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Digital Forensic Methodology for Detection of Abnormal Flight of Drones

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Abstract

When a drone accident has occurred, it is difficult to decide whether it is due to a crime, malfunction, mistake, or external force. Although the cause of the accident is elucidated through analysis of artifacts or flight data, there are many limitations. In this study, we present a method for detecting an abnormal flight using the motor current values and controller direction values of a drone. The experimental result revealed that, in the case of a normal flight, the current values of four motors were similar in hovering state and the current value of rear motors were increased when the drone was flying forwards. In the case of an abnormal flight, when the drone moved rightwards due to external force in hovering state, the current values of the two motors on the right side were increased greatly. After a period of time following the movement to the right side, the current values of all the motors converged to 0. In the future, motor current values and controller direction values may be used to determine whether an abnormal flight in a drone accident has occurred because of external force by wind, birds, persons, or the like.

I. Introduction

The global civilian drone market is expected to grow from 14 billion dollars in 2018 to an estimate of 43 billion dollars in 2024[1]. In Korea, the use of drones in the public sectors has increased remarkably from around 300 in September 2017 to around 2,900 in May 2020[2], The applications of drones are expanding from search, patrol and supervision, to agriculture, safety inspection of facilities, survey, disaster assistance, etc. Despite the industrial and social benefits of drones, however, they are constantly used for crimes and terrorism. In 2015, a small drone crashed on the grounds of the White House in the United States [3]. In 2018, Gatwick Airport in the United Kingdom was shut down for about 36 hours because a drone flew near the runway [4]. In Korea, a beach monitoring drone crashed due to radio interference in 2015 [5], and a drone flew down onto a citizen due to building wind in 2019 [6].

A regarding aircraft, an “abnormal flight” is defined as “a situation that may inevitably occur due to weather and maintenance problems”. A drone is legally defined as “a vehicle capable of navigating without a pilot on board.” Aircraft and drones are both machines and systems that can fly. The “weather” factor can be viewed as a natural factor, and the

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"maintenance problem" can be judged as a physical error. As a result, the abnormal flight shown in this study can be defined as a situation that can inevitably occur due to natural factors such as wind, as well as a third party or tide unrelated to steering. By applying this, this study tried to derive data values that can discriminate between abnormal and normal flight.

As the drone accidents and crimes continue to happen, it is becoming more important to identify whether the cause of an accident is an abnormal flight due to the defect of the drone, miscommunication, mistake of the operator, or external force by wind, birds, persons, etc,. Therefore, we present a method for verifying an abnormal flight caused by external force by using drone motor current values and controller direction values. Unlike the previous method of analyzing artifacts, this method uses the current values of motors.

For this, previous studies about drone forensics and flight data analysis are described in Section II, experiments for normal and abnormal flight of a DJI drone are designed in Section III, and a method for verifying the cause of an accident using motor currents and controller directions for normal and abnormal flight is presented in Section IV. As a result, in this study, we analyzed the case in which drones were moved by external forces to identify the change data, and from that, we wanted to indicate an indicator to distinguish between normal and abnormal flights to determine the cause of the accident. A conlusion of this study is stated in Section V.

II. Related Research

In previous studies on drone forensics, most of its purpose was to identify artifacts and thereby develop an analytical framework. Furthermore, studies on drone model-specific artifacts analysis have been actively conducted with case analysis on specific drone models from specific manufacturers, such as DJI's Phantom 4 drone.

The previous research studies on drone forensics have been centered on artifact analysis, framework design, etc. of specific models. U. Jain et al. (2017) analyzed the architecture of five models with different weights and presented a forensic model [7]. Ankit Renduchintala et al. (2019) developed an application which designs a forensic framework using two drones and extracts, analyzes and visualizes flight data [8]. Clark et al. (2017) developed an open source tool (DROP) capable of extracting an encoded DAT file from the storage of DJI Phantom 3 and analyzing GPS, flight time and battery depletion [9]. They have proposed a method of predicting a user by analyzing the data of a drone and a mobile device, and identified that the data in the DAT file can be deleted or changed.

