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Developing quadcopter using Pixhawk 2.4.8 for enhancing atmospheric physics learning

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***Abstract*—Implemented project-based learning using drones is more fun and the concepts delivered are easily understood by students. This research has built a DIY drone using an F450 quadcopter to improve the quality of the learning process such as basic concepts of atmospheric physics. The main system of the drone is a Pixhawk 2.4.8 flight controller where the system is set up via Mission Planner to work on autopilot. For atmospheric physics learning, atmospheric data such as temperature, relative humidity, and air pressure is collected using BME280 sensors on the drone and on the ground. The sensor is controlled by Arduino Uno and a data logger has also been developed to store data into a Micro SD card for post hoc analysis. Once the drone is tested for flight stability, it can be applied to measure atmospheric parameters including flight altitude and precipitable water vapor. With this development, the system can be utilized to quantitatively show the relationship between atmospheric parameters and ultimately can predict other related parameters as well as able to provide interpretation of measurement results as evidence of improved understanding.**

***Keywords*—Developing quadcopter; Pixhawk 2.4.8; Arduino Uno, BME280; learning enhancement**

I. INTRODUCTION

RECENT advances in civilian drone technology have increased their use in various sectors such as hobbies (recreation), research, business, and public services. Drones are very reasonable and can be applied to help educate the nation. One of the classic problems in the teaching and learning process is how a difficult concept can be delivered effectively and easily understood by students. There are still many technical subjects that are difficult to explain theoretically but have to be delivered conventionally due to the limited facilities and infrastructure in an institution as well as limited human resources. Ideally, students are motivated, given space and framework in which they able to creative, and express their ideas in a way that is relevant, interesting, and useful. Courses in Electrical Engineering such as sensors, robotics, and from microcontrollers to remote sensing require learning media such as practicum. Practicum or demonstration method can bridge the gap in understanding concepts as well as hone skills through the ability to identify, design, formulate, conduct experiments, analyze data, and solve engineering problems [1,2]. However, in a pandemic situation, online practicum and especially when students spend their own pockets to buy electronic components for a few subjects is very expensive and burdensome. This is a real challenge in developing a Project-Based Learning (PBL) strategy based on learning by doing, namely a hands-on learning approach coined by John Dewey where students must interact with their environment to adapt and learn [3]. The success of this method will lead to experiential learning [4] where students who experience the phenomenon will be able to remember concepts that have been understood for a long term.

This paper contributes to the development of a drone that can be utilized to improve understanding of Atmospheric Physics. As electrical engineering students at one hand and later working in the industrial sector, they must have the ability to design, create, and implement systems built to solve problems. In this project, the system developed is expected to facilitate the gap between theory and fact, for example, if the humidity reaches 100%, should it rain? With a self-made system, developers will be able to perform their own maintenance, modifications, and further advance their electronic skills. Recently, the use of drones for various purposes has beneficial to the industry include cost savings, speed of work, increased security, and efficient data collection [5]. Many types of drones have been produced by manufacturers, especially for educational purposes [6]. The following briefly describes studies that apply drones in the educational environment, especially for teaching in higher education [7]. Studies using micro-drones/UAVs in geological fieldwork such as aerial surveys, field mapping, and monitoring have been proposed by Jordan [8]. Fung and Watts [9] documented the use of drones as a new technological filming tool to enhance student learning in the field of analytical and environmental chemistry via environmental sampling exercises. The use of drones in a structured way to teach fundamental concepts of geospatial technology [10], GeoSTEM Education [11], and pedagogical technology [12] within a STEM (Science, Technology, Engineering, and Mathematics) framework from elementary to tertiary education has been carried out massively. Hall and Wahab [13] have also discussed the increasingly widespread application of drones as a tool for research in the social sciences as drones in archeology have made it possible to access artifacts and photographic taken from drones is the main key data needed in the study of social communication. From a brief piece of drone applications in the learning process in universities, drones are widely used for research, competition, and community services rather than for learning media. Drones are more widely used as a medium of teaching and learning in

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high schools with a particular focus on STEM education. To strengthen the learning process in higher education, it is necessary to adapt regulations and new mindsets towards drone technology for the mutual benefit of various parties and stakeholders. In addition, the state of the readiness of lecturers (attitudes, competencies, and obstacles) for the application of drone-based teaching and learning should be assessed [11,14]. From the outcome on the use of drones as a learning platform published work above, it was very helpful in improving understanding, construction, and interpretation of the content covered. It can be concluded that the technological device proposed in this pedagogical process promises to significantly improve student learning in STEM or other fields.

In the context of using drones as learning media, most of the drones applied in previous research for education are RTF (ready-to-fly), while in this paper we will propose to build our own drone such as used for the study of atmospheric physics. Therefore, the developing steps of DIY drone will be explained in detail. An example of using drones to collect meteorological elements such as temperature, relative humidity, pressure, elevation, and latitude and longitude using a six-rotor UAV (hexacopters) has been proposed by Zhang et al. [15]. The DJI Phantom 4 Pro quadcopter plus an infrared surface temperature sensor has been used to measure similar atmospheric parameters as in [15] in the atmospheric boundary layer [16]. In addition to measuring atmospheric parameters, the vehicles developed to achieve the mission must also be adapted to financial and local weather conditions. Most drones are very sensitive to extreme weather. There are two types of aerial drones that have commonly been used, i.e. multirotor airborne and fixed-wing [17]. One of the advantages of the multirotor that will be employed in this project is its ability to take off and land vertically. Their limitation is on the range and flight endurance of around 20-50 minutes [18]. The most commonly used multirotors are tricopters, quadcopters, hexacopters, and octacopters where these UAVs such as DJI (Da-Jiang Innovations) with self-mounted cameras or special UAVs for industrial purposes fall into the commercial category. A quadcopter is a vehicle of an unmanned aircraft system or UAV, similar to a helicopter but with four rotors on each arm.

