tag{31}$$

where constants K_P, K_I and K_D regulate the behaviour of the controller: K_P drives the short-term action, K_I drives the long-term action, and K_D drives the action on the basis of the “error trend”.

4. DISCUSSION AND CONCLUSSION

To control the quadcopter, Euler angles (ϕ, θ, ψ) must be measured by using Gyroscoptes, Accelerometers, Magnetomet-ers, etc... Gyroscopes measure angular velocities which can be integrated in order to derive the angle. However, measuring by Gyroscopes, numeric integration is affected by approximation errors. Moreover, Gyroscopes are affected by an offset, i.e. they give none-zero value when the measure should be zero, such an offset is not constant over time and depends on the temperature. Therefore, in case just using only Gyroscopes to measure Euler angles, the estimated angle is not reliable.

For measuring by Accelerometers, acceleration over the three axis (a_x, a_y, a_z) can be measured. If the sensor is static sensed values are the projections of g vector in the sensor reference system, two functions detemine roll and pitch is given by

$$\begin{cases} \phi = \tan^{-1}\dfrac{-a_y}{-a_z} \\ \theta = \tan^{-1}\dfrac{a_x}{\sqrt{a_y^2 + a_z^2}} \end{cases} \tag{32}$$

but if the object is moving (e.g. shaking) other accelerations appear, leading to the computed angles are not reliable.

In this research, two kinds of sensor, Gyroscopes and Accelerometers, have been employed for measuring Euler angles. We have two different sources of the same information which are affected by two different error types. We can use both measures by fusing them in order to adjust the error and obtain a reliable information.

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