Although it is meaningful in that they attempted the syntax analysis of the DAT file, there is a limitation in that the open source tool cannot be used universally because the data that can be acquired such as the DAT file and decoding method are different among drones. Kao et al. (2019) compared and analyzed the flight data for DJI Spark in the drone, memory card and mobile device and identified that there is no high correlation. But it was confirmed from the analysis of time data and artifacts that the GPS data of the drone and the mobile device are related with each other [10]. Hamdi et al. (2019) detected the user's e-mail address in the DJI GO app and the sources of files by analyzing flight data from DJI Phantom 4 and various mobile devices connected thereto[11]. Yousef and F. Iqbal established a scenario of seizing DJI Mavic Air and conducted experiments of acquiring and analyzing various artifacts [12]. The scenario, however, lacked specificity and the analysis of date, timestamp, GPS, altitude, longitude, lattitude, etc. was insufficient. M. Yousef et al. (2020) compared the data that could be obtained from four DJI models using an open source tool and a universal tool, and proposed a procedure for acquiring drone data [13]. As mentioned above, although the previous researches used forensic process, artifact analysis, flight data visualization, etc. to investigate the cause of an accident or a crime, there has been limitation in distinguishing an abnormal flight due to wind, birds, persons, etc. from normal flight.

Therefore, in this study, we try to derive data that can analyze the causes by dividing normal flights and abnormal flights.

III. Design of Experiment

A.Experimental methods

We present a method for distinguishing normal flight from abnormal flight using motor current values and controller direction values. The first experiment was performed on March 19, 2021 at Gwangnaru Drone Park in Seoul, South Korea (temperature 15.3 °C, mean wind speed 7.9 km/h), The second experiment was performed on April 6, 2021 in Namyang-si, Gyeonggi-do, South Korea (temperature 13.9 °C, mean wind speed 9 km/h). For normal flight, motor current values and controller direction values were collected by conducting sudden stop, quick start, sudden rotation, etc. For abnormal flight, motor current values and controller direction values were measured by jerking the drone rightwards in hovering state. Hovering means staying in the same place in the air, this is maintained by varying motor outputs when an external force is applied. Although, it may be more accurate to collect the motor current values and controller direction values by applying physical force on both sides, the external force was applied only on the right side because all the conditions except direction were identical. As the drone, Phantom 4 Pro (four motors) of DJI (China) which accounts for over 70% in the global private drone market [14]. The drone was controlled with the mobile device iPhone 12 (A2403), and Samsung Micro SD card EVO (32 GB) was inserted in the drone.

Data acquisition was carried out in a sports mode with GPS turned on and the obstacle avoidance sensor off, in order to measure the maximum values for abnormal flight. Since flight record files are generated every time the drone is turned off, data were acquired by turning on and off the drone several times. Computational analysis was performed with Windows 10. After acquiring flight record files from the drone by executing DJI Assistant 2 for Phantom, the data were visualized using DJI Flight Log Viewer. However, since the DJI Flight Log Viewer cannot show related numerical values, the data were converted to a CSV file using CsvView/DatCon. As a result, it was confirmed that the data of GPS-based latitude and longitude, distance travelled, battery, motors, controllers, etc. are recorded with 0.1-second intervals. The data were analyzed and visualized using Excel 2016.

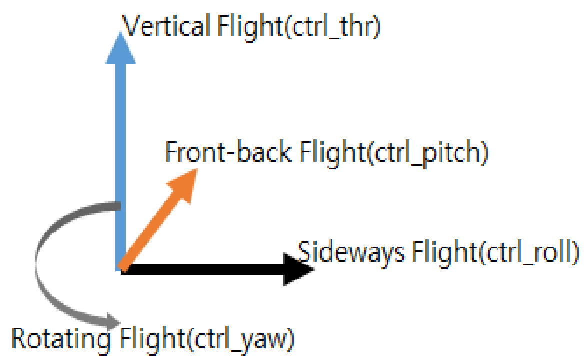

Fig. 1 Types of controller directions values.