To be able to measure atmospheric parameters in the air at a certain altitude with stability, the vehicle developed is a quadcopter with a quadcopter type. The factor in choosing this quadcopter is the ease of designing, installing, and the firmware has been provided by the Ardupilot. This quadcopter is controlled by a Pixhawk flight controller. To measure and store atmospheric data obtained from drones, an automated weather system (AWS) using the Adafruit BME280 sensor has also been developed [19]. The sensor is controlled by Arduino and mounted under the drone body as a payload. In other words, the focus of this paper is to develop a quadcopter using the Pixhawk for Atmospheric Physics learning targets. One of the advantages of the system developed for atmospheric learning is the inclusion of precipitable water vapor (PWV) parameter, which has not been found in other existing systems. PWV is a measure of the total amount of water vapor content in mm or kg/m^2 in a vertical column extending from the Earth's surface to the top of the atmosphere (below 10 km or tropospheric region). This parameter is useful for improving weather forecasts, especially when there is a potential for rain or thunderstorms, or when the atmospheric data is obtained over a long-term, it can be used for climate change studies [20,21].

The rest of this paper is organized as follows. Section 2 focuses on materials and methods for developing drones and AWS that are feasibly employed to enhance learning in atmospheric physics. Section 3 presents the results of the drone development, the measurement, and the data collected. Section 4 discusses the results obtained including the challenges of developing drones, provides a physical interpretation of the measurement results, and compares the results with ground truth datasets. Finally, Section 5 presents conclusions and provides suggestions for future work.

II. Materials and Methods

A drone is a type of flying robot that is physically controlled by remote control (RC) from the ground station. The signal transmitted by the RC is received by the receiver on the drone. This signal drives the Brushless DC motor (BLDC) through the Electronic Speed Controller (ESC) and finally spins the propeller. Flysky is the brand for the transmitter as well as the receiver brand used in this study. To design a drone that can fly stably and be able to take measurements or monitoring as desired, the general steps of how the system works can be described as the block diagram of Fig. 1. This is a DIY project. Referring to Fig. 1, after selecting and assembling all the primary components, the drone is set up and synchronized as autopilot. Calibration and settings can be carried out via the Mission Planner as control inputs. Input controls are all control parameters required by the drone to characterize or function itself as autopilot. After all calibration steps have been done and the drone is ready to be tested to fly. If the drone can't fly, then all connections or settings need to be rechecked. In short, drones that are airworthy and flying stable will be able to take off, hover, collect data according to the installed sensors, and land smoothly. The following subsection describes the design of the system and components used along with their functions and how to set up. An AWS payload will also be briefly discussed.

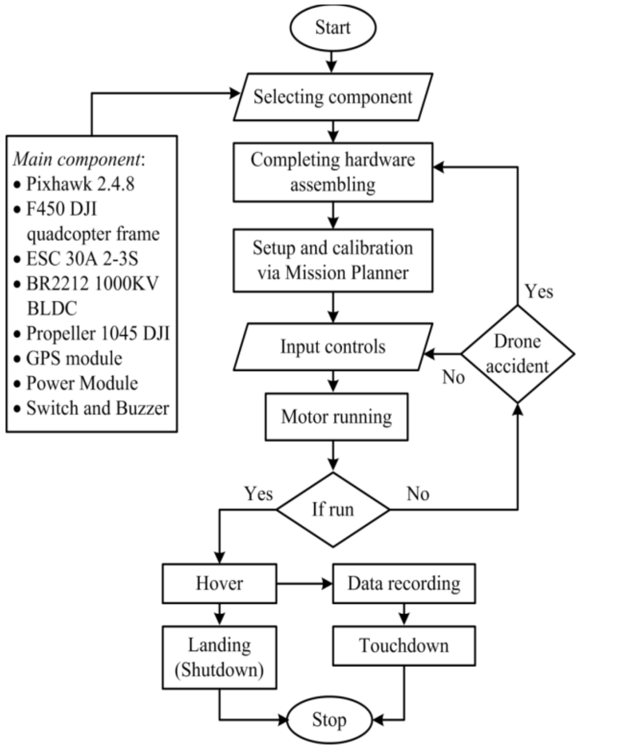

Fig. 1. The flow of how the quadcopter control system works in this study.

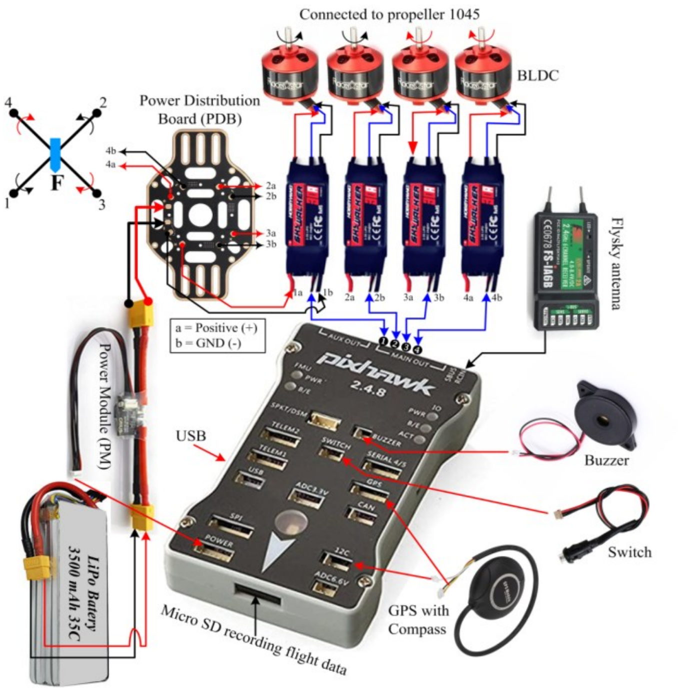

Fig. 2. The DIY of quadcopter using Pixhawk 2.4.8 and their basic connection for our work.

