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Swiss Transportation Safety Investigation Board STSB

Final Report No. 2390 by the Swiss Transportation Safety Investigation Board

concerning the accident involving the drone Matternet M2 V9, SUI-9903,

on 9 May 2019

Ob der Hueb, city district 6 of Zurich

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General information on this report

This report contains the Swiss Transportation Safety Investigation Board's (STSB) conclusions on the circumstances and causes of the accident, which is the subject of the investigation.

In accordance with Article 3.1 of the 12th edition of annex 13, effective from 5 November 2020, to the Convention on International Civil Aviation of 7 December 1944 and Article 24 of the Federal Act on Civil Aviation (CAA, SR 748.0) of 21 December 1948 (as amended on 1 May 2022), the sole purpose of the investigation of an aircraft accident or serious incident is to prevent accidents or serious incidents. The legal assessment of accident/incident causes and circumstances is expressly no concern of the investigation. It is therefore not the purpose of this investigation to determine blame or clarify questions of liability.

If this report is used for purposes other than accident prevention, due consideration shall be given to this circumstance.

The definitive version of this report is the original report in German and therefore binding.

All information, unless otherwise indicated, relates to the time of the accident.

All times in this report, unless otherwise indicated, are stated in Local Time (LT), valid for the territory of Switerzland, which corresponded to Central European Time (CET) at the time of the accident. The relation between LT, CET and Cordinated Universal Time (UTC) is:
LT = CET = UTC + 2 hours

Synopsis

Aircraft	Matternet M2 V9	SUI-9903
Operator	Matternet Inc., 3511 EdisonWay, Menlo Park, CA 94025 USA	
Owner	Matternet Inc., 3511 EdisonWay, Menlo Park, CA 94025 USA	

Drone pilot	American citizen, born 1985				
Licence	At the time of the event, no official licences can be obtained for this type of unmanned aircraft system. Training by the operator has taken place.				
Flying experience	**total**	549:51 h	**during the last 90 days**	9:16 h	
	on type	9:16 h	**during the last 90 days**	9:16 h	

Location	Ob der Hueb, city district 6 of Zurich		
Coordinates	249 909 / 684 218 (*Swiss Grid* 1903) N 47° 23' 41'' E 008° 33' 15'' (WGS[1] 84)	**altitude**	555 m/M
Date and time	9 May 2019, 10:39 hrs		

Type of operation	Commercial[2]
Flight rules	Not applicable
Point of departure	University of Zurich (UZH) Irchel, Zurich Oberstrass
Destination	University Hospital of Zurich (USZ), Zurich Fluntern
Flight phase	Cruise
Type of accident	Crash after malfunction

Injuries to persons

Injuries	Crew	Passengers	Total of occupants	Third persons
Fatal	0	0	0	0
Serious	0	0	0	0
Minor	0	0	0	0
None	0	0	0	Not applicable
Total	0	0	0	0

Damage to aircraft	Destroyed
Other damage	None

[1] WGS: World Geodetic System, the WGS 84 standard was adopted for aviation by decision of the International Civil Aviation Organization (ICAO) in 1989.

[2] In the context of the required operating approval, the Federal Office of Civil Aviation (FOCA) does not distinguish between commercial, non-commercial or scientific drone operators.

1 Factual information

1.1 Flight preparations and history of flight

1.1.1 General

According to Art. 2 of Regulation (EU) 996/2010 in conjunction with Art. 3 lit. b of the Ordinance on the Safety Investigation of Transport Incidents (OSITI), the Swiss Transportation Safety Investigation Board (STSB) is in principle also responsible for the investigation of accidents and serious incidents involving unmanned aircraft. Drone technology and the use of unmanned aircraft systems are becoming increasingly important and are likely to develop into an essential branch of aviation in the near future.

From the preliminary clarifications on the present incident, the STSB recognised a significant potential for prevention, so that an investigation was opened based on Art. 20 para. 4 OSITI. In addition, third parties on the ground were endangered by the crash.

1.1.2 Pre-flight history

It was a mission on behalf of Swiss Post, during which blood samples had been transported on the outbound flight to the University of Zurich (UZH) Irchel. The accident occurred without load on the return flight to the University Hospital of Zurich (USZ), Fluntern. Swiss Post was the client and service provider and purchased the service from Matternet being the operator of the drone.

1.1.3 History of flight

About one minute after take-off from the University of Zurich (UZH) Irchel, the drone automatically triggered the flight termination system (FTS) and initiated an emergency descent with a parachute. After ejection of the parachute, the connecting rope broke and the drone hit the forest floor near playing children without deceleration (cf. figure 1). The drone was destroyed on impact; no one was injured.

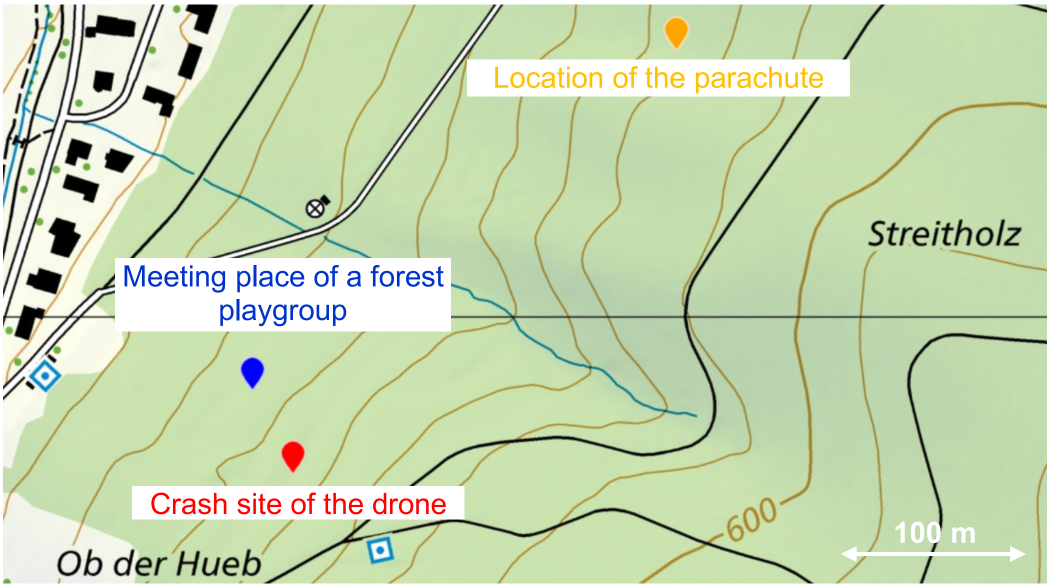

Figure 1: Crash site of the drone (red marker) in the wooded area "Ob der Hueb", about 500 m southeast of the University of Zurich (UZH) Irchel, not far from children playing in the woods (blue marker). The parachute (orange marker) was recovered in the trees about 330 m to the northeast. Source of map: Federal Office of Topography.

Neither the children nor the two kindergarten teachers who observed the crash of the drone at a distance of about 50 metres from the crash site (cf. figure 1) could perceive an acoustic warning signal.