B. Types of data

The DJI drone was storing data values as controller:ctrl_(direction) and motor current values as motor:current_(direction). Four types of controller direction values are stored in the CSV file. They are Controller:ctrl_roll (hereinafter, referred to as 'sideways flight (ctrl_roll)'), Controller:ctrl_pitch (hereinaf-

TABLE I
CONTROLLER DIRECTION VALUES AND MOTOR CURRENT VALUES

	Direction	**Data value**	**Abbreviation**
Controller direction values	Sideways Flight	Controller:ctrl_roll	Sideways flight(ctrl_roll)
	Front-back Flight	Controller:ctrl_pitch	Front-back flight(ctrl_pitch)
	Rotating Flight	Controller:ctrl_yaw	Rotating flight(ctrl_yaw)
	Vertical Flight	Controller:ctrl_thr	Vertical flight(ctrl_thr)
Motor current values	Right front	Motor:Current:RFront	Right front(RFront)
	Left front	Motor:Current:LFront	Left front(LFront)
	Left back	Motor:Current:LBack	Left back(LBack)
	Right back	Motor:Current:RBack	Right back(RBack)

ter, referred to as 'front-back flight (ctrl_pitch)') and Controller:ctrl_yaw (hereinafter, referred to as 'rotating flight (ctrl_yaw)'), the vertical flight is expressed by Controller:ctrl_thr (hereinafter, referred to as 'vertical flight (ctrl_thr)') as illustrated in Fig. 1. The direction value is in a range from –1 to 1. The sideways flight (ctrl_roll) has a positive value for the right side and a negative value for the left side. The front-back flight (ctrl_pitch) has a positive value for the front side and a negative value for the back side. The vertical flight (ctrl_thr) has a positive value for the upward direction and a negative value for the downward direction. And, the rotating flight (ctrl_yaw) has a positive value for the clockwise direction and a negative value for the counter-clockwise direction.

Among the drone data covered in this experiment, the controller direction values and motor current values are shown in Table I.

The current values of the motors at different positions of the wings of the drone are as follows: Motor:Current:RFront (hereinafter, referred to as 'right front (RFront)'), Motor:Current:LFront (hereinafter, referred to as 'left front (LFront)'), Motor:Current:LBack (hereinafter, referred to as 'left back (LBack)'), and Motor:Current:RBack (hereinafter, referred to as 'right back (RBack)'). In the experimental data, the unit of time is 0.1 second, and the unit of current is ampere (A).

IV. Analysis of Experimental Result and Limitation

A. Normal flight data

1) Hovering flight

When the drone was in hovering state for 3.7 seconds, all the controller direction values, i.e., sideways flight(ctrl_roll), front-back flight(ctrl_pitch), rotating flight(ctrl_yaw) and vertical flight(ctrl_thr) were 0 as illustrated in Fig. 2. The mean current value of each motor was relatively constant between 2.87 A and 6.90 A, with right front(RFront) 4.92 A, left front(LFront) 5.59 A, left back(LBack) 5.33 A, and right back(RBack) 3.78 A as stated in Fig. 3.

2) Forward flight

When the drone flew forward normally for 5.5 seconds, the controller direction values were as follows: front-back flight (ctrl_pitch) = 1, others = 0. Sideways flight (ctrl_roll) was 0.2, which occurred due to control mistake during forward flight and was considered having no effect on the experiment because the value was small Fig. 4. The mean current values of the four motors were right front (RFront) 4.01 A, left front (LFront) 3.80 A, left back (LBack) 5.75 A, and right back (RBack) 6.05 A. The current values were higher

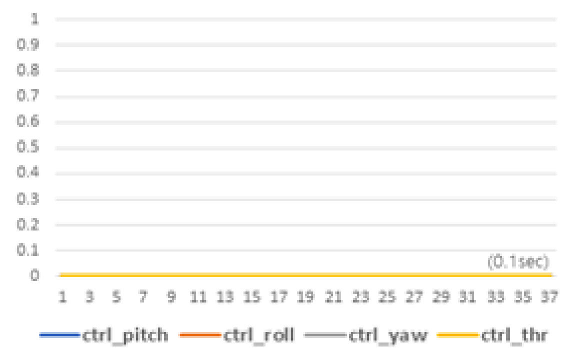

Fig. 2 Change in controller direction values in hovering.

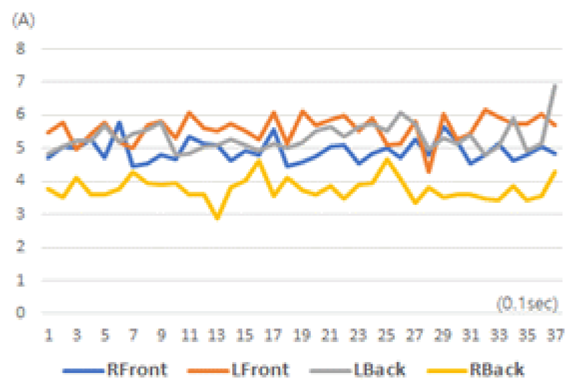

Fig. 3 Change in motor current values in hovering state.