A. Quadcopter System Design and Implementation

Referring to Fig. 1, as the basis for designing and implementing the system being built, the modules used in this work to develop a quadcopter are briefly described as follows.

1) Pixhawk 2.4.8 Flight Controller

Pixhawk 2.4.8 is the advanced 32-bit 2M flash memory ARM Cortex core M4 with FPU STM32F427 high-performance processors, can run NuttX RTOS real-time operating system, operated at frequency 168 MHz, 256K RAM, and equipped with 32 bit STM32F103 failsafe coprocessor. Inside the board, it is contained four sensors, viz. LSM303D 3 axis 14 bit accelerometer/magnetometer (compass), MPU6000 6-axis accelerometer/magnetometer, L3GD20 3 axis digital 16-bit gyroscope, and MS5611 high-precision Barometer [22]. The board integrates with PX4FMU and PX4IO. Power and interfaces on the outside of the board can be seen in Fig. 2. For basic operation, the board is connected to Power Module (PM), Global Positioning System (GPS) with compass, switch button and multitone buzzer, Flysky antenna connected to RCIN via PPM/CH1, ESC, and USB for connecting laptops. Each output of the ESC as a speed controller is connected to a BLDC, and finally, each BLDC has mounted a propeller. The direction of rotation of the motor/propeller is in accordance with the placement of the ESC connection on the Power Distribution Board or PDB (see the figure). Motors 1 and 2 spin counter-clockwise (CCW) and motors 3 and 4 spin clockwise (CW). BLDC is a servo motor to convert electrical energy into mechanical energy to drive the elevator, rudder, and aileron [23]. It has a stator and rotor as power-producing units to produce thrust by turning the propeller. This propeller produces lift for the aircraft so that the quadcopter is able to take off, hover, and landing.

From Fig. 2, the PM has two outputs, one with 5V dc and connected to the POWER port of the pixhawk (6 pin cable) and the other output is connected to the PDB on the F450 frame to power ESC. The PM input is from the LiPo battery (3500 mAh 35C) which is capable of producing a constant voltage of 11.1 V dc. The output voltage converted to 5V via PM must be exactly 5.0V, if is less than 5.0V, the autopilot will not work, or work but not stable. While the GPS cable is mounted in two ports, one to I2C port with 2-wire (device type HMC5883 for the MAG) and other to GPS port with 4-wire (device type LSM303D SPI for positioning data during flight) and the GPS direction must be mounted in the direction of the pixhawk (Forward). The SD card on the pixhawk was installed to store configuration files, flight logs, mission information, etc. Buzzers and switch buttons must also be installed for safety; if one of them is omitted then the autopilot will not work. To activate the autopilot, the switch button must be pressed until the light is steady (not blinking), and then the armed process on the RC can be started. Before moving the throttle, the Flysky antenna must be remotely connected to RC via a binding process. Binding is the process of synchronizing signals between a receiver (Rx) and an RF transmitter (Tx). The Rx has two pins that are short-circuited together using a binding plug and the other is connected to one of the ESC output pins (e.g. Ch2). The Tx that uses a 2.4 GHz has a BINDKEY on RC (Flysky FS-i6 was not shown in Fig. 2). When the BINDKEY and Power on the RC are turned on together, the Rx LED will blink rapidly and glow steadily, and then Rx will respond to the movement of the stick. Unplug the binder indicating the binding process has been successful to which autopilot also responds with a special tone. The next steps are mandatory settings for all hardware used via the Mission Planner, such as rotor/frame type, Pixhawk, or APM as well as calibration for acceleration (Accel.), Compass, Radio control, ESC, flight modes, and failsafe. Details for these settings will be explained in the following sections.

2) Setup the Pixhawk

After all components are installed (except the propeller) then the setting for autopilot is ready to be done. The Mission Planner firmware has been downloaded from the ArduPilot Web [24]. Sometimes Windows 7, Ultimate 64 bit requires a .NET Framework 4.8 Runtime to be installed. After that, install the MissionPlanner-latest.msi. If it turns out that this firmware cannot be run or connected to our device (ERROR: no response from the device) then installs MissionPlanner-1.3.75.msi, or the latest version. A successful installation before connecting as autopilot is displayed in Fig. 3.

Fig. 3. Successfully installed Mission Planner Version 1.3.75 for ground station.

As evidence of the rapid development of the drone industry, many online Ground Control Station (GCS) installation instructions such as Mission Planner, QGroundControl, APM Planner 2, and so on are now available. One of the most important guidelines for installing Mission Planner can be found on the ArduPilot homepage [22, 24]. Figure 4 shows a successful connection between Pixhawk and Mission Planner. Once connected, we can perform calibration procedures such as frame selection, initial parameters, accelerometer calibration, compass, radio calibration, ESC calibration, and flight modes. A successful calibration with GPS locked is indicated by the rotation of the four motors. Note that the receiver and transmitter are linked to allow remote arming. The propeller rotation must generate thrust to allow the drone to loiter and maneuver while maintaining flight.