1.2 Aircraft information

1.2.1 General

Registration	SUI-9903
Aircraft type	Matternet M2 V9
Characteristics	Drone
Manufacturer	Matternet Inc., 3511 EdisonWay, Menlo Park, CA 94025 USA
Operator/owner	Matternet Inc., 3511 EdisonWay, Menlo Park, CA 94025 USA
Year of manufacture	2018
Serial number	M2-0033
Propulsion	Quadrocopter[3] with four XRotor PRO 6215 180KV electric motors. Propeller Mejzlik 24"
Energy source	Lithium-ion battery (flight accumulator) with a capacity of 756 Wh
Maximum gross take-off weight	13.2 kg
Maximum payload weight	2 kg
Cruise speed designed into the flight control software and managed by the autopilot	16 m/s (equivalent to 58 km/h)
Never exceed speed	30 m/s (equivalent to 108 km/h)
Maximum wind component	8 m/s (gusts 12 m/s)
Maximum range (no wind)	20 km with a payload of 1 kg 15 km with a payload of 2 kg
Communication	GSM[4] network
Area of operation	By day and night
Relevant equipment to avoid collisions	Collision Warning Device Flarm[5], Anti-Collision Lights

1.2.2 Information on the flight termination system

The drone was equipped with an autonomous flight termination system (FTS) that triggers the ejection of the parachute when required (cf. figure 2). This melts a fusible wire that secures the pretensioned FTS parachute in its container inside the

[3] A quadrocopter (also quadcopter) has four rotors or propellers arranged in a plane and acting vertically downwards to generate lift or propulsion.

[4] GSM: Global System for Mobile communication

[5] Flarm: A traffic information and collision avoidance system usually used in general aviation, especially in light aircraft and gliders.

drone. Subsequently, the motors are stopped. With the parachute fully open, the drone descends at a vertical speed of 3 to 5 m/s, according to the manufacturer's specifications. The impact energy of the drone descending to the ground with a maximum payload is 156 J at the most as per manufacturer. An electrically generated warning signal sounds to warn third parties on the ground.

Figure 2: Image sequence of the parachute ejection during a test of the autonomous flight termination system (FTS). There are no danger and warning labels for first responders on the drone (source: Matternet).

1.2.3 Control of the drone

The drone was equipped with a flight controller of the type Pixhawk Cube Black 2.1 from the manufacturer ProfiCNC, to which two redundant GNSS[6] modules including a magnetometer were connected as a compass to determine the position.

ArduCopter was used as firmware[7] on the Pixhawk Cube. This software is available as open source[8], so that one can also make one's own modifications to it. In May 2019, a software version modified by Matternet based on ArduCopter 3.5.0-rc5 (as of May 2017) was used on the crashed Drone; Matternet's own version number of this modification was mttr-0.4.24. In January 2019 the earlier version mttr-0.4.20 was in use.

Flight guidance along several waypoints was controlled by a navigation system developed by Matternet. It was connected to the flight controller, which – in guided mode – transmitted the control commands for flying along the waypoints to the flight controller.

For stabilisation and control of the flight attitude, the Pixhawk Cube contained three redundant inertial measurement units (IMU) of different design, which were equipped with accelerometer and gyroscope sensors as well as two of them with magnetometers. For barometric altitude control, there were two pressure sensors in the Pixhawk Cube.

The ArduCopter software converts the raw data of the IMU sensors, the GNSS modules and their magnetometers as well as the barometers into the system parameters for position, attitude, orientation and motion vectors. These are derived iteratively from the sensor data, some of which still contain errors, using mathematical methods such as "smoothing" and extended Kalman filters (EKF).

The data of the redundant sensors are processed virtually parallel[9] to each other in several computing processes (EKF lanes). One of the lanes is given priority, i.e. its results are used for the actual flight control. If the data of this prioritised lane is

[6] GNSS: Global Navigation Satellite System, a collective term for satellite systems such as Global Positioning System (GPS), Global Navigation Satellite System (GLONASS) or the Chinese satellite navigation system BeiDou.

[7] Firmware is the software embedded in electronic devices that performs basic functions.

[8] GNU General Public License Version 3 (https://github.com/ArduPilot/ardupilot/blob/master/COPYING.txt – last visited on 06.06.2023)

[9] The Pixhawk Cube Black's Central Processing Unit (CPU) does not support true multiprocessing.

no longer considered sufficiently trustworthy, for example because one of the sensors included in the EKF calculations has failed or is delivering implausible data, the system automatically switches to another lane.

In addition, EKF variance is continuously determined, which result from the deviation of the results of the EKF lanes from each other. If these EKF variants exceed a threshold value, a configurable action can be triggered if required. In the case of the Matternet drone, the flight termination system was linked to this (cf. chapter 1.2.2).

The software version of the crashed drone only allowed the parallel calculation of two EKF lanes, which means that no false signal can be isolated, as would be possible with three parallel lanes. Only newer software versions of the ArduCopter software allow this.

A parameter called "EK2_IMU_MASK" is used in the configuration of the flight controller to define the assignment of the three IMUs in software, namely which of the three IMUs is included in the calculations for the two lanes.

In practice, the data from the two IMUs are usually used so that the vibrations of a drone in flight have as little influence as possible. The default value for the parameter is initially set to 3[10]. For drones of common design, this keeps the EKF variance low as long as both IMUs are working correctly.

According to the manufacturer Matternet, the hardware with regards to the drone's control remained unchanged between the flights in January 2019 and the accident flight on 9 May 2019.

1.2.4 Service Bulletin

In Service Bulletin (SB) 0000002[11] published in mid-April 2019 in the discussion forum of the flight controller manufacturer, the latter addressed problems in connection with the data supplied by the IMU and its further processing in the EKF lanes. Since 2 May 2019, the manufacturer recommended, among other things, that the parameter "EK2_IMU_MASK" be set to the value 7. This should ensure that all three IMUs are included in the calculations and thus allow three parallel lanes to isolate an erroneous signal. Since ArduCopter version 3.6.12, a subsequently optimised failover logic[12] ensured that faulty IMU data was detected as best as possible and reprioritised accordingly between the EKF lanes.

Upon request, the manufacturer Matternet explained that the flight controller installed in the SUI 9903 had been acquired in the last quarter of 2018. Thus, it does not fall within the period of Service Bulletin SB 0000002, which was published by its manufacturer in April 2019.

In the meantime, the manufacturer stipulates that *"All copter users to be on at least ArduCopter 4.x and SB2 parameters, regardless of cube age."* (cf. https://discuss.cubepilot.org/c/MSB/16). This means that in the meantime not only flight controllers from the period initially addressed by SB 0000002 should be configured according to the instructions and their software updated, but that in general all Pixhawk Cubes should in the meantime be updated to at least ArduCopter 4.x and the parameters adjusted accordingly.

[10] These are values that are resolved into a binary bit mask, e.g. 3 ≡ 110, 5 ≡ 101, 7 ≡ 111.

[11] SB-0000002: Safety/Service Bulletins - CubePilot – last visited on 06.06.2023)

[12] A failover logic controls the switching between several redundant systems or, in the case of sensors, the use of which of the data supplied by the sensors is given priority.

1.2.5 Operation and monitoring

Each flight of the drone is monitored by a flight director (FD) using GPS data that is streamed to the operator's server via a GSM connection. In addition to various meteorological data, information on surrounding air traffic is also available.

In any conflict situation, the FD has the possibility to intervene in the flight process with the following commands:

- land: The drone is landed on the spot;
- hold: The drone hovers in place;
- resume: The drone resmues the mission;
- return: The drone returns to the starting point.

Manual control of the drone beyond the visual line of sight (BVLOS) is not possible, but is only provided for in the event of any take-off and landing problems by the drone pilot (operator). These pilots undergo internal training with the drone operator, whereby experience from drone operation in the private sector is a prerequisite. Further information on operational aspects can be found in the summary report on the incident involving the largely identical drone SUI-9909 of 25 January 2019.

1.3 Meteorological information

1.3.1 General weather situation

A depression with a core over the North Sea determined the weather in Switzerland. At its southern edge, the westerly wind zone stretched from the Atlantic to Central Europe.