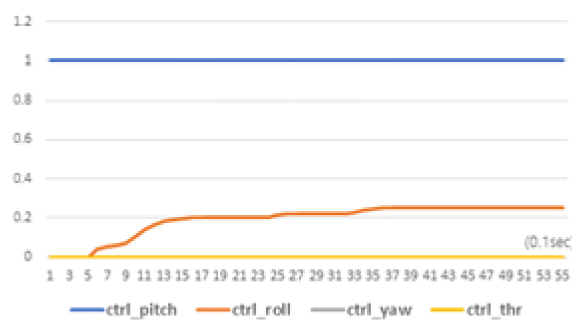

Fig. 4 Change in controller direction values during forward flight.

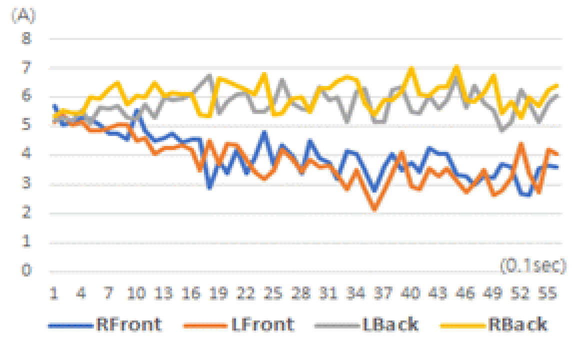

Fig. 5 Change in controller motor current values during forward flight.

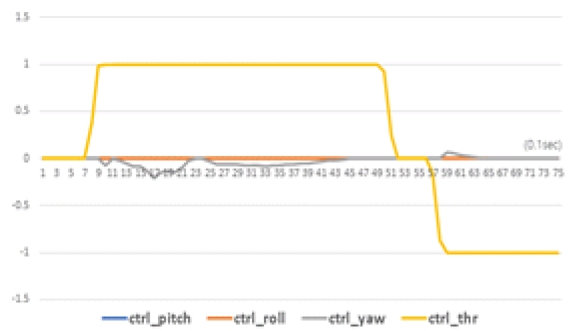

Fig. 6 Change in controller direction values during vertical flight.

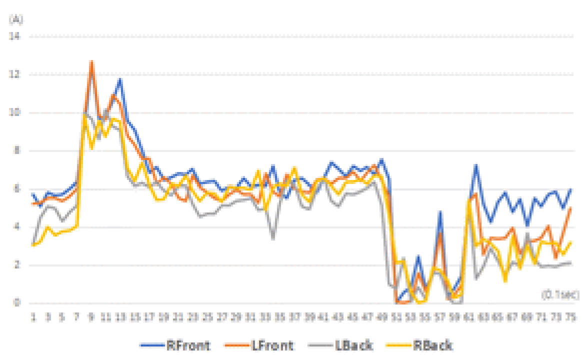

Fig. 7 Change in motor current values during vertical flight.

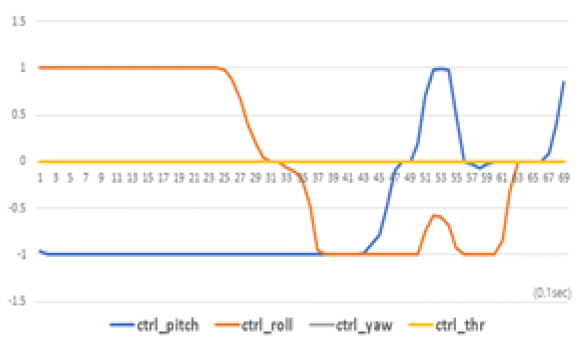

Fig. 8 Change in controller direction values during sideways and front-back flight.

