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Test method for flight stability of a multi-copter unmanned aircraft system (UAS) under wind and rain conditions

Méthode d'essai relative à la stabilité en vol d'un multicoptère télépiloté dans des conditions de vent et de pluie

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Foreword

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Introduction

Multi-copter unmanned aircraft (UA) find a wide variety of applications ranging from individual hobbies, such as image capture and racing, to a rapidly increasing number of commercial purposes, such as precision farming, delivery, and inspection. Multi-copter UA control and flight dynamics are unique relative to those of well-known fixed and rotary wing configurations, and therefore must be fully understood to ensure their safe usage and integration into commercial applications. This document identifies a manner of determining system level flight stability by evaluating the multi-copter UA's automated control system capability to maintain its spatial position when faced with a variety of simulated temperature, wind, gust, rainfall and ice conditions. The test method for the flight stability of the multi-copter unmanned aircraft system (UAS) provides the test condition, procedure, report format, etc. The principal advantage of the test method is its ability to evaluate the flight stability of a multi-copter UAS considering actual flight conditions. All tests are performed considering real-time flight status. The purpose of the test method is to evaluate and improve the flight stability of a multi-copter UAS through experiments conducted under various environmental conditions.

Test method for flight stability of a multi-copter unmanned aircraft system (UAS) under wind and rain conditions

1 Scope

This document specifies the procedures for testing flight stability of a multi-copter unmanned aircraft system (UAS) and is applicable to multi-copter type UAS that can take-off and land vertically. A commercial multi-copter UAS weighing over 250 g to less than 150 kg is discussed in this document. Further, this document is applicable to military and civilian multi-copter UAS. However, quantitatively specific stability criteria for the test are not specified in this document.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
flight stability
ability to maintain the parameters of motion (linear and angular positions, speed) within predefined tolerances and time when exposed to external disturbances

Note 1 to entry: Flight stability of a multi-copter UAS can be defined as its spatial precision of take-off, landing, hovering and moving intended by a pilot or autopilot flight program used while being subjected to various flight environments.

3.2
manual mode
mode in which an aircraft flies with complete autopilot stabilization of three axes of motion (pitch, roll, and yaw), heading hold (via a compass), height hold (via barometric pressure sensor), and lateral position hold (via GNSS or optically)

Note 1 to entry: The pilot commands the aircraft to move to a different height or lateral position as required. Once the pilot control input is released, autopilot stabilizes the UA.

3.3
autopilot mode
mode in which an aircraft moves according to pre-programmed waypoints (vertically or horizontally) and/or performs take-off or landing operations without any pilot input

Note 1 to entry: Flight control for the entire duration or for some parts of the flight is performed without a pilot.

4 General principles

4.1 Test purpose

The purpose of this test method is to measure the flight stability of a multi-copter UAS under given operational conditions. To check the overall performance of each component of the multi-copter UAS, such as propulsion, control, and battery management systems, an actual test flight of the multi-copter UAS in a test device is performed. For flight stability evaluations of the multi-copter UAS, actual flight conditions are considered, while all tests are performed inflight. The proposed stability test method and device are expected to satisfy numerous commercial multi-copter UAS manufacturers and developers by evaluating and improving the flight stability of their multi-copter UASs via experimental results.

4.2 Test condition

Flight stability measurements of a multi-copter UAS are performed in a test device especially designed for simulating flight conditions and measuring real-time spatial position of a multi-copter UA. In the test device, the multi-copter UA is capable of flying under several environmental conditions, such as temperature (from −20 °C to 50 °C), wind speed (from 0 m/s to 30 m/s), rain fall (from 0 mm/h to 20 mm/h, from 0 °C to 50 °C), ice (from −20 °C to 0 °C) and gust. Testing relative to rainfall does not assess the ingress protection (water) of the multi-copter UAS. Particularly, position data of the multi-copter UA during the stability test are stored to evaluate flight stability. The test conditions are adjusted depending on the purpose and operation condition of the multi-copter UAS because not every multi-copter UA test requires a high cost test device or a long test period. Based on the instructions of the manufacturer, battery safety care and storage should also be considered. For instance, battery should be kept in warm conditions (0 °C at least) before conducting the test to ensure its proper functioning. The test should be performed considering the flight conditions according to the various payloads attached to the multi-copter UA.

4.3 Test apparatus

The test apparatus consists of devices capable of generating wind, gust, rain and measuring the position of multi-copter UA during flight stability test. If the test apparatus satisfies the required experimental conditions, it can be installed indoors or outdoors, but the environment should be free from electromagnetic interference. To secure stable global positioning system (GPS) signal strength, the roof and side walls of the test apparatus are built of a material with good GPS signal transmittance. A laminar (or turbulent) wind generator is used to maintain constant wind speed and quality to reproduce a natural environment during the flight stability test. The test section volume (width × height × depth) is determined by the size (diagonal length from rotor to rotor) of the multi-copter UA. A rainfall device using specified equipment, such as multiple nozzles, is used to spray water. The wind gust test should be performed using various controllable wind gust generation methods, such as an oscillating vane gust generator.[1] The wind speed difference for gust should be adjustable through the gust generating device according to the wind speed of the test condition in progress. A three-dimensional position measuring device is used to measure the real-time position of the multi-copter UA using various measuring instruments (motion capture camera, IR camera, video camera, ultra-sonic sensor, UWB, etc). When video-recording-based measurement systems are considered, grid markers should be included on the walls and floor of the test apparatus. The example general specifications of the test device are presented in Table 1. The wind nozzle size should be such that the target air velocity can be set according to the size of the multi-copter UA and test area. Generally, the wind nozzle size should be at least 1,5 times larger than of the multi-copter UA.