1.3.2 Weather at the time and in the region of the accident

The weather was dry with little wind.

Weather	cloudy and dry
Clouds	1/8 – 2/8 at 1000 ft AAE[13] LSZH 5/8 – 7/8 at 7000 ft AAE LSZH
Visibility	50 km
Wind Airport Zurich (LSZH)	200 degress, 4 kt varying between 160 and 240 degrees
Wind Hönggerberg, ETHZ[14]	in gusts at 6 kt
Temperature and dewpoint Airport Zurich (LSZH)	10 °C / 6 °C
Temperature and dewpoint Hönggerberg, ETHZ	8 °C / 4 °C
Atmospheric pressure (QNH)	1003 hPa (pressure reduced to sea level, calculated with the values of the ICAO[15] standard atmosphere)
Hazards	None

[13] AAE: Above Aerodrome Elevation

[14] ETHZ: *Eidgenössische Technische Hochschule der Stadt Zürich*, Swiss Federal Institute of Technology Zurich

[15] ICAO: International Civil Aviation Organization

1.3.3 Astronomical information

Position of the sun	Azimuth 118°	Elevation 45°
Lighting conditions	Day	

1.4 Wreckage and impact information

The drone was largely destroyed on impact with the forest floor (cf. figure 3). One propeller blade was not found at the accident site. Furthermore, no remains of the connecting rope to the emergency parachute were found on the structure of the drone. The acoustic warning signal was faintly audible at the crash site.

Figure 3: Final position of the destroyed drone SUI-9903 at the crash site

The severed parachute with an intact connection to the bridle became entangled between two trees about 330 m northeast of the crash site (cf. figure 4).

Figure 4: Location of the parachute separated from the drone

The connecting rope was cut at the drone end and showed signs of cuts and cracks (cf. figure 5).

Figure 5: Cut and tear point of the connecting rope

The attachment point on the structure of the drone showed clear deformations (cf. figure 6).

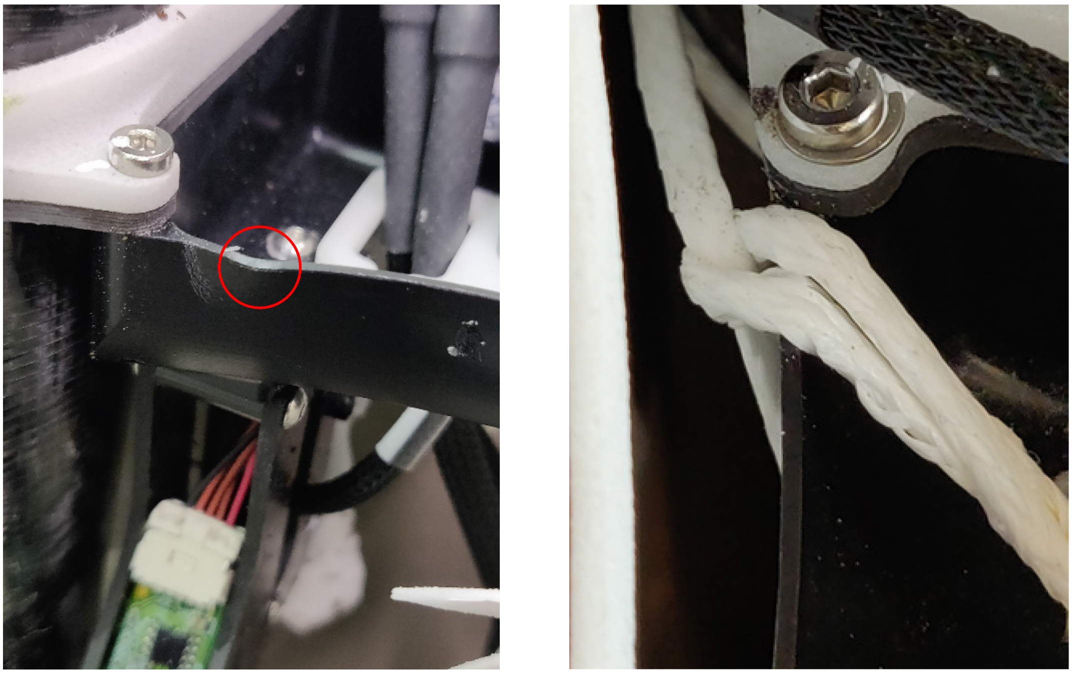

Figure 6: Clearly visible deformation of the sharp-edged attachment point (red circle) on the SUI-9903 drone involved in the accident (left) as well as the intact attachment of the connecting rope of an identical drone (right).

1.5 Investigations of the propulsion units and the flight termination system

During the forensic examination of the FTS release mechanism and the attachment of the parachute by the Zurich Forensic Science Institute, the following was found:

- The fusible wire securing the parachute in its container inside the drone had burnt through, as is intended in the context of an FTS activation (cf. chapter 1.2.2).
- The drone-side attachment point of the parachute, which was a boom of a propulsion unit, had a sharp edge at the deformed point (cf. figure 6).
- A crack fracture could be identified on the connecting rope. Compared to an identical parachute, the last piece of about 4 cm was missing, which corresponded to the circumference of the boom of the drone to which the line was attached. This missing piece of the connecting line could not be found.
- All four motor axles were free-floating and showed no imbalance or axial play.
- One of the four propellers was undamaged and showed no imbalance.
- One propeller blade was not found at the accident site.
- The four propulsion units, each consisting of a motor and propeller as well as the governor housed in the corresponding boom, were subject to a high degree of destruction that could be attributed to the impact.

1.6 Recordings

1.6.1 General

The memory card recovered from the crashed drone contained recordings from three flights on 9 May 2019:

- A short test flight early in the morning on Frauenklinikstrasse in Zurich, near the University Hospital Zurich (USZ). This was mainly manually controlled and concluded with a few waypoints set in the area of the hospital. The ground speed during this test flight was no more than 8 m/s.
- The outbound flight from the University Hospital of Zurich (USZ) to the University of Zurich (UZH) Irchel;
- The return flight from the University of Zurich (UZH) Irchel to the University Hospital of Zurich (USZ), where the accident occurred.

In addition, various log files of previous test flights conducted in the USA between 24 January 2019 and 4 April 2019 were found in a "Trashes" folder (cf. chapter 1.6.3).

1.6.2 Log file of the accident flight

The log file of the accident flight included records from 10:03:33 to 12:41:26. During this time, the engines were activated three times; the actual flight took place between 10:37:35 (take-off) and 10:38:48 (impact). The map shows the completed part of the flight including some waypoints (cf. figure 7).