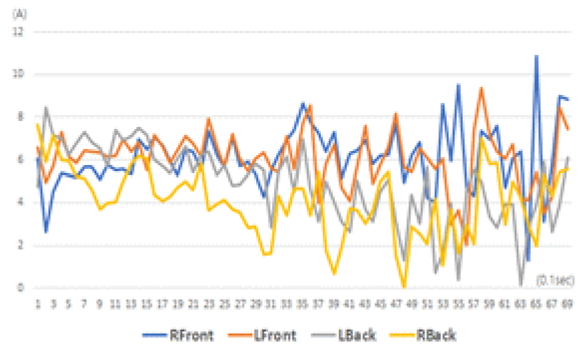

Fig. 9 Change in motor current values during sideways and front-back flight.

for the back motors (LBack, RBack) than the font motors (RFont, LFront), which suggests that the motors at the back side consumed more current because stronger powering is required there for the forward flight as illustrated in Fig. 5.

3) *Free flight*

With all the conditions under control, the drone was allowed to fly freely upward and downward and the change in the current values of the four motors was monitored. That is to say, the controller direction values of sideways flight (ctrl_roll), front-back flight (ctrl_pitch) and rotating flight (ctrl_yaw) were set to 0, and vertical flight (ctrl_thr) was increased from 0.9 second to 5.1 seconds up to the maximum value (+1) and then decreased from 5.6 seconds to 7.5 seconds down to the minimum value (-1) as shown in Fig. 6. As a result, it was confirmed that the current values of the four motors were increased and decreased in a similar pattern, suggesting that they consumed similar amount of current, see Fig. 7.

In addition, with the front-back movement and rotation under control, the drone was allowed to fly freely forward and backward and sideways and the change in the current values of the four motors was monitored. That is to say, the vertical controller direction values of flight (ctrl_thr) and rotating flight (ctrl_yaw) were set to 0, and the drone was flown freely rightward and backward until 3.2 seconds after the beginning of flight, leftward and backward until 4.7 seconds, and leftward and forward until 5.6 seconds. As a result, the current values of the four motors were irregular, see Fig. 8. The result was quite different from that of Fig. 7. wherein only one

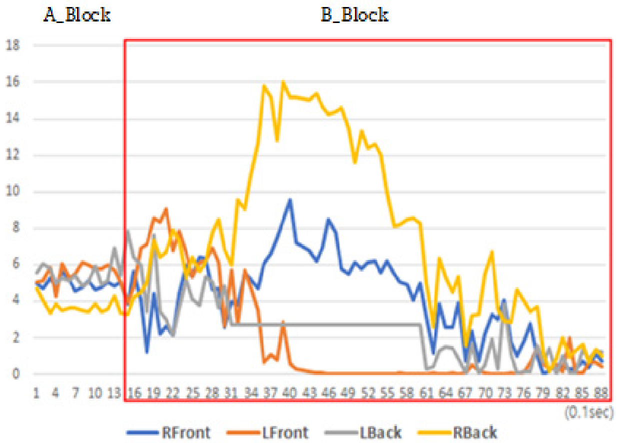

Fig. 10 Change in motor current values when drone in hovering state was moved rightward.

