NORTH SOUTH UNIVERSITY

Department of Electrical & Computer Engineering (ECE)

CSE499B SENIOR DESIGN II
Section: 11
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Project Title:
Precise Controlled Semi-Autonomous Ultrasonic Sensor Based Obstacle Avoidance Drone

Technical Article

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SCORE:	REMARKS:
PENALTY:	

1. Introduction:

An unmanned aerial vehicle, commonly known as a Drone, is a remote-controlled flying vehicle with a vast potential in various sectors. Initially developed for military applications, drones are advancing in sectors like agriculture, surveillance, security, entertainment, and aerial photography, promising a bright future for technology in Bangladesh. The global drone market size was estimated at USD 19.89 billion in 2022 and is expected to grow at a compound annual growth rate of 13.9% from 2023 to 2030.[12] In 2024, the revenue generated from the drone market is approximately \$2.9 million USD and has an annual growth rate of 9.29%.[13] Although the use of drones is rapidly increasing in Bangladesh. Unfortunately, we are lagging behind in the manufacturing of drones. The demand for drones in Bangladesh is mainly mitigated by importing drones from China. Several local importers import drones from companies like DJI, Parrot, Carrera, etc.

The average cost of a professional drone ranges from 50,000 BDT to 300,000 BDT. However, it is possible to reduce the price of drones if produced locally. With the view of developing locally made drones at a comparatively cheaper price, we have redesigned the flight controller, radio control (RC) transmitter, and receiver, the First-Person view (FPV) camera module and found that it is truly possible to build a professional drone below 25,000 BDT. The price can be further reduced if different parts of the drone, such as the frame, BLDC motor, and ESC, are locally manufactured.

2. Theoretical Foundation and Equations for Precise Controlled Drones:

Designing the control system for this precise-controlled drone involves a comprehensive understanding of numerous theoretical foundations and equations from multiple fields, including mechanics, control theory, electronics, and signal processing. The dynamics of the drone can be described using Newton-Euler equations, which are fundamental in understanding the motion of a rigid body. These equations are divided into translational dynamics, governed by Newton's second law, $\boldsymbol{F}=m\boldsymbol{a}$, where $\boldsymbol{F}$ represents the sum of all external forces acting on the drone, $\boldsymbol{m}$ represents the mass of the drone, and $\boldsymbol{a}$ is the acceleration of the center of mass.[1] The rotational dynamics, on the other hand, are described by $\boldsymbol{\tau}=\boldsymbol{I\alpha}$, where $\boldsymbol{\tau}$ denotes the torque, $\boldsymbol{I}$ is the moment of inertia, and $\boldsymbol{\alpha}$ angular acceleration.[1]

Quadcopters, specific dynamics are determined by the forces and torques generated by its four rotors. The thrust force produced by each rotor is given by $F_i = k_f \omega_i^2$, where F_i is the thrust generated by the i-th rotor, k_f is the thrust coefficient, and ω_i is the rotor's angular velocity.[2] Similarly, the torque generated is $\tau_i = k_m \omega_i^2$, with τ_i being the torque generated by the i-th rotor and k_m the torque coefficient.[2]

To manage the drone's orientation and navigation, coordinate transformations between different frames, such as the body and the inertial frames, are essential. This involves the use of a rotation matrix $R = R_z(\psi) R_y(\theta) R_x(\phi)$ for three-dimensional rotations using yaw (ψ), pitch (θ), and roll (ϕ)angles.[3]

Control theory is integral to drone operation, with Proportional-Integral-Derivative (PID) controllers being a common approach due to their simplicity and effectiveness. The PID controller equation is

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + kd \frac{de(t)}{dt}$$

where $u(t)$ is the control input, $e(t)$ the error signal, and K_p, K_i, K_d the proportional, integral, and derivative gains, respectively.[5]

For more advanced control, state-space representation models the drone's dynamics with equations such as $\dot{x}(t) = Ax(t) + Bu(t)$ for state vector $X(t)$, state matrix A, input matrix B, and the control input vector $u(t)$.[6] The output equation is $y(t) = Cx(t) + Du(t)$ where $y(t)$ is the output vector, and C and D are the output and feedthrough matrices, respectively.[6] The Linear Quadratic Regulator (LQR) approach optimizes control by minimizing a cost function $J = \int_0^\infty (x^T Q x + u^T Ru) dt$ where Q and R are weight matrices that penalizes state deviation and control effort.7