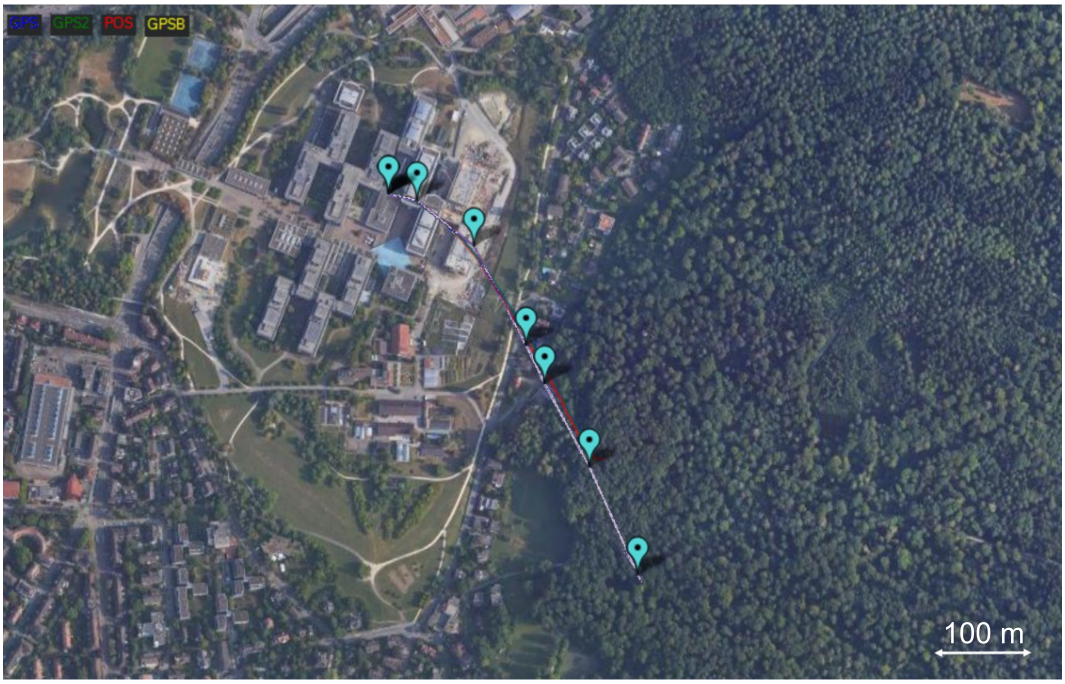

Figure 7: Map representation of the accident flight of SUI-9903 on 9 May 2019 according to the log files (source: STSB)

The drone initially ascended vertically to 92 m above the launch point on a magnetic heading of initially 302°. Subsequently, as the drone continued to climb, it also picked up speed in a horizontal direction, slowly turning towards the next waypoint. At 10:38:22, it reached a speed of 12.5 m/s over ground.

From this point onwards, all three IMUs recorded clearly increasing vibrations, and the associated acceleration values were sometimes well above 30 m/s². As a result, the drone continuously accelerated and decelerated by varying the pitch angle, which repeatedly exceeded the maximum value of -20° to +20° defined for this drone. This led to violent oscillations of the attitude, with the speed of the drone over ground varying between around 13 m/s and 17 m/s at peaks.

In addition to the vibrations detected by the Inertial Measurement Units (IMU) via the acceleration sensors, there were noticeable deviations between the data of the first two units (IMU1 and IMU2) and IMU3 in all three axes from 10:38:24 onwards; those along the Y-axis are shown as an example (cf. figure 8).

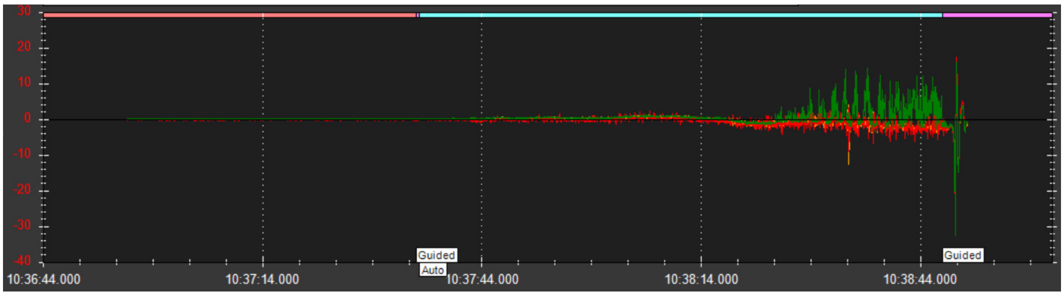

Figure 8: Time course of the deviations from the dimensionless values of the accelerometers using IMU1 (orange), IMU2 (red) and IMU3 (green).

A detailed view of the time ranges from 10:38:21 to 10:38:27 (cf. figure 9) and from 10:38:31 to 10:38:38 (cf. figure 10) clearly shows that strong deviations in the acceleration values of IMU3 occurred abruptly from 10:38:24, while IMU1 and IMU2 continued to deliver similar acceleration values. In the further course of time, these deviations increased in regular cycles.

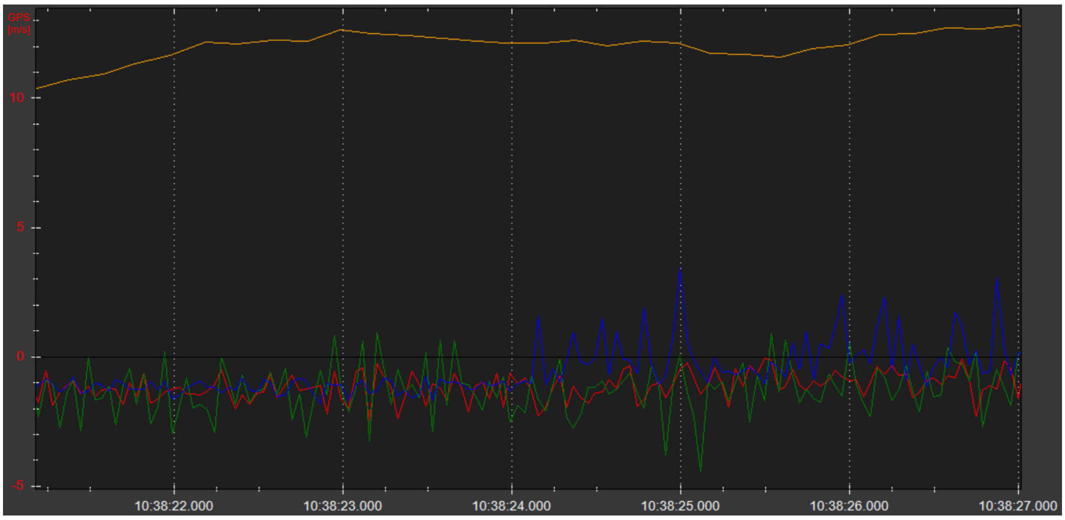

Figure 9: Time section (10:38:21 to 10:38:27) of the course of the deviations from the dimensionless values of the acceleration sensors using IMU1 (red), IMU2 (green) and IMU3 (blue) as well as the GPS speed (orange) in m/s.

Figure 10: Time section (10:38:31 to 10:38:38) of the course of the deviations from the values of the acceleration sensors using IMU1 (red), IMU2 (green) and IMU3 (blue). From about 10:38:32, a clear oscillation (blue line) with a frequency of about 2/3 Hz can be seen.

In deviation from the default value of 3 (cf. chapter 1.2.3), the parameter "EK2_IMU_MASK" was set to 5 for the drone involved in the accident. This means that the data from IMU1 and IMU3[16] were used for the calculations of the two EKF lanes.

At 10:38:46, the variances of the values calculated in parallel in the EKF lanes exceeded a critical limit. The event "EKFCHECK_BAD_VARIANCE" was logged in the log file, which triggered an error-handling programme for the deviations that had become too large. The flight termination system (FTS) was coupled to this in the present drone sample (cf. chapter 1.2.2). At the time, the drone was at an altitude of about 185 m above the elevation of the take-off point and, due to the rising terrain in the area, about 100 m above ground. With the FTS release, all motors of the four propulsion units were stopped. The impact of the drone was recorded at 10:38:48.