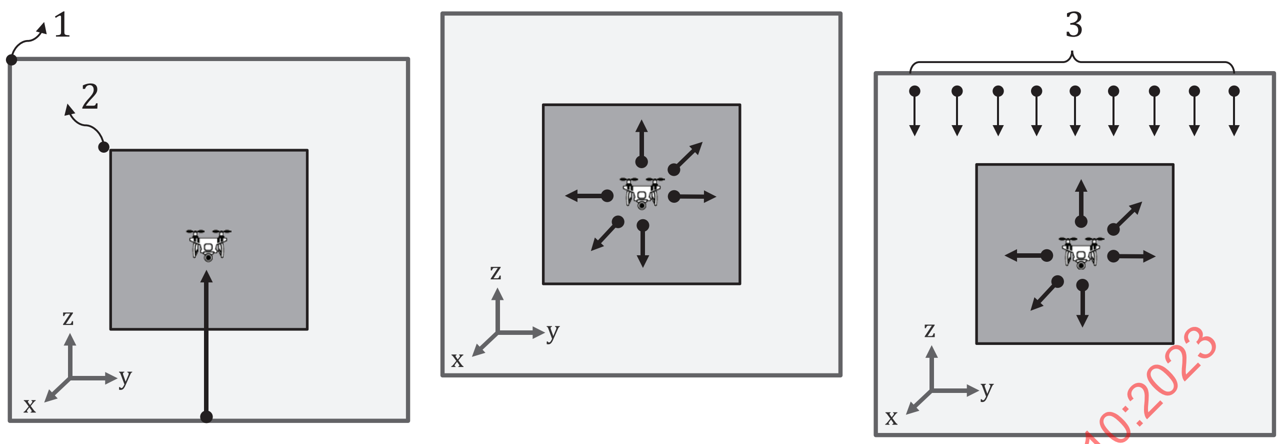
Table 1 — The example specification of test device for commercial multi-copter UAS (250 g to 25 kg)

Item	Contents
Wind nozzle size	4 m × 4 m
Wind speed	0 m/s to 30 m/s
Wind gust generation method	Oscillating vane gust generator
Test section size	8 m × 8 m × 12 m ($w \times h \times d$)
Rainfall simulation system	20 mm/h (max.)
Measuring system for 3-dimensional position of multi-copter UA	centimetre grade error

4.4 Test method

4.4.1 General

The flight stability test evaluation method consists of six cases as specified in 4.4.2 to 4.4.7. In the first test case, take-off and landing spatial precision measurements are performed under the specified wind speed within predefined sampling time. In the second test case, rainfall conditions are added to the first test case before evaluation. For in-flight stability measurements under the specified wind speed within the predefined sampling time, the third test case is used. The fourth test case is used to measure the flight stability with added rainfall conditions to the third test case. In the fifth test case, 360° rotational flight precision measurements are performed under the specified wind speed within predefined sampling time. In the sixth test case, rainfall conditions are added to the fifth test case before evaluation. The flight stability for take-off and landing is performed while adjusting the wind speed, gust condition (wind speed difference), rainfall amount and measuring the flight path deviation. The flight stability for the spatial motion for six directions (up, down, left, right, forward, and backward) and the rotational motion for 360° are evaluated while adjusting the wind speed, gust condition (wind speed difference), rainfall amount and measuring flight path deviations. The six test cases for evaluating the flight stability of the multi-copter UAS are considered to satisfy various evaluation requests as much as possible. Therefore, it is not mandatory to perform all test cases; the tester and the requester select the suitable test case according to relevant requirements. Each flight stability evaluation is determined by the flight path deviation between the desired and measured values using a measuring system with centimetre-level positioning accuracy. The concept of the overall test method and the considered conditions are shown in Figure 1 and Table 2, respectively.



a) Take-off and landing stability under wind

b) Six-directional flight stability under wind

c) Six-directional flight stability under wind and rain

Key

1 test section

2 wind nozzle

3 rainfall nozzle

Figure 1 — The test method for evaluation of the flight stability

Table 2 — The test method and condition for flight stability evaluation

Test item	Multi-copter UA motion	Test condition	Position measurement
Take-off and landing stability under wind(gust)	Vertical take-off ↔ landing	Temperature: −20 °C to 50 °C Wind speed: 1 m/s to 30 m/s	Real time measuring three-dimensional position of multi-copter UA
Take-off and landing stability under wind(gust) and rainfall	Vertical take-off ↔ landing	Temperature: −20 °C to 50 °C Wind speed: 1 m/s to 30 m/s Rain fall: 0 mm/h to 20 mm/h	
Six-directional flight stability under wind(gust)	Six-directional flight	Temperature: −20 °C to 50 °C Wind speed: 1 m/s to 30 m/s	
Six-directional flight stability under wind(gust) and rainfall	Six-directional flight	Temperature: −20 °C to 50 °C Wind speed: 1 m/s to 30 m/s Rain fall: 0 mm/h to 20 mm/h	
360° rotation flight stability under wind(gust)	360° rotational flight	Temperature: −20 °C to 50 °C Wind speed: 1 m/s to 30 m/s	
360° rotation flight stability under wind(gust) and rainfall	360° rotational flight	Temperature: −20 °C to 50 °C Wind speed: 1 m/s to 30 m/s Rain fall: 0 mm/h to 20 mm/h	

The range of wind speed is set from light air to violent storm based on the Beaufort wind force scale,[2] while the range of rainfall intensity is set from light to heavy rain based on the rainfall intensity categorization.[3] The maximum wind speed and rain fall rate can be determined by the requester. The considered maximum wind speed and rainfall rate of 30 m/s and 20 mm/h, respectively, are not mandatory. To ensure sufficient intensity of rainfall, droplets of size ranging from 0,5 mm to 4,5 mm are considered.[4] Most of gust generation methods create a wind speed difference for gust by adjusting the direction of the wind generated by wind generator. Therefore, the test procedure is to adjust the wind speed difference for gust after adjusting the wind speed. All test cases include a step to adjust the wind speed difference for gust; but if a gust test is not performed, this step can be skipped.