For accurate state estimation, sensor fusion plays a crucial step. This is implemented by applying the Kalman filter. This recursive algorithm estimates the state of a dynamic system from noisy measurements through a two-step process:

a) The predict step: $\hat{x}_{k|k-1} = A\hat{x}_{k-1|k-1} + Bu_{k-1}$
b) The Update Step: $\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(z_k - H\hat{x}_{k|k-1})$

where $\boldsymbol{K_k}$ is the Kalman gain, $\boldsymbol{P_k}$ the estimate covariance, $\boldsymbol{H}$ the measurement matrix, and $\boldsymbol{Q}$ and $\boldsymbol{R}$ the process and measurement noise covariances, respectively.[8]

To control the speed of the motor, Pulse Width Modulation (PWM) is used, and this is defined by ***Duty Cycle***=$\frac{T_{on}}{T_{total}}$ where $\boldsymbol{T_{on}}$ is the time the signal remains high, and $\boldsymbol{T_{total}}$ is the total time period.[9] Wireless communication protocols such as Wi-Fi, Bluetooth, or custom RF communications are used for remote control and telemetry.[10]

The practical implementation involves hardware and software integration. The drone's brain is the flight controller that sends necessary control signals. Flight controller firmware integrates control algorithms, sensor fusion, and communication protocols to manage drone operation.[11] The Electronic Speed Controller (ESC) interprets the control signal PWM to regulate motor speed.[11] Integration of GPS and the Inertial Measurement Unit (IMU) is essential for maintaining a stable flight and accurate navigation.

3. The Flight Controller:

Designing a flight controller instead of purchasing one ready-made one is the most challenging part of this project. It takes a lot of understanding and practical knowledge about the function of flight controllers deeply. We also need to know the basic principles of sensors, processors, communication protocols, and transmitter pins. The sensors required for building the controller are:

a. U-Blox NEO 6M GPS
b. BMP-280 Pressure sensor
c. MPU-9250
d. HC-SR04 - Ultrasonic distance sensor
e. Arduino Nano.

A GPS module is essential for navigation, tracking, mapping, surveying, etc. It allows to share the pinpoint location of the drone with its user, get the direction of its desired destination, and receive a real-time update about its flight. The NEO-6 module series comprises stand-alone GPS receivers featuring the high-performance U-Blox 6 positioning engine. We have selected this GPS module because it can operate in all weather conditions (from -40 to 85 degrees Celsius temperature), consumes low power (3.3V), and has a 5Hz position update rate that helps to deliver real-time information about the location and position of the drone. This GPS module is lightweight (12g) and smaller (22x30x13mm) and delivers excellent performance in a compact design, making it the perfect choice for our flight controller.

However, there is a drawback of GPS technology. GPS doesn't function properly in indoor environments or if the signal strength is low. We have included an MPU-9250 sensor equipped with an accelerometer, magnetometer, and gyroscope to remove that limitation. These three values contribute to making the drone more stable. The accelerometer measures the angular velocity and helps determine the drone's position and orientation. The gyroscope measures the rate of rotation and helps in balancing the drone. A magnetometer helps scan the area and determine if there is any magnetic field surrounding the system. It also allows obtaining geo-referenced maps of the area. To boost drone flight performance and stability, the MPU-9250 is a good choice. It is the smallest motion-tracking device with a dimension of (3x3x1mm), consumes less power, and provides high performance at a reduced cost. Although three independent sensors can do the same, the circuit design becomes more complex.