1.6.3 Outbound flight and previous flights

A comparison of the data from the log files of the outbound flight as well as the previous test flights from 24 to 26 January 2019, showed some significant differences to the accident flight of 9 May 2021:

- During the accident flight, the current consumption of the propulsion units was around 30 A when the strong oscillations occurred. During the outbound flight, significantly higher power was demanded from the propulsion units as compared to the accident flight, without any critical vibrations or oscillations; the current consumption was up to 40 A, with the battery voltage at a similar level.
- The software version of the test flights in January 2019 differed from the software version of the flight on 9 May 2019 (cf. chapter 1.2.3).
- Despite the significantly higher flight speed of up to 20 m/s, the recorded vibration values remained below 30 m/s^2 during the test flights in January 2019. The associated current consumption of the propulsion units was around 40 A and was thus above the maximum values of 35 A achieved during the accident flight.
- During the flights at that time, the vibration values of IMU1 and IMU3 were largely similar, while IMU2 provided significantly deviating values (cf. footnote 16).

[16] The numbering is based on the data from the log files; an assignment of the physically installed IMU units, i.e. IMU1&2 damped and IMU3 undamped, is not possible based on the log files.

- The tilt angle of the drone was between 10° and 15° before the oscillations occurred; the maximum value set in the configuration of the flight controller is from 20°.

1.6.4 Sensors concerning environmental conditions

The drone's flight accumulator has temperature and single cell monitoring. However, there was no indication in the log files that this data is passed on to the flight controller and telemetry. According to Matternet, this data is monitored and recorded by a separate system.

1.7 Requirements for parachute recovery systems

Since September 2018, an international standard, F3322[17], has been available that specifies the design, fabrication and testing requirements of installable, deployable parachute recovery systems (PRS) of small unmanned aircraft systems (SUAS) to reduce the impact energy of the system. Furthermore, compliance with these specifications is intended to support an applicant in obtaining permission from a civil aviation authority to fly over populated areas.

It lists both technical and operational requirements for parachute rescue systems in the event that the critical number motor failures is reached. Among other things, a manual triggering device should be installed in addition to an autonomous triggering system.

Furthermore, it is stated that the connected risers shall not be caught on, damaged, or cut by blemishes, burrs or sharp edges when opening the parachute housing. Likewise, the parachute and the attachment lines must be protected from abrasion during ejection and must not become entangled so that the drone can descend from the parachute at the specified rate of descent.

Similarly, the application of danger and warning labels for first responders, including specifications regarding their size, inscription and positioning on the drone (cf. figure 11), is specified.

Figure 11: Sample of danger and warning labels for first responders (source: F3322)

The descent rate of a drone descending to the ground on a parachute is proportional to the root of its total mass, as further explained in the standard specification F3322. With regard to limits on the impact energy with which the drone on the

[17] cf. *«Standard Specification for Small Unmanned Aircraft System (SUAS) Parachutes»* of the American Society for Testing and Materials (ASTM), ASTM-F3322-18 – last visited on 06.06.2023

parachute may hit the ground, the standard specification refers to the specifications of the respective civil aviation authorities. It also points out that at the time of publication, most authorities had not yet set limits.

2 Analysis

2.1 Technical aspects

2.1.1 Software version

According to the manufacturer, the drone's hardware had not been modified between the flights in January 2019 and the accident on 9 May 2019. The software versions used during this period, modified by Matternet, were based on the ArduCopter 3.5.0-rc5 software (as of May 2017), which only allowed a quasi-parallel calculation of two EKF lanes. This made it impossible to isolate a false signal (cf. chapter 1.2.3).

During the recordings of the test flights from 24 to 26 January 2019, the IMU1 and IMU3 showed largely similar vibration values (cf. chapter 1.6.3). Therefore, the value 5 of the parameter "EK2_IMU_MASK" in the configuration of the flight controller, which determined the inclusion of IMU1 and IMU3 or the exclusion of IMU2 in the calculations for the two lanes, was quite appropriate and understandable in deviation from the default value 3. Also, on 9 May 2021, the choice of this parameter had no effect on the outbound flight to the University of Zurich (UZH).

Only on the return flight to the University Hospital of Zurich (USZ) did the vibrations of the IMU3 increase after about one minute of flight time, at 10:38:24 (cf. blue line in figure 9), and reach values of well over 30 m/s^2, at which the attitude determination and thus also the attitude control by the flight controller were already significantly impaired and the drone was put into an oscillating state.

Due to the unchanged configuration compared to January 2019, the values of IMU1 and IMU3 were included in the calculations of the two EKF lanes and, as a result of increasing differences between the data, led to the EKF variance being exceeded, which was logged as the event "EKFCHECK_BAD_VARIANCE" in the log file at 10:38:46 (cf. chapter 1.6.2).

The cause of the suddenly occurring vibrations, as recorded by IMU3 in deviation to the other two IMUs, cannot be clearly determined on the basis of the recordings and the traces on the wreckage or at the accident site. In the present case, the deviations can most likely be explained by a resonance due to an external factor such as a bird strike or possible preliminary damage to a propeller, which had an effect in the course of the flight. A malfunction of the IMU3 seems unlikely based on the records.

The manufacturer recommends a cruising speed of 16 m/s over ground. A maximum wind component of 8 m/s and gusts of 12 m/s are permitted (cf. chapter 1.2.1). In the present case, according to the meteorological report based on data from a nearby weather station (Hönggerberg), the wind at the time was 6 kt, i.e. about 3 m/s, from a direction of 160 to 240 degrees, i.e. diagonally from the front right to the direction of flight. With a still comparatively low cruising speed of 12.5 m/s at which the drone was moving forward shortly before the accident, the sudden occurrence of such strikingly high vibrations on the three IMUs cannot be explained by the low wind weather conditions. Furthermore, according to the log files, at the time the critical vibrations and oscillations occurred, the current consumption of the motors was around 25 % below the values that had been temporarily recorded on the outbound flight as well as in earlier test flights when the limit values defined for this drone type were reached. The tilt angle was only between 10° and 15° and thus also significantly below the limit value of 20° set in the configuration of the flight controller. Based on the aforementioned reasons, an overload situation can therefore be ruled out.

Regardless of the underlying cause, divergent IMU values in the course of the flight led to the associated limit value being exceeded and the error handling procedure being triggered, to which the flight termination system (FTS) was coupled with the triggering of the parachute. As long as the applied firmware of the flight controller corresponded to the software version ArduCopter 3.5.0-rc5, a selection had to be made in advance, as to which two of the three available IMUs were to be included in the calculations. As a result, the flight controller software lacked the ability, known as resilience, not to fail completely in the event of malfunctions or the failure of individual components, but to maintain control of the drone.

On flight controllers with three IMU, only from software version 3.6.12 onwards could this resilience be ensured with the corresponding configuration ("EK2_IMU_MASK = 7"). From then on, all three IMUs could be included in the calculations and three parallel lanes for isolating a diverging signal were also possible (cf. chapter 1.2.4). This gives the flight director more time to take appropriate measures to bring about a controlled termination of the flight.

2.1.2 Service Bulletin

The flight controller installed in the SUI-9903 was purchased in the last quarter of 2018 and therefore did not fall within the time period of the Service Bulletin (SB) SB 0000002, which was published in April 2019 (cf. chapter 1.2.4). Only with the subsequent extension on the part of the manufacturer, according to which all Pixhawk Cubes should generally be updated to at least ArduCopter 4.x and the parameters adjusted accordingly, did SB 0000002 also apply to the present flight controller. This illustrates the need for manufacturers and drone operators to communicate and implement firmware updates and Service Bulletin (SB) promptly and transparently.

From a safety perspective, a discussion forum on the Internet is not the right platform for the publication of such a safety-relevant change directive. In manned aviation, Safety Bulletins are usually published via a platform specifically provided for this purpose, such as an overview list for all SBs issued, with their number, revision number and date of issue.