4.4.2 Take-off and landing stability test under wind

According to the test purpose, the wind speed and temperature should be adjusted from 1 m/s to 30 m/s and −20 °C to 50 °C, respectively. Spatial deviations between the desired and actual paths should be measured during take-off and landing operations. The stability criterion is that the multi-copter UA should land in an upright position within a set distance from the take-off position.

4.4.3 Take-off and landing stability test under wind and rainfall

According to the test purpose, the wind speed, temperature, and rainfall intensity should be adjusted from 1 m/s to 30 m/s, −20 °C to 50 °C, and 0 mm/h to 20 mm/h, respectively. Spatial deviations between the desired and actual paths should be measured during take-off and landing operations. The stability criterion is that the multi-copter UA should land in an upright position within a set distance from the take-off position.

4.4.4 Six-directional flight stability test under wind

According to the test purpose, the wind speed and temperature should be adjusted from 1 m/s to 30 m/s, and −20 °C to 50 °C, respectively. Spatial deviations between the desired and actual paths should be measured during each six-directional flight, at least 1 m from the start position. The stability criterion is that the multi-copter UA can stay within a set three-dimensional boundary. The wind speed at which the multi-copter UA can no longer remain with the set boundary should be considered.

4.4.5 Six-directional flight stability test under wind and rainfall

According to the test purpose, the wind speed, temperature, and rainfall intensity should be adjusted from 1 m/s to 30 m/s, −20 °C to 50 °C, and 0 mm/h to 20 mm/h (mixed conditions), respectively. Spatial deviations between the desired and actual paths should be measured during each six-directional flight, at least 1 m from the start position. The stability criterion is that the multi-copter UA can stay within a set three-dimensional boundary. The wind speed at which the multi-copter UA can no longer remain with the set boundary should be considered.

4.4.6 Flight stability test under wind during a 360° rotational flight

According to the test purpose, the wind speed and temperature should be adjusted from 1 m/s to 30 m/s, and −20 °C to 50 °C, respectively. Spatial deviations between the desired and actual paths should be measured during a 360° rotational flight. The stability criterion is that the multi-copter UA can stay within a set three-dimensional boundary. The wind speed at which the multi-copter UA can no longer remain with the set boundary should be considered.

4.4.7 Flight stability test under wind and rainfall during a 360° rotational flight

According to the test purpose, the wind speed, temperature, and rainfall intensity should be adjusted from 1 m/s to 30 m/s, −20 °C to 50 °C, and 0 mm/h to 20 mm/h (mixed conditions), respectively. Spatial deviations between the desired and actual paths should be measured during a 360° rotational flight. The stability criterion is that the multi-copter UA can stay within a set three-dimensional boundary. The wind speed at which the multi-copter UA can no longer remain with the set boundary should be considered.

4.5 Measurement system

Any type of spatial precision measurement system, such as those using ultrasound, ultra-wideband, precision motion capture camera, and video recording, that considers flight motion of a multi-copter

UA can be used for measurements. The measurement system should measure the position of the multi-copter UA using a centimetre holder.

5 Test process

5.1 Preparatory procedure

The preparatory procedure should be performed as follows.

a) Check calibration status of measurement devices (wind speed measurement probe, position measurement device, etc.).

b) Set to a predefined temperature.

c) Measure and record atmospheric pressure.

d) Prepare and check the multi-copter UA.

e) Activate the ground control system to communicate with the multi-copter UA.

f) Power on the multi-copter UA.

g) Establish a multi-copter UA communication network with the ground control system.

h) Check and monitor the status (gyroscope, GPS, compass sensor, etc) of the multi-copter UA.

5.2 Test procedure

5.2.1 Take-off landing stability under wind

The test procedure shall be performed as follows.

a) Adjust the wind speed from 0 (m/s) to the targeted velocity (m/s).

b) Adjust the wind speed difference 0 (%, m/s) to the targeted wind speed difference (%, m/s) for the wind gust generation. (If the wind gust test is not performed, this step is skipped.)

c) Record the position and posture data obtained by the three-dimensional measurement system.

d) Record the position and posture velocity data obtained by the three-dimensional measurement system.

e) Save the log file obtained by the multi-copter UA.

f) Perform take-off under wind in manual or autopilot mode.

g) Perform landing under wind in manual or autopilot mode.

h) Adjust the wind speed from the targeted velocity (m/s) to 0 m/s.

5.2.2 Take-off landing stability under wind and rainfall

The test procedure should be performed as follows.

a) Adjust the wind speed from 0 m/s to the targeted velocity (m/s).

b) Adjust the wind speed difference 0 (%, m/s) to the targeted wind speed difference (%, m/s) for the wind gust generation. (If the wind gust test is not performed, this step is skipped.)

c) Adjust the rainfall intensity from 0 mm/h to the targeted rainfall rate (mm/h).

d) Record the position and posture data obtained using the three-dimensional measurement system.

e) Record the position and posture velocity data obtained using the three-dimensional measurement system.

f) Save the log file obtained by the multi-copter UA.

g) Perform take-off under wind in manual or autopilot mode.

h) Perform landing under wind in manual or autopilot mode.

i) Adjust the wind speed from the targeted velocity (m/s) to 0 m/s.

j) Adjust the rainfall intensity from the targeted rainfall rate (mm/h) to 0 mm/h.