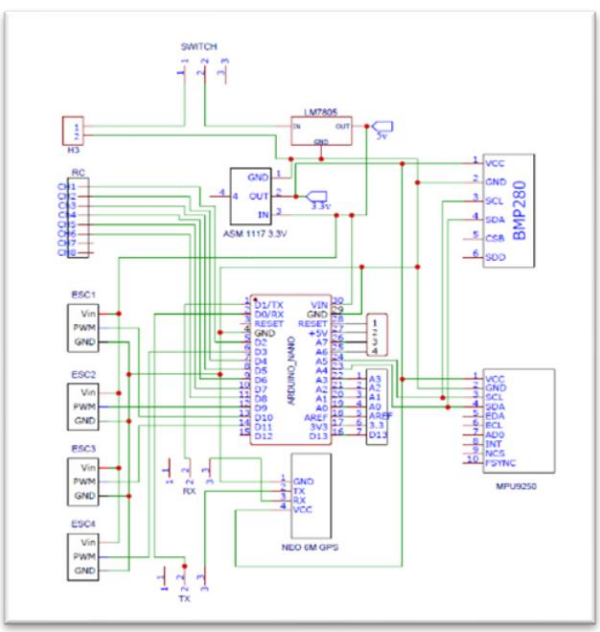

Figure 3.1a: Flight Controller Schematic Diagram

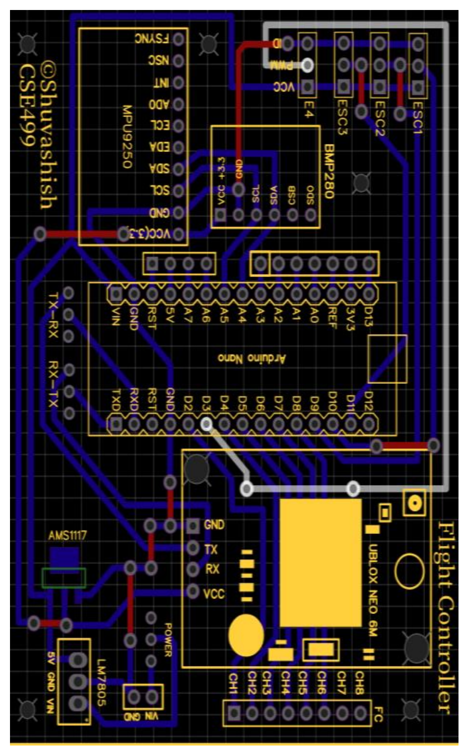

Figure 3.1b: Flight Controller PCB Layout

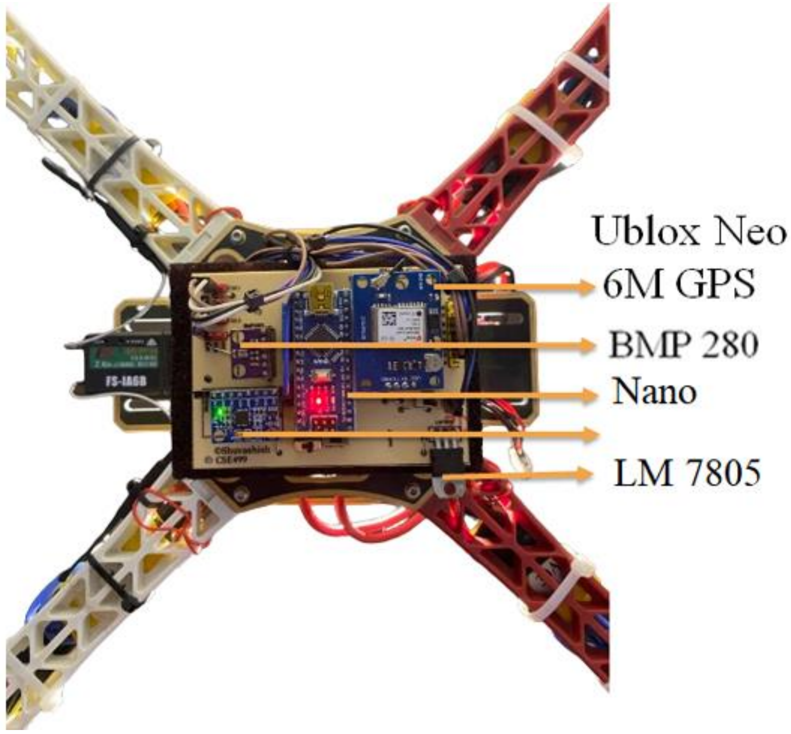

Figure 3.1c: Primary Flight Controller

We cannot ignore the air pressure during the flight time of a drone. For this reason, we have used a BMP-280 pressure sensor in our flight controller. It can measure temperature, pressure, and relative humidity with great accuracy. Drones utilize this pressure sensor to stabilize at an altitude, allowing hovering capabilities. MPU-9250 and BMP-280 combined help achieve precision flight for the drone.

4. The obstacle avoidance unit:

We have applied the potential field method for implementing obstacle avoidance. With this, we applied scalar fields to guide drones toward targets while repelling them from obstacles. This method integrates attractive potentials, defined as $\boldsymbol{U_{att}(q) = \frac{1}{2}K_{att}\left|\left|q - q_{goal}\right|\right|^2}$, which pull drones towards the goal, and repulsive potentials, defined as $\boldsymbol{U_{rep}(q) = \frac{1}{2}K_{rep}(\frac{1}{d(q)} - \frac{1}{d_0})^2}$ for $\boldsymbol{d(q) \leq d_0}$ and $\boldsymbol{0}$ otherwise, which push them away from obstacles.

The total potential field $\boldsymbol{U(q) = U_{att}(q) + U_{rep}(q)}$ combines this effect and drones navigate by following the negative gradient $\boldsymbol{v = -\nabla U(q)}$, facilitating smooth and real time path planning.