B. Automatic Weather System with BME280 sensors

After the quadcopter has been developed and tested, the next step is to collect atmospheric data on air using drones. For this purpose, two sets of automatic weather stations (AWS) have been developed, one is mounted on the drone body as a payload and the other is placed on the ground which later as a comparator of measurement results between the drone and on the ground. AWS for the ground is powered from a charger bank. Both AWSs have been developed by Suparta et al. [19] where the main components used can be briefly described as follows:

- Arduino Uno R3
  This controller uses the Atmega 328P as the main processor to control AWS and measurement. The affordable and the number of pins required by the sensor device are the reasons for choosing this type of Arduino.
- BME280 sensors
  The main core of AWS being able to measure temperature, humidity, air pressure, and also altitude at a certain location is the BME280 sensor manufactured by Bosch Sensortec. It allows the measurement of temperature in the range of -40ºC to +85ºC with ±1.0°C accuracy, relative humidity in the range of 0 to 100% with ±3% accuracy, and air pressure ranging from 300 to 1100 mb with ±1 mb absolute accuracy. The main consideration in choosing this type of sensor is its small size, sensitivity, high accuracy, low-power consumption, affordable price, and compatibility with Arduino.
- DS3231 RTC module
  This module is very widely used for time measurements because of its high accuracy. The advantage of this module is that the data can be saved back in the same file automatically according to the current time when the power is ON.
- 16×2 LCD with I^2C module
  This module serves to display the measurement results and as an indicator to show the functioning of the sensor or system.
- Micro SD card module
  This module is used to store measurement data for post hoc analysis.

In short, the entire system developed to collect atmospheric data using drones is illustrated as in Fig. 5. Note that before both AWSs were used to take measurements outdoors, they were calibrated to each other at the same position and time. Calibration data were collected for 18 hours indoors (HOME: 7°44’54” S, 110°26’16’’ E, and an elevation of 175 m above the mean sea level (asl)) with the aim to reduce external influences. The mean difference between AWS for drones was 1.17°C, 3.26 mb, and 1.98 mm higher than AWS for Ground Station for temperature, pressure, and PWV, respectively. Only the humidity of the two sensors shows almost the same readings and the altitude position based on Google Earth is correctly follows the sensors on the drone. Differences in readings between sensors may be due to the influence of internal components. The average difference between these two measurements will be used as calibration factors. Overall, both sensor readings consistently have the same variations and trends.

In a summary, the AWS in this work is capable of measuring temperature (T), air pressure (P), relative humidity (H), and altitude (ALT). The altitude from BME280 sensors can be determined by coding as below [19].

$$Altitude = bme280.readAltitude(SLP) \tag{1}$$

However, sometimes the Micro SD card cannot save all the parameters desired due to limited memory address or stack buffer overflows. In other words, only *P*, *T*, and *H* can be saved. Alternatively, the altitude of a site can be determined from air pressure measurements as the equation below [25].

$$Altitude = h_0 + \frac{T_0}{\beta}\left[\left(\frac{P_{air}}{P_0}\right)^{-1/\alpha} - 1\right] \tag{2}$$

where h_0 is the altitude of the site (in meter) which can be set = 0, T_0 is a standard temperature (288.15 K, or 15°C), P_0 is the standard atmospheric pressure at Sea Level Pressure or SLP (1013.25 mb), β is the standard temperature lapse rate [0.0065 K/m], α is a constant obtained from $\frac{g\,M}{R\beta} = \frac{(9.80665)(28.9644)}{(8314.32)\,(0.0065)} =$ 5.257 [26], and P_{air} is the reading of air pressure from a sensor (mb). Meanwhile, atmospheric water vapor in the form of precipitable water vapor (PWV) cannot be directly measured from the sensor, it is derived from the intermediation of pressure, temperature, and relative humidity measurements based on the least-squares or multiple linear regressions (MLR) method in the ANFIS network with the following equation [21].

$$PWV = \lambda_1 P_{air} + \lambda_2 T_{air} + \lambda_3 RH + \lambda_4 \quad (3)$$

where the regression coefficient values, λ_1 = -0.1707, λ_2 = 2.3614, λ_3 = 0.623 and λ_4 = 103.6103 are for air pressure (P_{air}), surface temperature (T_{air}), relative humidity (RH), and intercept, respectively.

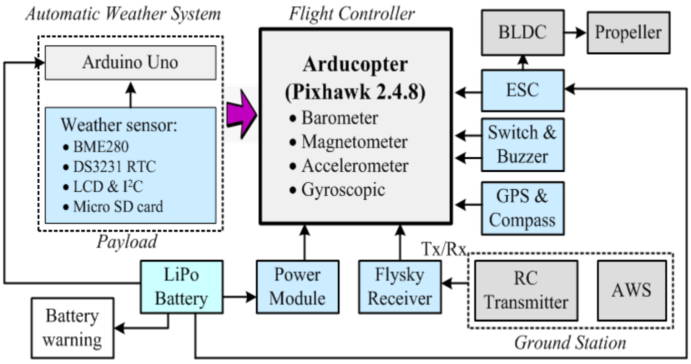

Fig. 5. The designed of quadcopter for implementing PBL in Atmospheric Physics.

All figures and tables should be numbered and always referred to in the text (e.g., Fig. 1 and Table I). Figures should be clear and high-quality finished artworks. The lettering should be large enough to be readily legible. Image quality is essential to how your graphics will be reproduced. If your pictures look low in quality on your printer or monitor, please keep in mind the quality cannot be improved after the submission.

III. Materials and Methods

A. Developed Quadcopter and Implementation

Based on Fig. 2 and Fig. 5, the results of this first part are a quadcopter (see Fig. 6) which was developed with the F450 quadcopter frame where Pixhawk 2.4.8 is used as the main flight controller. As shown in the figure in a RTF position, the BLDC and propellers are mounted on each end of the drone arm. This BLDC generates lift and propellers create thrust. GPS with a compass is installed at one of the bases of the pilot's right rear arm to avoid magnetic interference and point to F (Forward). As for the payload, it is containing AWS controlled by the Arduino Uno in the light blue box is mounted on the underbody of the drone. The 16x2 LCD is housed in the box to the right side of the pilot. Apart from displaying measurement readings, this LCD also shows whether AWS is working or not. Meanwhile, AWS for the ground station (yellow box) on the left side of the drone is used to compare the results of atmospheric data measured from drones. Note that both boxes are perforated with multiple vents to allow the meteorological sensors in the box to adapt to the external environment.