5.2.3 Six-directional flight stability under wind

The test procedure should be performed as follows.

a) Adjust the wind speed from 0 m/s to the targeted velocity (m/s).

b) Adjust the wind speed difference 0 (%, m/s) to the targeted wind speed difference (%, m/s) for the wind gust generation. (If the wind gust test is not performed, this step is skipped.)

c) Record the position and posture data obtained using the three-dimensional measurement system.

d) Record the position and posture velocity data obtained using the three-dimensional measurement system.

e) Save the log file obtained by the multi-copter UA.

f) Perform take-off under wind in manual or autopilot mode.

g) Record the position and posture data obtained using the three-dimensional measurement system.

h) Record the position and posture velocity data obtained using the three-dimensional measurement system.

i) Save the log file obtained by the multi-copter UA.

j) Perform up-down flight motion under wind in manual or autopilot mode.

k) Record the position and posture data obtained using the three-dimensional measurement system.

l) Record the position and posture velocity data obtained using the three-dimensional measurement system.

m) Save the log file obtained by the multi-copter UA.

n) Perform leftward–rightward flight motion under wind in manual or autopilot mode.

o) Record the position and posture data obtained using the three-dimensional measurement system.

p) Record the position and posture velocity data obtained using the three-dimensional measurement system.

q) Save the log file obtained by the multi-copter UA.

r) Perform forward–backward flight motion under wind in manual or autopilot mode.

s) Record the position and posture data obtained using the three-dimensional measurement system.

t) Record the position and posture velocity data obtained using the three-dimensional measurement system.

u) Save the log file obtained by the multi-copter UA.

v) Perform landing under wind in manual or autopilot mode.

w) Adjust the wind speed from the targeted velocity (m/s) to 0 m/s.

5.2.4 Six-directional flight stability under wind and rainfall

The test procedure should be performed as follows.

a) Adjust the wind speed from 0 m/s to the targeted velocity (m/s).

b) Adjust the wind speed difference 0 (%, m/s) to the targeted wind speed difference (%, m/s) for the wind gust generation. (If the wind gust test is not performed, this step is skipped.)

c) Adjust the rainfall intensity from 0 mm/h to the targeted intensity (mm/h).

d) Record the position and posture data obtained using the three-dimensional measurement system.

e) Record the position and posture velocity data obtained using the three-dimensional measurement system.

f) Save the log file obtained by the multi-copter UA.

g) Perform take-off under wind and rainfall in manual or autopilot modes.

h) Record the position and posture data obtained using the three-dimensional measurement system.

i) Record the position and posture velocity data obtained using the three-dimensional measurement system.

j) Save the log file obtained by the multi-copter UA.

k) Perform upward–downward flight motion under wind and rainfall in manual or autopilot mode.

l) Record the position and posture data obtained using the three-dimensional measurement system.

m) Record the position and posture velocity data obtained using the three-dimensional measurement system.

n) Save the log file obtained by the multi-copter UA.

o) Perform leftward–rightward flight motion under wind and rainfall in manual or autopilot mode.

p) Record the position and posture data obtained using the three-dimensional measurement system.

q) Record the position and posture velocity data obtained using the three-dimensional measurement system.

r) Save the log file obtained by the multi-copter UA.

s) Perform forward–backward flight motion under wind and rainfall in manual or autopilot mode.

t) Record the position and posture data obtained using the three-dimensional measurement system.

u) Record the position and posture velocity data obtained using the three-dimensional measurement system.

v) Save the log file obtained by the multi-copter UA.

w) Perform landing under wind and rainfall in manual or autopilot modes.

x) Adjust the wind speed from the targeted velocity (m/s) to 0 m/s.

y) Adjust the rainfall intensity from the targeted intensity (mm/h) to 0 mm/h.

5.2.5 360° rotational stability under wind

The test procedure shall be performed as follows.

a) Adjust the wind speed from 0 m/s to the targeted velocity (m/s).

b) Adjust the wind speed difference 0 (%, m/s) to the targeted wind speed difference (%, m/s) for the wind gust generation. (If the wind gust test is not performed, this step is skipped.)

c) Record the position and posture data obtained using the three-dimensional measurement system.

d) Record the position and posture velocity data obtained using the three-dimensional measurement system.

e) Save the log file obtained by the multi-copter UA.

f) Rotate from 0° to 360° under wind in manual or autopilot mode.

g) Perform landing under wind in manual or autopilot mode.

h) Adjust the wind speed from the targeted velocity (m/s) to 0 m/s.

5.2.6 360° rotation stability under wind and rainfall

The test procedure shall be performed as follows.

a) Adjust the wind speed from 0 to the targeted velocity (m/s).

b) Adjust the wind speed difference 0 (%, m/s) to the targeted wind speed difference (%, m/s) for the wind gust generation. (If the wind gust test is not performed, this step is skipped.)

c) Adjust the rainfall intensity from 0 mm/h to the targeted intensity (mm/h).

d) Record the position and posture data obtained using the three-dimensional measurement system.

e) Record the position and posture velocity data obtained using the three-dimensional measurement system.

f) Save the log file obtained by the multi-copter UA.

g) Rotate from 0° to 360° under wind and rainfall in manual or autopilot mode.

h) Perform landing under wind and rainfall in manual or autopilot mode.

i) Adjust the wind speed from the targeted velocity (m/s) to 0 m/s.

j) Adjust the rainfall intensity from the targeted intensity (mm/h) to 0 mm/h.

6 Examination and evaluation

Once the test procedures for flight stability measurements are followed, the experimental results are saved by the three-dimensional position measurement system for the multi-copter UAS. During the flight stability test, the three-dimensional position data of the multi-copter UA are measured and stored in real time using a centimetre holder. The three-dimensional position data of the multi-copter UA are considered the most important data for evaluation. The tester or requester defines the wind speed, rainfall, and tolerance for the measured position deviations, which are used for flight stability evaluations. The average values of wind speed and rainfall during the test are used to determine whether the test environmental conditions are satisfied. The tolerance for flight stability is calculated for each test using a general three-dimensional path error formula. Further detailed examples of the tests and evaluations are provided in Annexes A and B.