Integrating accurate sensors and ensuring computational efficiency are critical for practical application.[14]

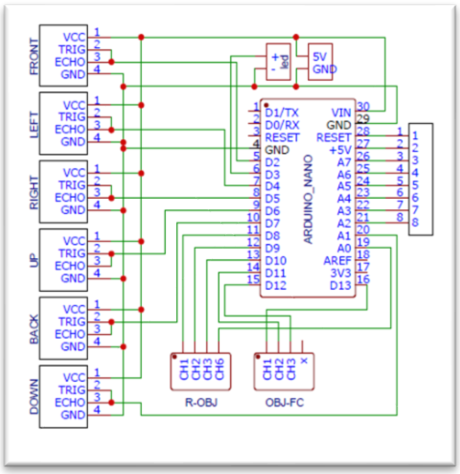

Figure 4.1a: Obstacle Avoidance Schematic Diagram

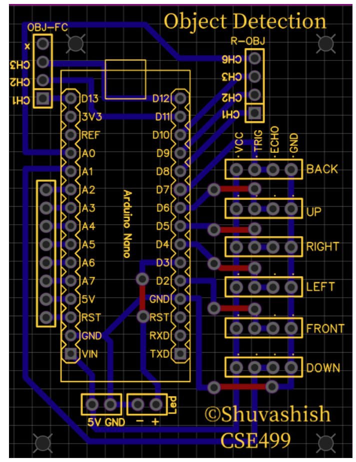

Figure 4.1b: Obstacle Avoidance PCB Layout

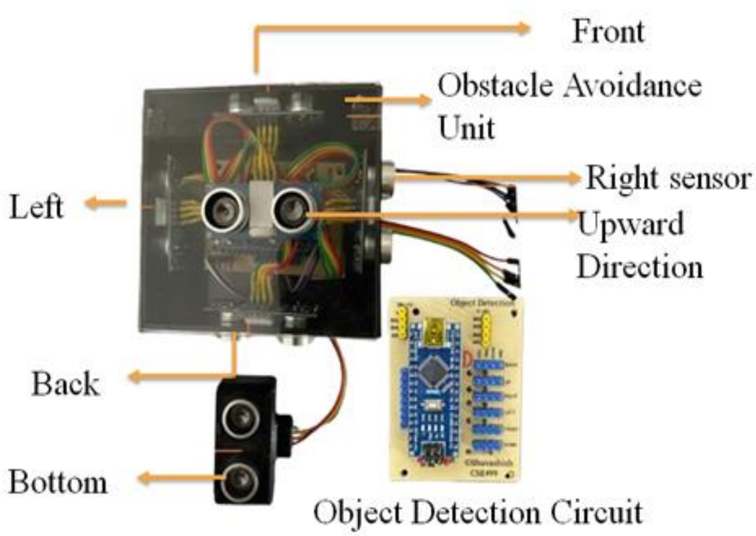

Figure 4.1c: Obstacle Avoidance Circuit

To implement object avoidance and collision avoidance, we have used six HC-SR04 - Ultrasonic distance sensors capable of detecting objects in six directions. This sensor provides an operating accuracy of up to 3mm and gives non-contact measurement functionality from 2cm to 400cm. It helps measure an object's distance from the drone and avoids any obstacle in the flight trajectory. To avoid a collision, the controller is programmed to move in the opposite direction if any object gets detected within 1.5 meters.

5. The Final Design:

We have designed the flight controller into two phases. The primary fight controller is designed with an Arduino Nano, where we have integrated different sensors, including GPS, MPU-9250, and BMP-280. This unit is equipped with all functionality for basic control and movement of the drone. The secondary unit is the obstacle avoidance unit, equipped with six HC-SR04 - Ultrasonic distance sensors. This unit can detect any object that the drone encounters during flight. The cost of the flight controller is around 3000 BDT. This flight controller is cheaper in price, but it can compete with the most advanced flight controller available in the market.