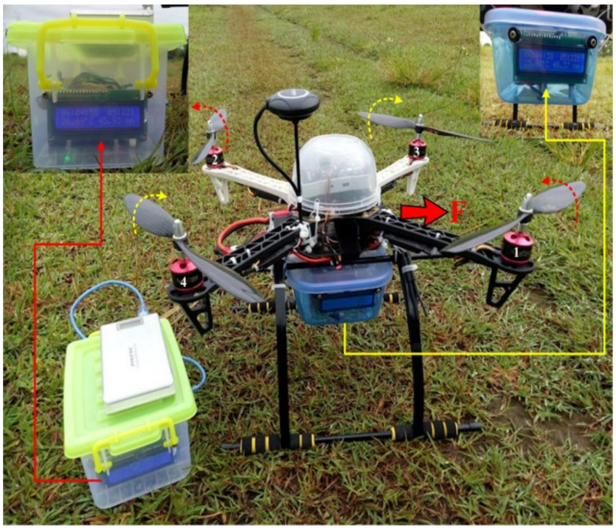

Fig. 6. A quadcopter that has been developed and is equipped with Arduino meteorological sensors as payload (light blue box) and AWS for ground-station (yellow box).

The quadcopter that has been developed and configured are ready to be tested for its functionality. Quadcopter can fly perfectly where all motors spin simultaneously according to the CW (clockwise) or CCW (counter-clockwise) direction (see Fig. 6). These directions were created to avoid torsion on the body with 1 & 2 and 3 & 4 (see Power Board of Fig. 2) is connected for CCW and CW, respectively. The drone is controlled via throttle movement on the Flysky RC transmitter (FS-i6) model 2, and once armed; it can fly and maneuver. With a lightweight carbon fiber propeller, the drone flies to a radius of 300 m based on the line of sight (LOS). The landing gear drone uses a multifunctional FPV (first person view) aerial photography gimbal mount set which is later planned to mount the camera. For this initial stage, the drone is not equipped with telemetry and cameras, so it is controlled to fly only around of height below 100 m above the ground. Drones are also flown by taking into account the existing regulations of the local government. In testing and measurements, drones were tested at the aircraft training field students, which are south of Adisucipto International Airport, or located at ITDA of Karang Janbe of Banguntapan, Bantul Regency (ITDA: 7° 47' 48.51" S, 110° 25' 08.33" E and an elevation of 105 m asl). In addition, drones were also tested in the rice fields of Bromonilan, Sambiroto, Purwomartani, Sleman Regency (SAMBI: 7°44'25.7"S, 110°26'49.6"E, and an elevation of 186 m asl). Both of these locations are in the Province of the Special Region of Yogyakarta. The geographical distance between these two locations is about 10 km.

B. Atmospheric Measurements

Fig. 7 shows the atmospheric data collected on October 1, 2021, in the ITDA area. Data on the ground station and quadcopter are both recorded every 10 seconds. In each panel of the figure shows T, H, P, ALT, and PWV which represent temperature (in degree Celsius), relative humidity (in %), air pressure (mbar), altitude or height above mean sea level or asl (m), and precipitable water vapor (mm) respectively. The blue up (↑) and blue down (↓) arrows on the altitude (ALT) panel indicate the drone in take-off and landing time positions, respectively. The first down arrow in the figure peaking at 05:22 am indicates AWS for the ground station is being moved to a safety place at a distance of about 5 m from the drone's take-off position. The difference readings between temperatures on the quadcopter before flying and on the ground station this morning was warmer by about 0.81°C and the relative humidity was obtained cooler by around 5.44%. With several maneuvers, the drone reaches its highest point up to 33.15 m from the ground at 05:39:00 am and on the air for about 12 minutes and 23 seconds. Furthermore, the PWV varies considerably according to the conditions of temperature, humidity, and air pressure where the difference before take-off is about 1.52 mm, and when vertically hover the PWV will significantly decrease.

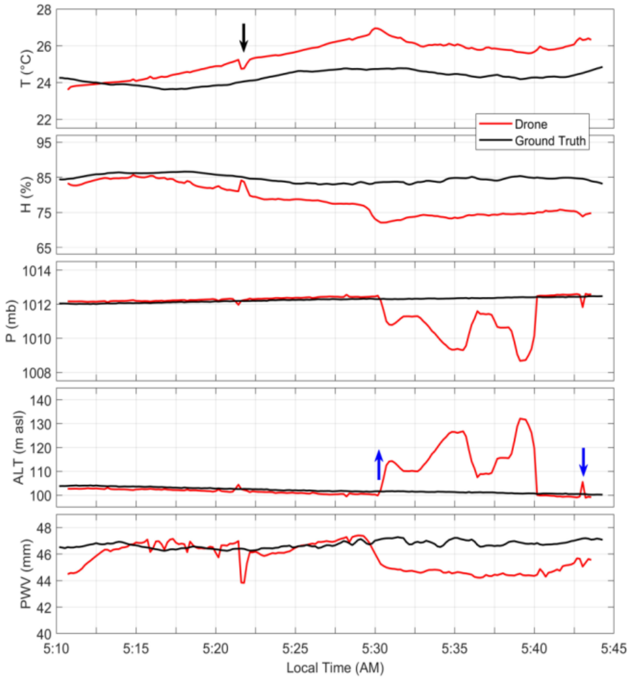

Fig. 7. Results of weather measurements in the early morning from drones and on the ground for October 1, 2021, at ITDA where Local Time = UTC + 07:00.