Annex A
(informative)

Examples of the multi-copter UAS flight stability test

A.1 Example of test apparatus

The example of an experimental apparatus used for evaluating the flight stability of a multi-copter UAS consisting of a wind generator and measuring device is discussed. The test section is shown in Figure A.1. Depending on the type of evaluation, additional test devices are added to simulate conditions such as wind gust, rainfall, and icing. The wind generator consists of two blowers and is designed to maintain a constant wind speed and quality during the flight stability test. A wind speed of approximately 30 m/s can be attained. The test section volume (width × height × depth) is designed such that a multi-copter UA-grade of 3 000 mm (from rotor to rotor) can be evaluated. Detailed schematics are presented in Figures A.2 and A.3.

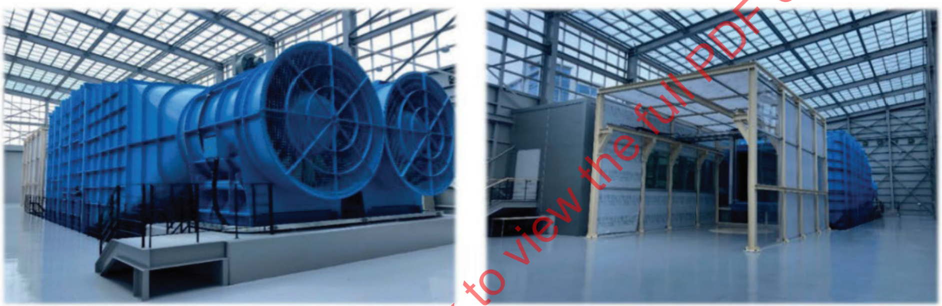
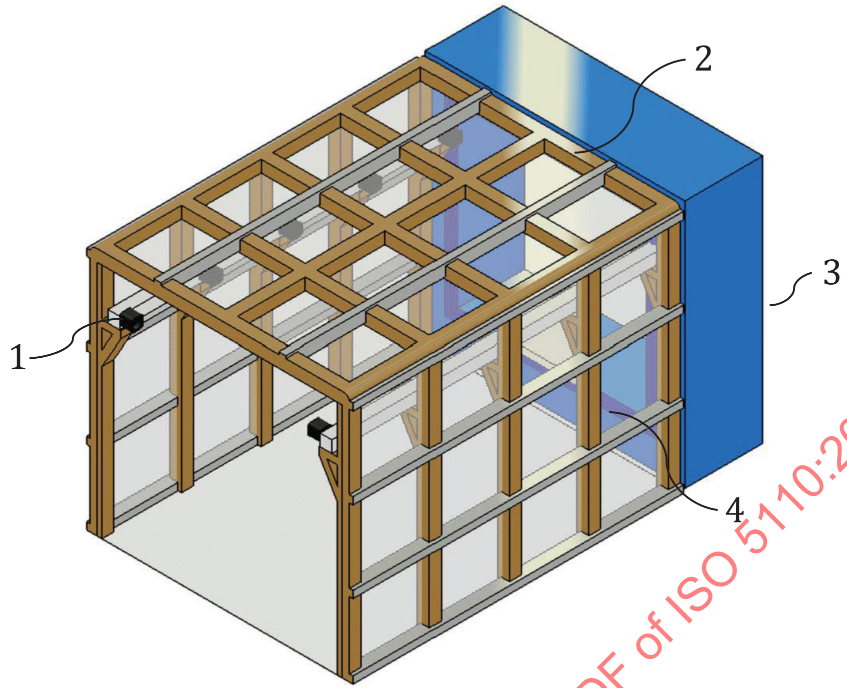


Figure A.1 — Wind generator and test section for the flight stability evaluation of the multi-copter UAS



Key

1 measurement device

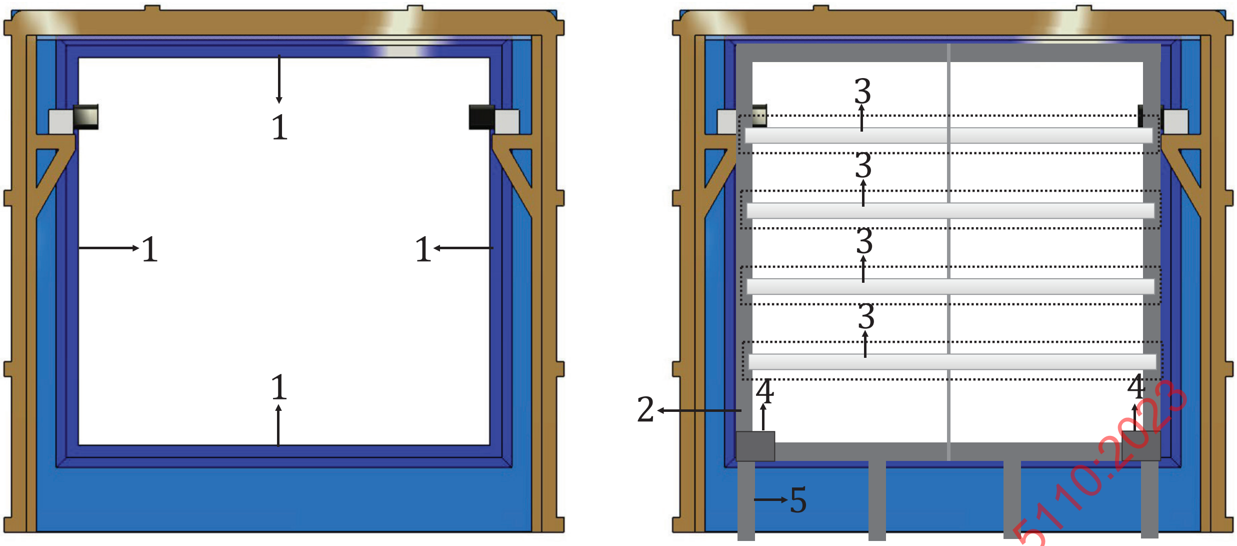
2 rainfall nozzle

3 blower

4 gust generator

Figure A.2 — Conceptual diagram of the overall test device used for the flight stability evaluation of the multi-copter UAS

Figure A.3 shows an example of implementation for the wind nozzle and gust generator. With the method in this document, the wind resistance test and the gust test can be performed in one facility. In this method, when performing the gust test, the gust generator can be installed in front of the wind nozzle to generate a gust. The gust generator consists of a blade that generate controllable gust, a servo motor that control the angle of the blade, and a movable support that can move the gust generator.