For this reason, the STSB issues a safety recommendation (cf. chapter 4.1.2.2) as well as a safety notice (cf. chapter 4.2.1.2).

2.1.3 Flight termination system

With the automatic triggering of the flight termination system (FTS), the motors of the four propulsion units were stopped, as was intended by design.

Based on the deformation of the aluminium chassis and the crack fracture on the connecting rope, it can be concluded that it was suddenly decelerated by the forces generated during the ejection of the parachute as a result of the braking effect and was cut at the sharp upper edge of the chassis (cf. figure 5 and figure 6). The connecting rope, which was designed for tractive force, was pre-damaged by the sharp edge at the drone-side attachment point. As a result, it could not withstand the tensile load of the deploying parachute and snapped. This separated the emergency parachute from the transport drone and the aircraft crashed without deceleration.

The acoustic warning signal was not heard by persons on the ground near the crash site, so it did not fulfil its purpose of warning third persons on the ground. Even though no one on the ground was injured in this case, the STSB classifies the breaking of the connecting rope and the weak warning signal as factors to risk, which should be given more attention in future (cf. chapter 4.1.1.2 and chapter 4.1.1.3).

2.2 Human and operational aspects

2.2.1 History of flight

The vibrations of all three IMUs, which increased within about 5 seconds, in connection with the configuration of the parameter "EK2_IMU_MASK" led to the tolerable deviations between the data of IMU1 and IMU3 being exceeded during the accident flight. This resulted in the automatic triggering of the flight termination system (FTS) at 10:38:46, causing the parachute to be ejected. These rapidly increasing vibrations were not apparent to the flight director (FD) from the data he was monitoring. Therefore, there was no need for him to take any action.

When the flight abort system was triggered, the FD lost control of the drone. After the connecting rope broke at the drone's attachment point (cf. chapter 2.1.3), the drone fell uncontrollably from about 100 m above ground into the forest and was destroyed 2 seconds later when it hit the forest floor without deceleration.

In the incident of the identical drone SUI 9909 of 25 January 2019 investigated by the STSB (cf. Summary Report), an emergency landing was also initiated within a few seconds as a result of a loss of the GPS signal by triggering the FTS. During this phase, the FD had no possibility to intervene in a corrective manner.

In both incidents investigated, it can be seen that the FD had no possibilities to intervene before the drone, which deviated from the mission profile, autonomously triggered the automatic flight termination system within a short time and the drone ended in a total loss. The STSB therefore issues a safety recommendation according to which the conditions for triggering the FD should be revised and a controlled termination of the flight should be brought about through appropriate measures (cf. chapter 4.1.2.3).

2.2.2 Maximum impact energy

According to the manufacturer, the vertical speed of the drone descending to the ground with a fully opened parachute should be between 3 and 5 m/s; at maximum take-off weight, the impact energy is no higher than 156 J (cf. chapter 1.2.2). In a purely kinetic consideration, the maximum impact energy comes to 165 J.

As stated in the standard specification F3322, the descent rate of a drone descending to the ground on a parachute is proportional to the root of its total mass. Based on a descent rate of 5 m/s for the loaded drone with a total mass of 13.2 kg, this results in a descent rate of 4.6 m/s for the unloaded drone with a mass of 11.2 kg, which is about 50 % higher than the lower value specified by the manufacturer (3 m/s). The associated impact energy for the drone without payload is thus around 118 J.

The value of the drone's impact energy, irrespective of its load and with a functioning parachute, is thus significantly above the so-called 80-joule limit, which goes back to the wound ballistics of military research from the time of the First World War[18] and is still used today as a limit value for fatal injuries in regulations of many governmental and supranational institutions.

An initial approach to protecting third parties on the ground from injury was provided by the Federal Aviation Authority (FAA) rule[19] published in January 2021 on the operation of small unmanned aerial systems over people. For the first time, the

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[18] cf. *«Schiesslehre für Infanterie unter besonderer Berücksichtigung des Gewehrs 98 mit S-Munition der Maschinengewehre und der Schiessvorschrift für die Infanterie 1906»*.

[19] *"Operations of Small Unmanned Aircraft Systems Over People"* (Rule 2021-04881) with an effective date of 6 April 2021.

rule specifies an impact energy limit of 11 ft lb (about 15 J) for unrestricted use of drones over people (category 2); for restricted use over people (category 3), the limit is 25 ft lb (about 34 J). The drone should not be capable of causing an injury that is more severe than the impact kinetic energy transfer from a rigid object at the aforementioned limits.

Measured against these lower limits for protection against injury, the M2 V9 drone thus posed a significant danger to third parties on the ground, regardless of the payload, despite the parachute. Even though no one was injured in this case, the STSB classifies this circumstance as factor to risk, which should be improved in future (cf. chapter 4.1.1.4).

2.3 Redundancy of the propulsion concept and extended sensor technology

All components of a drone, and mechanical components in particular, are subject to a certain probability of failure, often expressed as Mean Time Between Failure (MTBF) or Mean Time To Failure (MTTF).

In the case of a conventional quadrocopter concept with four propulsion units, such as the M2 V9 drone, a failure of one propulsion unit will inevitably lead to a crash or at least to the forced triggering of an automatic flight termination system.

In contrast, with sufficient dimensioning, a hexacopter can still land more safely or return to the take-off point even with two failed propellers, provided they are not directly adjacent.

With a larger number of propulsion units, a higher redundancy concept can be achieved with a lower probability of a total failure. If the probability of failure of a single propulsion unit is 1/x, this is 4/x for a quadrocopter. If we compare this in a simplified approach with the probability that two drives of a hexacopter will fail during a flight, the probability is $6/x * 5/x$, i.e. $30/x^2$. With an MTBF of a drive of typically 1600 h, this results in a probability of a total failure of 1/400 per operating hour for a quadrocopter and 1/85333 per operating hour for a hexacopter.

According to the description, the Matternet M2 V9 drone model involved in the accident has temperature and single-cell monitoring. However, there was no evidence in the recording files that this data is passed on to the flight controller and telemetry. Additional monitoring of air temperature and humidity would allow detection of condensation or condensation. This would make it possible to define operational conditions under which a take-off should be possible or a flight can be terminated in good time in the event of impending problems.

With regard to propulsion concepts with higher redundancy as well as extended sensor technology with regard to the environmental conditions, the STSB issues two further safety recommendations (cf. chapter 4.1.2 and 4.1.3).

3 Conclusions

3.1 Findings

3.1.1 Technical aspects

- The mass of the drone was within the permissible limits at the time of the accident.
- The investigation revealed no concrete evidence of pre-existing technical defects that could have caused or influenced the accident.
- For the Pixhawk Cube Black 2.1 flight controller, the manufacturer Matternet used a software version modified on the base version of the ArduCopter 3.5.0-rc5 firmware (as of May 2017).
- Due to this base version, the flight controller software could only use the data from two of the three redundant Inertial Measurement Units (IMU) to control the flight of the drone.
- For this reason, isolating one IMU was not possible due to its divergent data.

3.1.2 History of the flight

- The M2 V9 drone took off from the University of Zurich (UZH) Irchel at 10:37:35.
- After about one minute of flight, the flight control was significantly affected by the flight controller due to increasing vibrations, and the drone began to oscillate.
- At the same time, the vibration-related deviations between the IMU data reached a critical value at 10:38:46, whereupon the program unit was started for error handling.
- With this, the drone automatically triggered the flight termination system (FTS) and the emergency parachute was ejected.
- With the FTS triggered, all motors of the four propulsion units were stopped.
- After the parachute was ejected, its connecting rope broke because it had been damaged by the sharp edge at the drone's attachment point.
- As a result, the drone plunged into the forest from about 100 m above ground and was destroyed when it hit the forest floor without deceleration.
- The acoustic warning signal that sounded after the flight termination system was triggered was not heard by people near the crash site.