The second experiment on October 3, 2021, was carried out in the SAMBI area as depicted in Fig. 8. The purpose of this experiment is to compare the measurements obtained with different locations as well as to observe the stability of the drone while hovering with maneuvers. Similar to Fig. 7, the blue up (↑) and blue down (↓) arrows on the altitude (ALT) panel indicate the take-off and landing times of the drone, respectively. In this observation, the drone only maneuvers twice and flew for about 7 minutes. The weather difference between the drone and on-the-ground readings in this area before the quadcopter takes off is about 1°C warmer, 6% cooler, and 1.2 mm drop for temperature, relative humidity, and PWV, respectively. The drone has flown to a maximum height of 33.9 m at 05:44:13 am from the ground. The results of this measurement confirmed that the trend of all parameters obtained is almost similar to the location at ITDA, only the altitude at SAMBI is 76 m asl higher on average than at ITDA because it is nearby the Mount of Merapi.

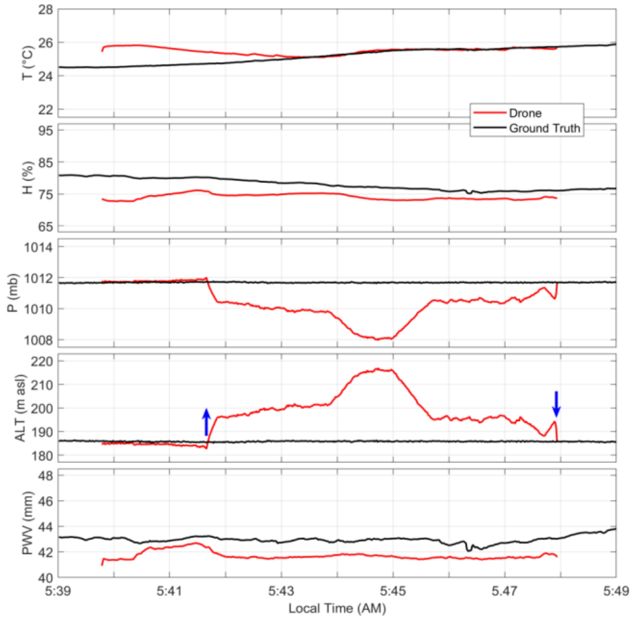

Fig. 8. Results of weather measurements in the early morning from drones and on the ground for October 3, 2021, Local Time at SAMBI area.

IV. Discussion

For the first result, the development and implementation of drones for PBL in Atmospheric Physics are discussed. The discussion will also be related to AWS that was developed using the BME280 sensor and controller by Arduino Uno. The second part will discuss the result of measurements from drones and on the ground.

A. Drone as a measurement vehicle

As shown in Fig. 6, the quadcopter is prepared to hover and collect atmospheric data. Fig. 9(a) for the top and bottom shows the drone successfully flew over ITDA in the early morning. Referring to the flight data, the position of the drone in Fig. 9(a) on the top is at a height of 27 m above the ground level. After hovering, maneuvering, and collecting the data, it was landed smoothly on the grassy ground which just a few meters from the take-off position as shown in Fig. 9(b).

From several flight tests carried out, the drone also experienced several obstacles such as all BLDC providing thrust and propeller turned according to its direction but undesiring to fly, flipping before takeoff, flying for a while then falling upside down, flying stable but AWS not recording data, blown by the wind, propeller detached, the battery suddenly drains quickly, etc. This experience is also very useful learning for flying a drone the next time. Of these problems, it is recommended to calibrate the vehicle and payload simultaneously, particularly in the Accel. step. Also recalibrate the drone when it is drifting, after crashing, not Return To Home (RTH), or there are suspicious components. This is necessary to maintain drone stability and a reliable failsafe. Since the quadcopter may crash from unexpected events, the Pixhawk board is protected with a plastic dome to minimize damage. The AWS sensors are also housed in a plastic case and the GPS antenna mast is attached on one of the bases of the drone arm. This pole is not screwed to one end of the armrest as recommended by manufacturers because if the drone falls the pole will be detached from the bolt and the GPS receiver will be physically damaged. Sometimes the AWS also cannot store data on the Micro SD card due to a lot of parameters to be saved. This can be handled by supplying a precise 5V to the circuit board. In addition, environmental conditions such as strong winds and drizzles must be considered to operate the drone. Our drones with a total weight of less than 1.5 kg or categorized as remotely piloted aircraft (RPA) are vulnerable to wind. This drone cannot work in all weathers.

Fig. 9. Unedited drone photos (a) from hover to landing preparation and (b) drone successfully landed.

As a summary of the drone developed in this study, it has the following characteristics: (a) can measure atmospheric parameters such as temperature, air pressure, relative humidity, altitude, and PWV; (b) type F450 quadrotor with a total weight of 1.2 kg and has the ability to fly up without payload to an altitude of 200 meters and a range of more than 500 m based on LOS where Geo Fence during this testing was configured to 300 m altitude and a range of 1 km; (c) able to fly for about 10 - 20 minutes on average depending on battery capacity, maneuvers performed, and weather conditions; (d) the data collected from drones can be utilized as a demonstration of teaching Atmospheric Science courses to high school students or college students majoring in geography or remote sensing. When the drone is operated at wind speeds above 10 m/s or fresh breeze [25], they cannot fly stable. This drone should be used outdoors in sunny weather, calm winds, and not drizzling. Qualitatively from their experimental results, the learning process with drones is very interesting and motivated because students can adapt to the outside environment as well as experiment with their drones. In conclusion, the use of drones to take measurements in the sky as well as monitoring and implementation in learning presents new challenges and helps provide new approaches to inculcate basic concepts or strengthen elusive scientific foundations with traditional learning.