Key

1 wind nozzle

2 gust generator

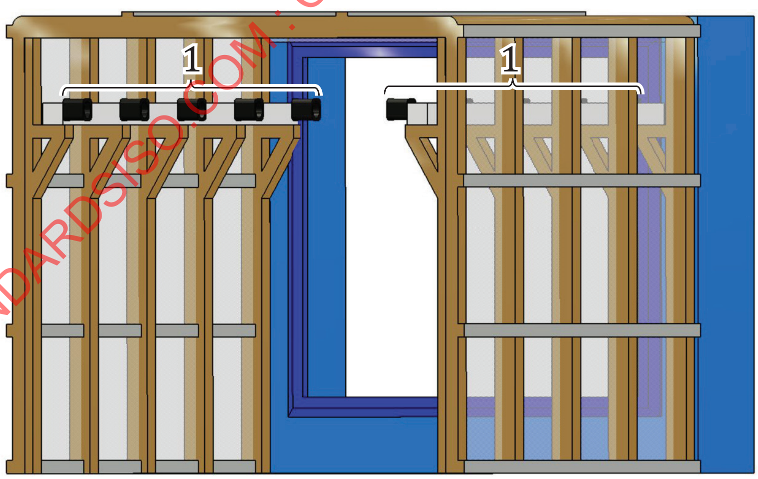
3 gust generator: oscillating vane

4 gust generator: servo motor to oscillate vane

5 gust generator: movable support

Figure A.3 — Blower and test section for the flight stability evaluation of the multi-copter UAS

Figure A.4 shows an example of the three-dimensional multi-copter UA positioning system that consists of multiple measurement devices, such as IR camera, ultrasonic sensor, and a computing system for the real-time positioning of the in-flight multi-copter UA.



Key

1 position measuring system: IR-based motion capture camera

Figure A.4 — Three-dimensional multi-copter UA position measuring system (example)

As shown in Figure A.5, a three-dimensional position measuring system is implemented with eight IR-based motion capture cameras. The measurement system can measure the flight path of the multi-copter UA in real time during the flight stability test. The flight path error with centimetre grade is computed automatically using saved measurement data without human intervention.

Figure A.5 — Three-dimensional position measuring system with 8 IR cameras(example)

A.2 Example of multi-copter UAS flight stability test

An example of the overall experimental apparatus is shown in Figure A.6, while Figure A.7 shows the camera configuration of the three-dimensional multi-copter UA position measurement system. The first test case shows an example of the take-off and landing stability tests performed and the results are shown in Figure A.8. The second case shows an example of a six-directional flight returning to its starting position and the experimental results of the stability tests are shown in Figures A.9 to A.14.

Figure A.6 — An example of the experimental apparatus for the flight stability test

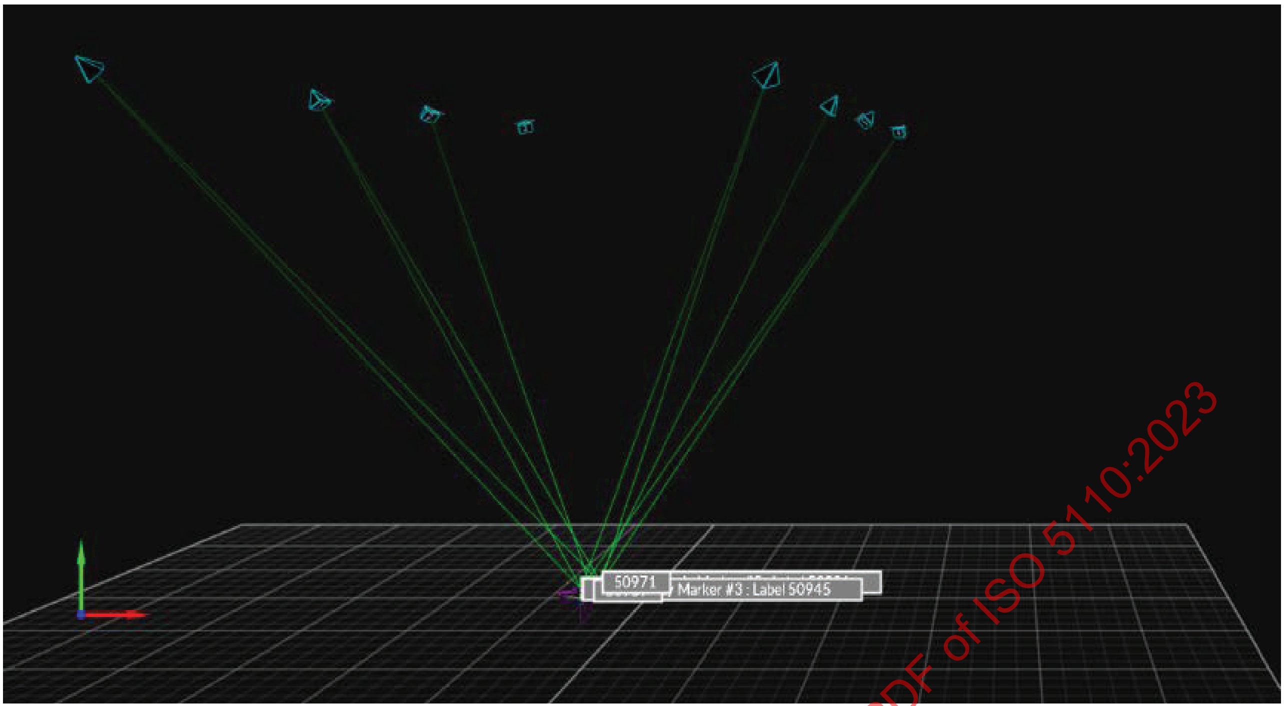
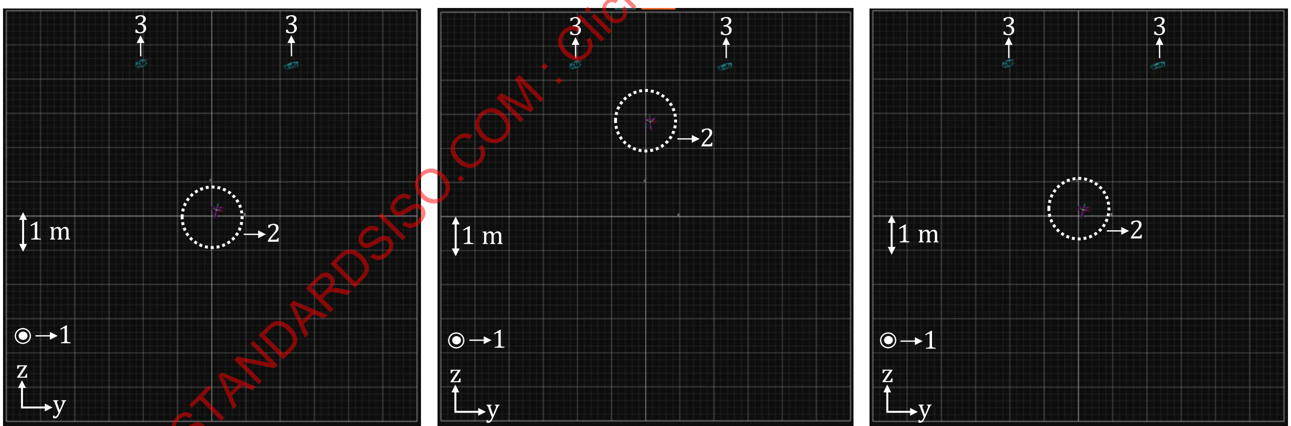