TABLE II
CHANGE IN MOTOR CURRENT VALUES WHEN DRONE IN HOVERING STATE WAS MOVED RIGHTWARD

Fly Time	RFront	LFront	LBack	RBack
15	3.84	3.92	7.86	3.25
16	5.66	4.79	6.44	4.18
17	4.06	6.92	5.96	4.48
18	1.19	7.12	3.44	5.04
19	4.44	8.58	7.60	7.32
20	2.18	8.32	3.41	6.44
21	2.66	9.04	3.02	6.68
22	2.14	6.78	2.14	7.94
23	4.44	7.82	3.62	7.31
24	5.99	6.63	5.22	5.30
25	5.38	5.38	4.15	6.44
26	6.44	6.16	3.80	5.61
27	6.36	6.22	5.35	6.16
28	4.66	6.90	5.06	7.78
29	4.69	6.11	3.64	8.47
30	2.55	**2.63**	4.86	6.86
31	3.99	5.72	**2.73**	6.02
32	3.79	2.74	2.73	9.55
33	5.56	5.71	2.73	9.02
34	5.23	4.79	2.73	10.94
35	4.74	3.50	2.73	12.67
36	6.05	0.67	2.73	15.82
37	6.66	1.06	2.73	15.20
38	7.47	0.80	2.73	12.80
39	**8.43**	**2.87**	**2.73**	**16.06**
40	9.57	0.58	2.73	15.20
41	7.23	0.32	2.73	15.19
42	6.98	0.20	2.73	15.14
43	6.80	0.14	2.73	15.02
44	6.20	0.06	2.73	15.40
45	6.92	0.05	2.73	14.69
46	8.46	0.03	2.73	14.26
47	7.76	0.01	2.73	14.41
48	5.81	0.03	2.73	14.64
49	5.47	0.04	2.73	13.44
50	6.11	0.04	2.73	11.62
51	5.80	0.03	2.73	13.30
52	6.16	0.04	2.73	12.40
53	6.20	0.02	2.73	12.60
54	5.54	0.02	2.73	12.03
55	6.17	0.04	2.73	9.96
56	5.52	0.04	2.73	8.14
57	5.04	0.05	2.73	8.23
58	4.89	0.04	2.73	8.50
59	4.04	0.03	2.73	8.55
60	5.02	0.03	2.73	8.26
61	**3.16**	0.03	0.26	4.96
62	1.17	0.06	0.46	2.58
63	3.85	0.04	1.26	6.36
64	2.55	0.04	1.53	5.36
65	2.54	0.05	1.44	4.48
66	3.95	0.04	0.87	5.32
67	0.72	0.05	0.05	**1.60**
68	2.36	0.52	1.63	3.24
69	0.71	0.21	0.09	3.31
70	2.22	0.07	0.54	5.50
71	3.30	0.03	1.90	6.70
72	3.00	0.04	0.26	3.60
73	4.10	0.04	3.84	2.93
74	1.82	0.10	1.09	2.86
75	0.97	0.02	0.05	4.62
76	1.86	0.18	0.14	4.02
77	2.75	0.68	0.12	3.45
78	0.97	1.45	1.55	3.68
79	0.02	0.59	0.65	1.18
80	0.22	0.28	1.4	0.14
81	0.48	0.49	0.04	0.85

TABLE II
Change in Motor Current Values When Drone in Hovering State was Moved Rightward (Continue)

Fly Time	RFront	LFront	LBack	RBack
82	0.42	0.15	1.00	1.98
83	0.28	2.03	0.08	0.96
84	0.29	0.08	0.08	1.31
85	0.72	0.11	1.38	1.68
86	0.37	0.62	0.76	0.65
87	1.16	0.68	1.26	1.37
88	0.71	0.40	1.23	1.04

(Units: 0.1 sec, A)

direction value was varied with the other three direction values under control. It is thought that the random free flight occurring in two or more directions leads to consumption of different amount of current among the motors and give such irregularity as shown in Fig. 9.

B. Abnormal flight data

When the drone was in hovering state, an operator grabbed the drone and moved it rightwards slowly for 5 seconds for about 3 m. When the change in the current values of the motors was monitored, a significant difference in current consumption was observed between the hovering zone (A_Block) for 1.4 seconds and the moving zone (B_Block) from 1.5 to 8.8 seconds. That is to say, whereas the current consumption in the hovering zone (A_Block) was 2-7 A, the current consumption in the moving zone (B_Block) varied variously in the early, middle and late stages. Especially, in the middle stage, the current values of right back (RBack) and right front (RFront) were high and those of left back (LBack) and left front (LFront) were low. In the late stage, all the current values of right back (RBack), right front (RFront), left back (LBack) and left front (LFront) converged close to ‘0’, see Fig. 10.

The change in motor values as shown in Table II are obtained when the drone is hovering and applied in the right direction. Immediately after the drone was grabbed, i.e., between 1.5 and 3.9 seconds, the current consumption by the four motors was 2.63-16.06 A, At 3.9 seconds in the middle stage, there was significant difference, with right back (RBack) 16.06 A, right front (RFront) 8.43 A, left back (LBack) 2.73 A and left front (LFront) 2.87 A. It is thought that the higher current values of the two motors on the right side in the middle stage is because they consumed more power to maintain the hovering state before movement to the right side by the external force.

In the late stage, the current consumption of all the four motors converged to ‘0.’ Although the drone tried to maintain the hovering state, it was failed by the external force. In the end, all the four motors stopped consuming current.