2) Atmospheric data collection and analysis

Referring to Fig. 9(a), the drone flies and carries an AWS payload. The AWS on the ground was powered early in a few minutes than the AWS on the drone (see Figs. 7 and 8). During airborne, the drone has made circular movements at a radius of about 200 m and maneuvered up and down 3 times (see ALT panel of Fig. 7 or Fig. 8) but still below 50 m of height. As the drone maneuvers up, the air pressure value inside the box decreases as indicated by a significant difference in readings between the sensors on the drone and on the ground. This happens due to the number of air particles decreasing (compressed air) and the gravitational force generated is also decreasing. The higher the point of a location or the vertical air pressure causes the temperature to be cooler and humidity is inversely proportional to temperature. While PWV in this region follows humidity trends, it decreases as the drone rises into the sky. Note that as recorded from ALT panel of Fig. 7, when the drone approaches ground level, it tries to rise again but cannot fly because its battery is running low as indicated by a battery alarm. The same result was also obtained in the second experiment (see Fig. 8). After the drone was ON for about 2 minutes, it started to take off at 05:41:53 WIB at the ground position or equal to an altitude of 182 m asl, and then maneuvered up and down twice. During this maneuver, the drone's movement is well controlled even if strong winds suddenly appear with cloudy weather. However, our drone ended up being crashed by the wind. This strong wind also affects the battery level to become weak quickly during maneuvers to fight the wind [27]. Overall, experiments with different days will produce different readings, but they still have a similar trend.

Based on the measurement results of Fig. 7, the relationship between atmospheric parameters measured at the ground and on the drone is presented in Fig. 10. The labels (a) and (b) in the figure show measurements taken at ITDA from the ground and on the drone only during fly from take-off (↑) to landing (↓), respectively. Putting the regression equation in each panel of figure will provide the ability to predict the future data. The R-squared (R^2) is the coefficient of determination to measure how well a model can predict the data. The higher R^2 with a long-term dataset would better the prediction model.

A similar plotting method as in Fig. 10 for the SAMBI area is also presented in Fig. 11. Based on the experiment above, it is very clear for ITDA and SAMBI that the altitude or elevation of a point is inversely proportional to the barometric pressure. This relationship is also followed by humidity which affects PWV oppositely, whereas PWV increased with increasing temperature. However, in the SAMBI area which is about 10 km from ITDA, the relationship of temperature and humidity to PWV both on the ground and on the drone was found tends to a linear relationship but not correlated at all. The main event recorded during the experiment was due to a very strong morning wind and the sky suddenly clouded over. The drone only hovered for about 7 minutes which is a bit shorter than in the first result of Fig. 7. This wind incident moves the air particles elsewhere which allows the sensor readings to change. This is indicated by almost the same reading of temperature between the drone and on the ground during fly (see the upper panel of Fig. 8). For the time being, from the two measurement results obtained indicate that the atmospheric parameters measured in a short time are strongly influenced by weather conditions at that time.

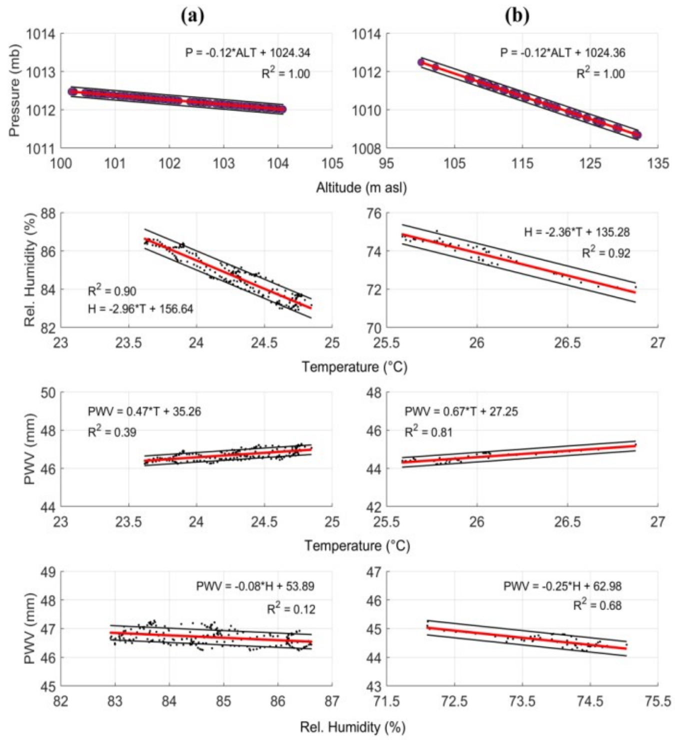

Fig. 10. The relationship between atmospheric parameters measured from (a) ground and (b) on the drone during flight for ITDA area on October 1, 2021.

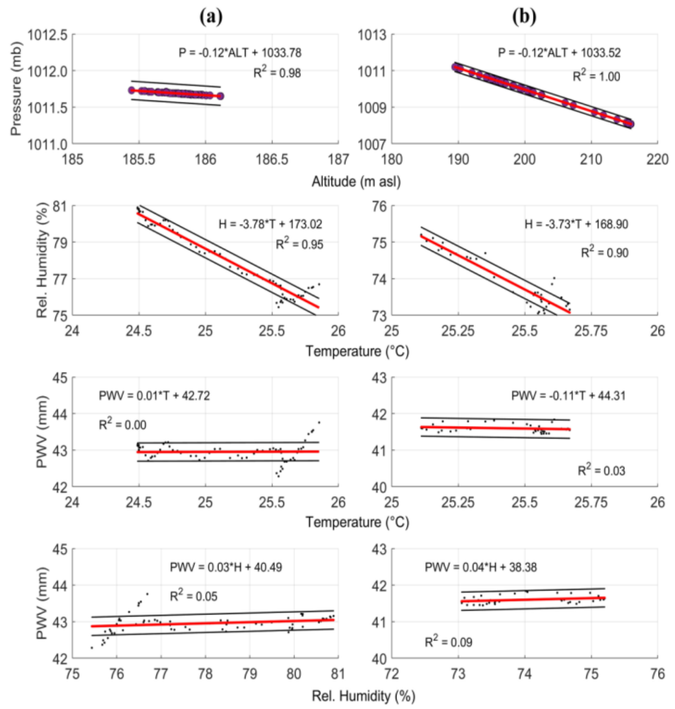

Fig. 11. The relationship between atmospheric parameters measured from (a) ground and (b) on the drone during flight for SAMBI area on October 3, 2021.