Figure A.7 — Camera configuration of the three-dimensional measurement system for recording the position of the multi-copter UA (example)

In this test case, the take-off and landing operations are performed with a take-off height of 3 m from the ground at a wind speed of 10 m/s. The flight stability for take-off and landing is evaluated using the experimental results.



a) Ready for test b) Take-off and hovering c) Landing

Key

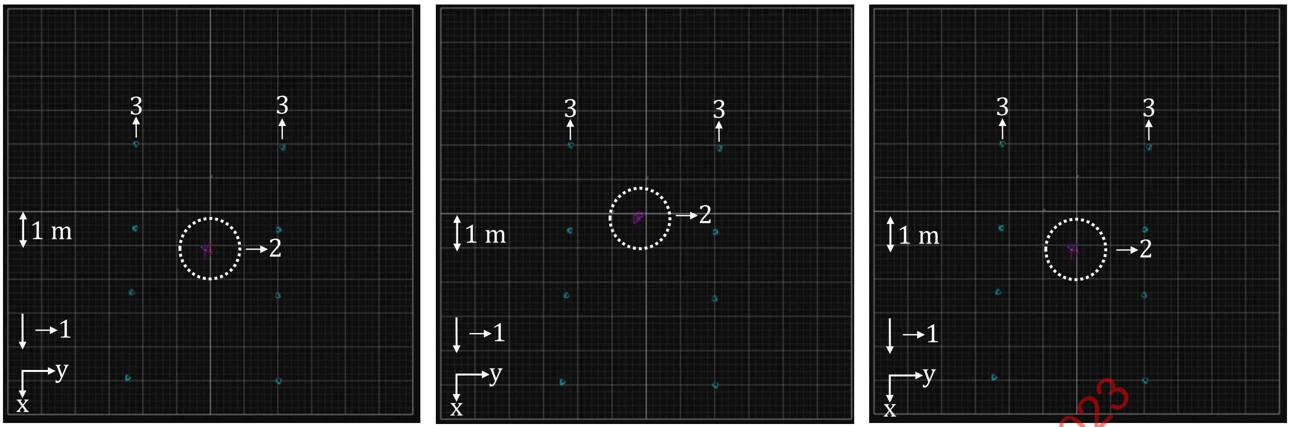
1 wind direction

2 multi-copter UA

3 motion capture camera

Figure A.8 — Example of the multi-copter UA position tracking from take-off to landing

In this test case, the flight stability test for a forward motion of 1 m from the starting point is performed at a wind speed of 10 m/s. The flight stability for forward flight is evaluated using the experimental data.



a) Ready for test b) Forward flight c) Return to start position

Key

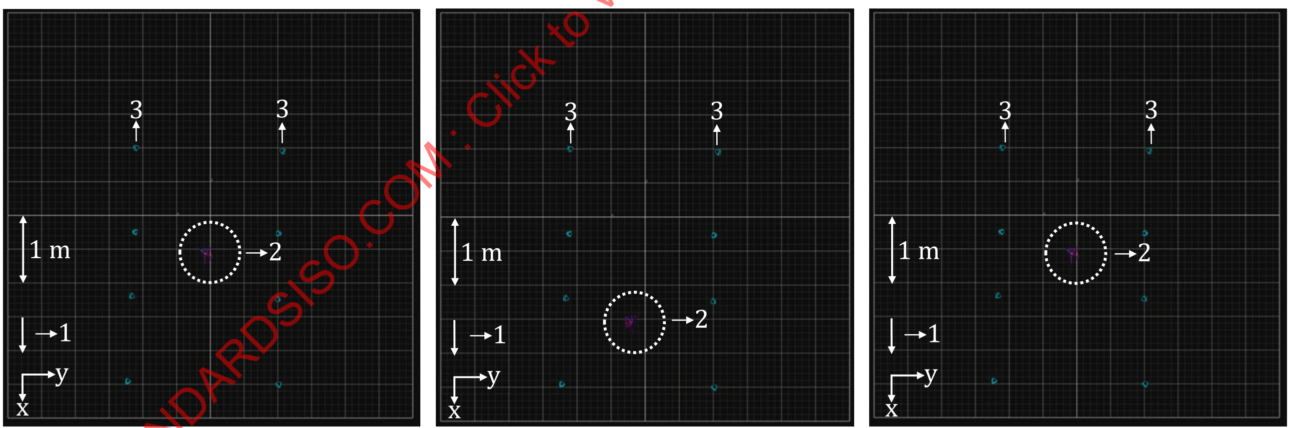
1 wind direction

2 multi-copter UA

3 motion capture camera

Figure A.9 — Example of the multi-copter UA position tracking for a forward motion of flight