3.1.3 General conditions

- The wind conditions had no influence on the accident.
- Since September 2018, an international standard has been available under the designation F3322 to define the design, manufacturing and test requirements for installable, deployable parachute rescue systems for drones.
- At the time of the accident, there were no regulations regarding the limits of impact energy to protect against serious injuries to third parties on the ground.

3.2 Causes

> In order to achieve its objective of prevention, a safety investigation authority shall express its opinion on risks and hazards that have been identified during the investigated incident and which should be avoided in the future. In this sense, the terms and formulations used below are to be understood exclusively from the perspective of prevention. The identification of causes and contributory factors does not, therefore, in any way imply assignment of blame or the determination of administrative, civil or criminal liability.

The accident, in which the drone triggered the automatic flight termination system and ejected the parachute during cruise flight, was due to increasing vibrations of unknown origin in conjunction with the lack of resilience of the flight controller software used.

After the parachute ejected, the connecting rope was cut at the sharp-edged, drone-side attachment point and snapped, causing the drone to hit the ground without deceleration.

The investigation identified the following factors, which did not influence the occurrence and course of the accident, but nevertheless represent a factor to risk:

- After the flight termination system was triggered, the audible warning signal was not heard by people not far from the crash site.
- Even when descending to the ground on its parachute, the drone’s impact energy would have clearly exceeded the limit value that had been usual in practice up to then.
- There were no stickers on the drone that could clearly interpreted as danger and warning labels .
- Redundancy of the propulsion concept.

4 Safety recommendations, safety advice and measures taken since the accident

4.1 Safety recommendations

In accordance with the provisions of Annex 13 of the International Civil Aviation Organization (ICAO) and Article 17 of Regulation (EU) No. 996/2010 of the European Parliament and of the Council of 20 October 2010 on the investigation and prevention of accidents and incidents in civil aviation and repealing Directive 94/56/EC, all safety recommendations listed in this report are intended for the supervisory authority of the competent state, which must decide on the extent to which these recommendations are to be implemented. Nonetheless, any agency, any establishment and any individual is invited to strive to improve aviation safety in the spirit of the safety recommendations expressed.

Swiss legislation provides for the following regulation regarding implementation in the Ordinance on the Safety Investigation of Transport Incidents (OSITI):

"Art. 48 Safety recommendations

1 The STSB shall submit the safety recommendations to the competent federal office and notify the competent department of the recommendations. In the case of urgent safety issues, it shall notify the competent department immediately. It may send comments to the competent department on the implementation reports issued by the federal office.

2 The federal offices shall report to the STSB and the competent department periodically on the implementation of the recommendations or on the reasons why they have decided not to take measures.

3 The competent department may apply to the competent federal office to implement recommendations."

The STSB shall publish the answers of the relevant federal office or foreign supervisory authorities at www.stsb.admin.ch to provide an overview of the current implementation status of the relevant safety recommendation.

The Swiss Transportation Safety Investigation Board prepared an interim report on the accident under investigation, which was published on 28 June 2019. In this interim report, the STSB issued safety recommendations no. 553 and no. 554. In this final report, the STSB issues safety recommendations no. 587 to 591.

4.1.1 Flight termination system and impact energy

4.1.1.1 Safety deficit

About one minute after take-off at the University of Zurich (UZH) Irchel, the M2 V9 drone automatically triggered the flight termination system (FTS) and initiated an emergency descent with a parachute. After ejecting the parachute, the connecting rope broke and the drone hit the forest floor without deceleration and was destroyed.

After the emergency parachute was deployed, the acoustic warning signal was not heard by people not far from the crash site, which meant that the purpose of warning third parties on the ground was not fulfilled.

As the investigation showed, the value of the drone's impact energy was significantly higher than the value of 80 J used in practice to date, regardless of its load.

4.1.1.2 Safety Recommendation No. 553

The Federal Office of Civil Aviation (FOCA) should take appropriate measures to ensure that the emergency parachute is capable of withstanding the possible load.

4.1.1.3 Safety Recommendation No. 554

The Federal Office of Civil Aviation (FOCA) should take appropriate measures to ensure that the acoustic warning signal can be heard by third parties on the ground when an emergency landing is initiated.

4.1.1.4 Safety Recommendation No. 587

The Federal Office of Civil Aviation (FOCA) should take appropriate measures to ensure that the impact energy of a drone descending to the ground by parachute does not pose a risk of serious injury to third parties on the ground.

4.1.2 Amendment instructions, controlled flight abortion and sensor technology

4.1.2.1 Safety deficit

About one minute after take-off at the University of Zurich (UZH) Irchel, the M2 V9 drone automatically triggered the flight termination system (FTS) and initiated an emergency descent with a parachute. After ejecting the parachute, the connecting rope broke and the drone hit the forest floor without deceleration and was destroyed.

As the investigation showed, the applied firmware of the flight controller based on the software version ArduCopter 3.5.0-rc5 was only capable of using two of the three available inertial measurement units (IMU) for the flight control of the drone. As a result, the flight controller's software lacked the ability, known as resilience, not to fail completely in the event of malfunctions or the failure of individual components, but to maintain control of the drone.

Only from software version 3.6.12 onwards was it possible to achieve this resilience with the corresponding configuration of the safety-critical parameter ("EK2_IMU_MASK = 7"), as published in a discussion forum of the flight controller manufacturer as Service Bulletin SB 0000002.

In the case of the accident involving the largely identical drone SUI-9909 on 25 January 2019 (cf. summary report), the FTS was also immediately triggered due to a loss of the GPS signal. As the investigation showed, the drone's flight attitude was still stable at this time and thus a landing under engine power, either manually controlled on sight or autonomously, would not have been fundamentally impossible.

When operating under extreme climatic conditions, corresponding flight-critical parameters such as ambient temperature and humidity are not included in practice. This would allow a flight mission to be aborted early or not carried out at all under certain conditions.

4.1.2.2 Safety Recommendation No. 588

The Federal Office of Civil Aviation (FOCA) should ensure that operators of drones that are used in scenarios with higher risk – in particular for flights beyond the visual line of sight (BVLOS) over populated areas – comply with Service Bulletins on flight-critical components or their software.

4.1.2.3 Safety Recommendation No. 589

The Federal Office of Civil Aviation (FOCA) should ensure that the manufacturer revises the conditions for triggering the automatic flight termination system so that suitable measures (contingency procedures) are taken to achieve a controlled flight abortion before the parachute is triggered and the drone descends to the ground in an uncontrolled manner.

4.1.2.4 Safety Recommendation No. 590

The Federal Office of Civil Aviation (FOCA), together with the operator or manufacturer, should take appropriate organisational or technical measures to ensure that take-off is prevented in unsuitable environmental conditions which could lead, for example, to condensation or icing.

4.1.3 Redundancy of the propulsion concept

4.1.3.1 Safety deficit

About one minute after take-off at the University of Zurich (UZH) Irchel, the M2 V9 drone automatically triggered the flight termination system (FTS) and initiated an emergency landing. After ejecting the parachute, the connecting rope broke and the drone hit the forest floor without deceleration and was destroyed.