To clarify the result obtained for T and H to PWV on Figs. 10 and 11, the daily average of ground-based meteorological data for September and October of 2021 is plotted in Fig. 12. The data with WMO ID: 96851 (7° 43' 51.6" S, 110° 21' 14.4" E, and an elevation of 182 m asl), located 13.5 km from SAMBI or 15 km from ITDA. The air pressure data is not provided online by this agency. Instead, it was estimated based on the surface temperature measurement with the barometric formula, $P_h = P_0\, e^{-Mgh/kT}$, or can be determined from equation (2), where the altitude is replaced with the elevation. Fig. 13(a) confirms the opposite relationship between temperature and relative humidity. Although the temperature quantitatively does not correlate with relative humidity, they affect an increase in PWV as presented in Figs. 13(b) and 13(c). Conversely, high air pressures values (Fig. 13(d)) will reduce the amount of water vapor content on the Earth's surface. By comparing Fig. 13 with Figs. 10 and 11, the ground results at SAMBI tend to follow the weather at BMKG Sleman. One possibility is that they have approximately the same altitude. From our measurement results, the water vapor content in the vertical atmosphere tends to decrease following the trend of air pressure. Vertical water vapor decreases as the number of air particles decreases or the number of water molecules released due to radiation. The relationship of these atmospheric parameters may vary according to geographic location and local weather conditions. On the other hand, this hands-on experiment can be an interesting learning enrichment where students will gain a deeper understanding of natural phenomena.

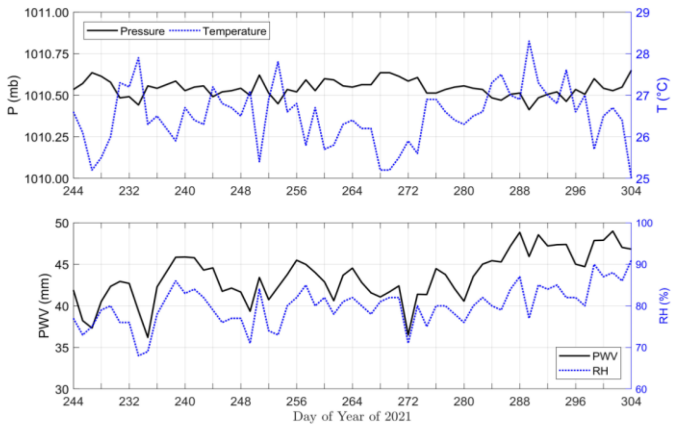

Fig. 12. The daily average of surface meteorological data obtained from the BMKG Sleman (The Agency of Meteorology, Climatology, and Geophysics of Indonesia) for September and October 2021.

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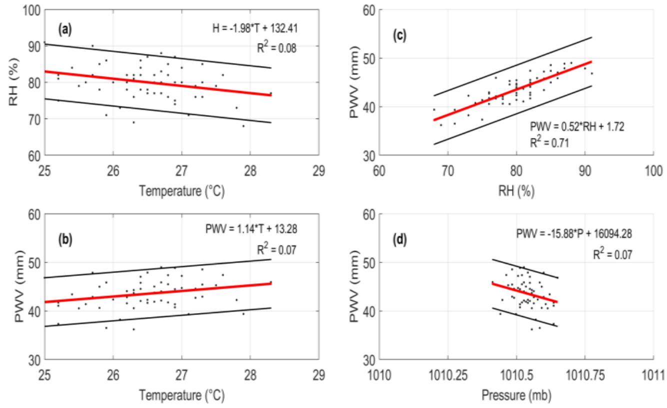

Fig. 13. The relationship between atmospheric parameters for September – October 2021 data from BMKG Sleman.

CONCLUSION

This research has succeeded in developing a quadcopter drone using the Pixhawk including a payload containing AWS. The vehicle can fly and work stably and is capable of taking measurements and storing data during the mission. After the mission ends, the data collected such as temperature, pressure, relative humidity, altitude, and PWV is plotted for visualization and interpretation. It is found that the temperature is inversely proportional to the relative humidity, and the water vapor content decreases as the altitude of the drone get higher. However, not necessarily at a point with high humidity will generate a lot of water vapor. In other words, air pressure is inversely proportional to altitude. In conclusion, the pattern of the relationship between these parameters is in stark contrast to the conventional measurement method where we have to take measurements for at least 24 hours to infer trends. By insightful the relationship of these basic atmospheric parameters, predictions of other related parameters such as forecasting the weather or climate prediction can be made. In addition to strengthening the foundation in understanding the dynamics of the atmosphere, the construction of this drone is also useful in robotics courses, especially flying robots where college students can practice directly in designing and its implementation.

The goal of this work is to provide a framework for designing a quadcopter and to demonstrate the functionality, measurement, and analysis of the results obtained. This basic framework is useful for lecturers or teachers in designing learning tools or media to improve student understanding. One of the ongoing analyzes in this research is quantifying feedback from students about concepts understood using drones compared to conventional methods. This is a topic for further research where questionnaires need to be designed to capture the effectiveness of project-based learning. In addition, drones can also be advanced by adding additional devices in the future to be used optimally and autonomously such as for surveillance, monitoring, or surveying.

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