In this test case, the flight stability test for a backward motion of 1 m from the starting point is performed at a wind speed of 10 m/s. The flight stability for backward flight is evaluated using the experimental data.



a) Ready for test b) Backward flight c) Return to start position

Key

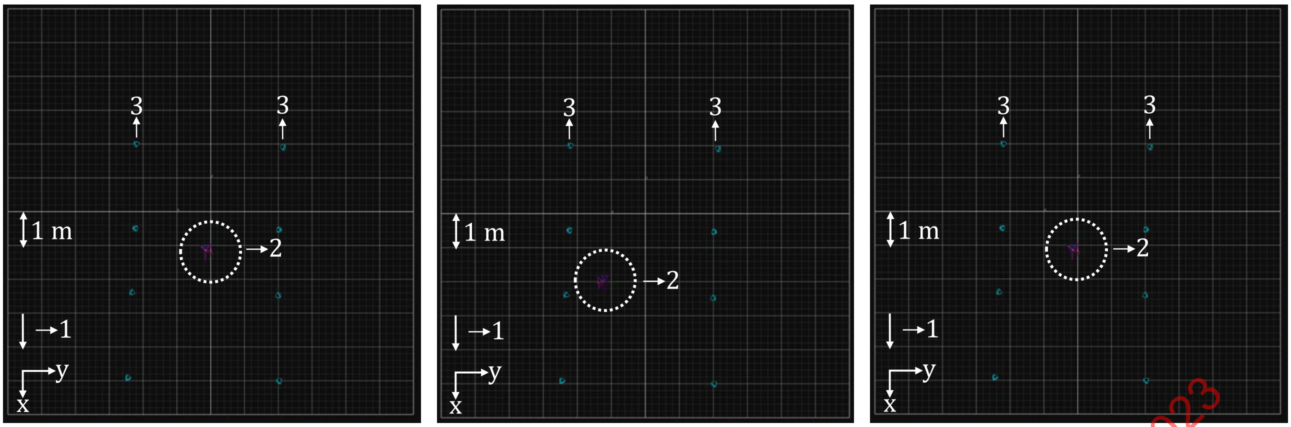
1 wind direction

2 multi-copter UA

3 motion capture camera

Figure A.10 — Example of the multi-copter UA position tracking for a backward motion of flight

In this test case, the flight stability test for a leftward motion of 1 m from the starting point is performed at a wind speed of 10 m/s. The flight stability for the leftward flight direction is evaluated using the experimental data.



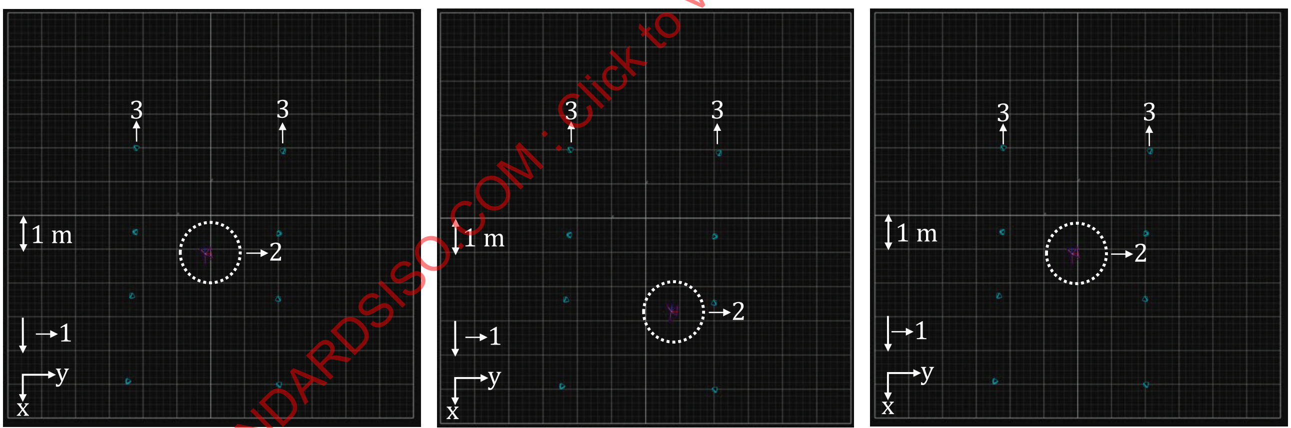
a) Ready for test b) Leftward flight c) Return to start position

Key

1 wind direction
2 multi-copter UA
3 motion capture camera

Figure A.11 — Example of the multi-copter UA position tracking for leftward flight direction

In this test case, the flight stability test for a rightward motion of 1 m from the starting point is performed at a wind speed of 10 m/s. The flight stability for the rightward flight direction is evaluated using the experimental data.



a) Ready for test b) Rightward flight c) Return to start position

Key

1 wind direction
2 multi-copter UA
3 motion capture camera

Figure A.12 — Example of the multi-copter UA position tracking for rightward flight direction

In this test case, the flight stability test for an upward motion of 1 m from the starting point is performed at a wind speed of 10 m/s. The flight stability in the upward direction of the flight is evaluated using the experimental data.