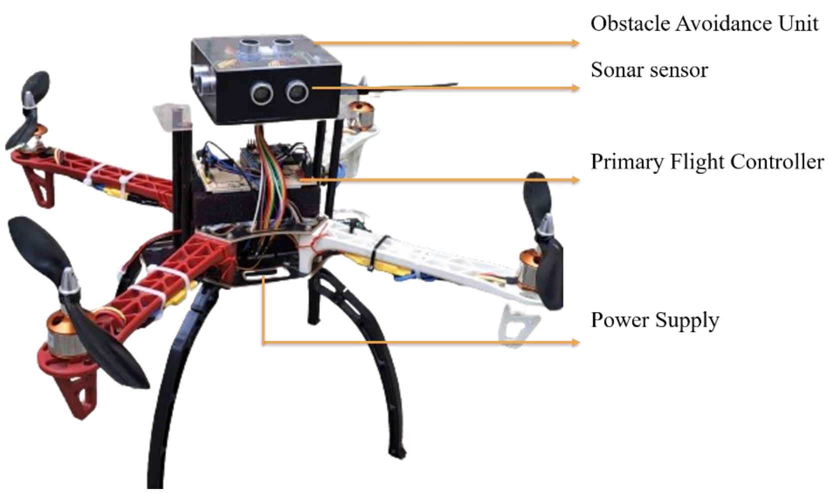

Figure 4.1: Precise Controlled Obstacle Avoidance Drone

6. Technical Specifications of this drone:

Parameters	
Range	Maximum 1.5Km in radio line of sight
Time of flight	<=25 minutes
Weight	1149 gram
Flight Altitude	200 feet (According to CAAB rule)
Operating temperature range	0° to 50° Celsius

Parameters	
Fail-safe features	- Emergency Return to Launch position option - Geofencing option to restrict both horizontal and vertical flight envelope of the drone - Autonomous return to home or land (programmable) in case of power loss - Collision avoidance System
MPU-9250 IMU Sensor	YES
U-Blox 6N GPS	YES
BMP-280 Pressure Sensor	YES
HC-SR05 Ultrasonic Sonar Sensor	YES
Camera Resolution	2 megapixels
Battery Capacity	2200 mah, 3S
ESC	30A
Motor	4x 1400Kv brushless Motor

7. Conclusion:

In conclusion, this project represents a significant step forward in drone technology, aimed at delivering a highly controlled and versatile UAV system focusing on precision and adaptability. Through proper project planning, we have navigated challenges, expanded capabilities, and laid the groundwork for a drone system that promises enhanced stability, safety, and reliability across various applications. This budget-friendly drone is equipped with all the necessary features along with an obstacle avoidance system and is capable of precise movement and control. As we move forward, the opportunities for this technology are boundless, and the potential for impactful contributions in industries such as agriculture, aerial photography, infrastructure inspection, and beyond is substantial.

8. References

1. Meriam, J. L., & Kraige, L. G. (2002). Engineering Mechanics: Dynamics (5th ed.). Wiley.

2. Bouabdallah, S., Murrieri, P., & Siegwart, R. (2004). Design and control of an indoor micro quadrotor. In Proceedings of the 2004 IEEE International Conference on Robotics and Automation (Vol. 5, pp. 4393-4398).
3. Craig, J. J. (2004). Introduction to Robotics: Mechanics and Control (3rd ed.). Pearson.
4. Kuipers, J. B. (2002). Quaternions and Rotation Sequences: A Primer with Applications to Orbits, Aerospace, and Virtual Reality. Princeton University Press.
5. Åström, K. J., & Hägglund, T. (2006). Advanced PID Control. ISA - The Instrumentation, Systems, and Automation Society.
6. Ogata, K. (2010). Modern Control Engineering (5th ed.). Prentice Hall.
7. Anderson, B. D. O., & Moore, J. B. (2007). Optimal Control: Linear Quadratic Methods. Dover Publications.
8. Welch, G., & Bishop, G. (2006). An Introduction to the Kalman Filter. University of North Carolina at Chapel Hill, Department of Computer Science.
9. Erickson, R. W., & Maksimovic, D. (2001). Fundamentals of Power Electronics (2nd ed.). Springer.
10. Rappaport, T. S. (2002). Wireless Communications: Principles and Practice (2nd ed.). Prentice Hall.
11. Escalante, C. J., & Gómez, R. (2016). Design and Implementation of a Quadcopter. International Journal of Computer Applications, 147(2), 1-5.
12. Commercial Drone Market Size, Share & Trends Analysis Report By Product, By Application, By End-use, By Propulsion Type, By Range, By Operating Mode, By Endurance, By Region, And Segment Forecasts, 2023 – 2030.
13. https://www.statista.com/outlook/cmo/consumer-electronics/drones/bangladesh
14. Rimon, E., & Koditschek, D. E. (1992). The construction of analytic diffeomorphisms for exact robot navigation on star worlds. Transactions on Robotics and Automation, IEEE, 8(4), 477-490.
15. Koditschek, D. E. (1987). Exact robot navigation by means of potential functions: Some topological considerations. Proceedings of the IEEE International Conference on Robotics and Automation, 1, 1-6.