In the case of a conventional quadrocopter concept with four propulsion units, as was the case with the M2 V9 drone examined here, a failure of one propulsion unit inevitably leads to a crash or at least to the forced triggering of an automatic flight termination system. Propulsion concepts of drones with 6 or more propulsion units show a significantly lower probability of failure in this respect.

4.1.3.2 Safety Recommendation No. 591

The Federal Office of Civil Aviation (FOCA) should ensure that the manufacturer aims to use a redundant propulsion concept – in particular for flights over populated areas – in order to reduce the propulsion-related failure probability due to material wear or exogenous factors such as bird strike.

4.2 Safety advice

The STSB may publish safety advice in response to any safety deficit identified during the investigation. Safety advice shall be formulated if a safety recommendation in accordance with Regulation (EU) No. 996/2010 does not appear to be appropriate, is not formally possible, or if the less prescriptive form of safety advice is likely to have a greater effect. The legal basis for STSB safety advice can be found in article 56 of the OSITI:

"Art. 56 Information on accident prevention

The STSB may prepare and publish general information on accident prevention"

4.2.1 Amendment instructions

4.2.1.1 Safety deficit

About one minute after take-off at the University of Zurich (UZH) Irchel, the M2 V9 drone automatically triggered the flight termination system (FTS) and initiated an emergency descent with a parachute. After ejecting the parachute, the connecting rope broke and the drone hit the forest floor without deceleration and was destroyed.

As the investigation showed, the applied firmware of the flight controller based on the software version ArduCopter 3.5.0-rc5 was only capable of using two of the three available inertial measurement units (IMU) for the flight control of the drone. As a result, the flight controller's software lacked the ability, known as resilience, not to fail completely in the event of malfunctions or the failure of individual components, but to maintain control of the drone.

Only from software version 3.6.12 onwards was it possible to achieve this resilience with the corresponding configuration of the safety-critical parameter ("EK2_IMU_MASK = 7"), as published in a discussion forum of the flight controller manufacturer as Service Bulletin SB 0000002.

At a later date, the manufacturer stipulated that *"All Copter users to be on at least ArduCopter 4.x and SB2 parameters, regardless of cube age"*, (cf. https://discuss.cubepilot.org/c/MSB/16), without specifying a release date.

4.2.1.2 Safety Advice No. 44

Target Group: Manufacturer of drone components and associated software

Manufacturers of drones and drone components should ensure that Service Bulletins (SB) relating to drone components or their associated software are clearly listed, identified and dated, and that the timing of any revisions can be identified by the operator. Prompt communication to the operators concerned should also be ensured.

4.3 Measures taken since the accident

The measures taken, of which the STSB is aware, are mentioned below without further comment.

4.3.1 Federal Office of Civil Aviation

The following is a list of measures that the FOCA has taken since 9 May 2019.

"Actions taken immediately in the aftermath of the incident:

- *Modification of the parachute system by incorporating the Matternet Safety Bulletin SB-M2-001.*
- *The parachute rescue system shall comply with the specifications of the ASTM F3322 standard, with design review as evidence.*
- *Repetitive inspections of the parachute system shall be defined in the maintenance documentation.*
- *The ground speed shall be reduced by 20 % (reduce V_{max} from 20 m/s to 16 m/s).*

Conditions for the resumption of operations

Current operations of SwissPost/Matternet using M2-V9 in Zurich have been approved and resumed based on JARUS Guidelines on Specific Operations Risk Assessment (SORA) Version 2.0 risk analysis, in which:

- *The high robustness level of the ground risk mitigation measures "M2" (i.e. the parachute requirements) were validated by a competent third party.*
- *The level of safety and integrity required for a risk mitigation measure "M2" of high robustness, was validated based on ASTM F3322-18, demonstration flight test data and Federal Aviation Administration (FAA) review.*

- *The Matternet M2-V9 is equipped with a 100 dB buzzer.*
- *The Matternet M2V9 is designed to fly in visible moisture and has been tested to withstand significant weather conditions. The UA has been subjected to more stringent testing than the DO-160 Category R waterproof test*

Current criteria for applications for an operational authorization (valid as of 31 May 2023)

On January 1st 2023, the Commission Delegated Regulation (EU) 2019/945 'on unmanned aircraft systems and on third-country operators of unmanned aircraft systems' and Implementing Regulation (EU) 2019/947 'on the rules and procedures for the operation of unmanned aircraft' entered into force in Switzerland. These regulations address the requirements on unmanned aircraft systems and the rules and procedures for the operation of unmanned aircraft across European Member States.

Therefore, the FOCA currently assesses UAS operations in the 'specific' category by applying the Acceptable Means of Compliance 1 to Article 11 of (EU) 2019/947, which is based on the JARUS Specific Operational Risk Assessment (SORA) V2.0. The SORA methodology is the foundation of the risk-based regulation, in which the rules and procedures applicable to UAS operations should be proportionate to the nature and risk of the operation and adapted to the operational characteristics of the UAS and the characteristics of the area of operations.

This methodology was already the basis to approve Matternet operations in 2019 and the SORA V2.0 addresses, among other things, the safety deficits identified by the STSB in the course of the investigation on SUI-9903's incident. In this approach, design requirements are dependent on the complexity of an operation and on the outcomes of the risk assessment, i.e. by assessing the intrinsic risk of a UAS operation and the application of mitigations. It includes operational procedures for dealing with technical problems with drones and systems that support the operation of drones, as well as operational procedures for dealing with adverse operating conditions."

4.3.2 Matternet

"The following non-exhaustive list of changes in design or operations were made after the May 2019 UZH incident:

Software / GNC updates

- *Changed EK2_IMU_MASK to 3, this tells the EKF lane 1 to use the first IMU and EKF lane 2 to use the 2nd IMU (rather than using 1st & 3rd IMU as configured previously). Both IMU 1 and 2 are isolated against high frequency vibrations.*
- *Kept INS_USE3 =1 (i.e., 3rd IMU, which is non-isolated, enabled as a backup in case the first two IMU's fail).*
- *Arming check now includes both EKF lanes being present and healthy.*
- *Set INS_FAST_SAMPLE = 5, this enables fast sampling of accelerometer data. This reduces aliasing when high frequency vibrations are sensed.*
- *Flight controller lane switching algorithm was modified to prefer EKF lane 1 before arming.*

Hardware updates

- *Shock cord mounting on the chassis improved by eliminating sharp edges and adding stainless steel sheathing over areas in contact with the chassis.*
- *Dual shock cords added for redundancy.*
- *Parachute system updated and tested per ASTM F3322-18 including ASTM standardized warning label.*
- *Added a louder 100 dB buzzer that sounds after FTS as the aircraft descends under a parachute.*
- *Modification of the Buzzer to be a continuous siren rather than an on/off beep.*

Quality and test process changes

- *Flight qualification testing routes were updated to include max velocity with max ascent rate limitations.*
- *A flight log data analysis tool looks at every flight for automated error / exception identification.*

Operational Mitigations

- *Maximum operational ground speed was reduced by 20 % to mitigate incidence of high vibrations due to possible higher power requirements (20 m/s which was reduced to 16 m/s).*
- *Maximum operational wind speed was reduced by 20 % to avoid excessive power requirements and subsequent possible vibrations.*

Organizational

- *Hiring of Head of Safety*
- *Safety management system and safety organization integrated within the company.*
- *Implementation of the Baldwin Safety tool."*

This final report was approved by the Board of the Swiss Transportation Safety Investigation Board STSB (Art. 10 lit. h of the Ordinance on the Safety Investigation of Transportation Incidents of 17 December 2014.

Bern, 6 June 2023 Swiss Transportation Safety Investigation Board