The four controller direction values were all 0 for a total of 8.8 seconds in the hovering zone (A_Block) and the moving zone (B_Block) as illustrated in Fig. 11. But, the distance travelled was increased from 7.56 m at 1.5 seconds to 11.45 m at 8.8 seconds by 3.89 m. This means that the drone was moved by 3.89 m although the controller was not operated, showing that the movement was an abnormal flight due to external force, see Fig. 12.

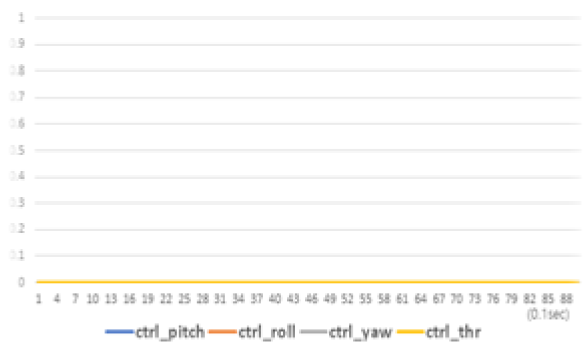

Fig. 11 Change in controller direction values in abnormal flight.

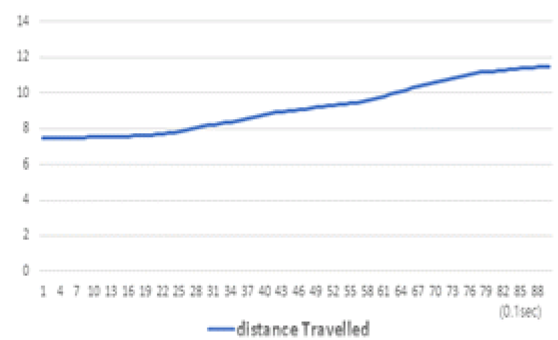

Fig. 12 Change in distance travelled in abnormal flight.

C. Experimental result and limitation

From the measurement of controller direction values and motor current values for normal flight and abnormal flight, the following seven facts were identified. First, in the hovering state of normal flight, all the controller direction values were 0 and the current values of the four motors showed similar patterns. As the drone flew in a forward (backward) direction, the motor current value of the motor in the opposite, i.e., back (front), side was increased. For vertical flight, the current values of the four motors were increased or decreased together. In case of free flight in two or more direction, such as front-back flight or sideways flight, the current values of the four motors were irregular.

In the case of an abnormal flight, when the drone in hovering state was moved rightward (leftward) by external force, it showed a tendency to move leftward (rightward) to maintain the hovering state, and the current values on the opposite, i.e., right (left), side were increased. In addition, when the drone was moved further rightward (leftward) by external force, the current values of all the four motors converged to 0 after a period of time. Finally, the increase in the distance travelled without change in controller direction values could be determined as abnormal flight by external force.

There is limitation, however, in generalizing this result because only a small number of experiments were conducted with DJI Phantom 4 Pro. In addition, there may be errors in the measurement data because wind speed could not be completely controlled for the experiment and the motors could consume current only partly. Furthermore, the external force applied to move the drone rightward could not be measured mathematically. Nonetheless, this experiment is meaningful in that a method for distinguishing a normal flight from an abnormal flight by external force such as wind, birds, persons, etc. using the current values and controller direction values of the drone.

This experimental result can be usefully used to determine whether the collision, crash or banned flight of a drone, which results in damage to people, cars or facilities, has occurred due to an external force such as wind, birds, persons, etc., not by the operator.

V. Conclusion

We conducted experiments for distinguishing a normal flight from an abnormal flight using the motor current values and normal flight, the current values of four motors were similar. As the drone flew in a forward (backward) direction, the motor current value of the motor in the opposite, i.e., back (front), side was increased. In the case of an abnormal flight, when the drone in hovering state was moved rightward (leftward) by external force, the current values on the opposite, i.e., right (left), side were increased. When the drone was moved further rightward (leftward) by external force, the current values of all the four motors converged to 0 after a period of time.

This experiment may be used to find out the cause of an accident by distinguishing a normal flight from an abnormal flight by external force such as wind, birds, persons, etc. Above all, we present a new method capable of finding out the cause of an accident using current values, beyond controller artifact analysis. It seems that a follow-up study will be necessary on the change in the current values of the motors when a drone which is flying vertically, forward/backward or sideways, or rotating is stopped or moved in the same or opposite direction by external force.

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