

ACCIDENT

Aircraft Type and Registration:	DJI Matrice 210 (UAS, registration n/a)	
No & Type of Engines:	4 electric motors	
Year of Manufacture:	2018 (Serial no: 0GODF4R023001)	
Date & Time (UTC):	4 September 2018 at 1451 hrs	
Location:	Tilbury Docks, Essex	
Type of Flight:	Emergency services operation	
Persons on Board:	Crew - N/A	Passengers - N/A
Injuries:	Crew - N/A	Passengers - N/A
Nature of Damage:	Destroyed	
Commander's Licence:	N/A	
Commander's Age:	42 years	
Commander's Flying Experience:	11 hours (of which 11 were on type) Last 90 days - 2 hours Last 28 days - 2 hours	
Information Source:	Aircraft Accident Report Form submitted by the pilot and further enquiries by the AAIB	

Synopsis

After about six minutes into the flight, a battery low voltage condition was detected by the UAS causing it to enter an automatic landing mode. Shortly afterwards, while the aircraft was 20 m above the ground, it powered down and the electric motors stopped, causing it to fall to the ground. An investigation of this and similar accidents was conducted by the manufacturer which found that the batteries' State of Charge (SOC) was indicating an erroneously high level of charge remaining. Safety actions were taken by the CAA to introduce operational restrictions while a fix was being found, and by the manufacturer to develop and 'push out' firmware changes to the battery and aircraft.

History of the flight

The accident occurred on the third flight of the aircraft that day. The aircraft was being operated in a cordoned-off area to maintain a safe distance (ie at least 50 m) from persons, vehicles, vessels and structures not under the operator's control, as per their procedures. Between each flight the batteries powering the aircraft were changed – the batteries installed for the accident flight were new, with the latest firmware installed (v01.00.00.71), and fully charged. Six and a half minutes into the accident flight, with the aircraft about 20 m above the ground, the pilot, who was visual with the aircraft, saw a battery system error displayed on the controller. The pilot then selected the HOME button on the controller; however, the aircraft appeared not to respond. A few seconds later, while the aircraft was above a road within the cordoned-off area, the motors stopped and it fell to the ground.

The damaged aircraft was sent to the manufacturer for repairs and analysis of the recorded onboard data. A copy of the recorded data was subsequently provided to the AAIB for further analysis.

Aircraft description

The DJI Matrice 210 is an Unmanned Aircraft System (UAS). The aircraft (Figure 1) is a quadcopter fitted with dual smart TB50 or TB55 batteries and has a maximum takeoff mass of 6.14 kg. It is controlled on the ground using a handheld flight controller via radio frequency with a maximum transmission distance of 7 km and a software application (app) running on a tablet device attached to the controller. The app on the tablet device offers touch-screen controls and shows live HD images from the aircraft's camera.

Safety modes include features such as Return to Home (RTH) to ensure the safe return of the aircraft to the takeoff point if the control signal is lost or if the batteries' remaining State of Charge (SOC) reduces to a pre-set level. It will also automatically initiate a landing if there is insufficient SOC to reach home. Battery voltage is also monitored and an RTH or landing will be initiated if the voltage becomes critically low; however, as battery voltage does not fall linearly as the battery is discharged, it is not a reliable means of predicting the capacity required to ensure a safe return or landing. A storage device in the aircraft is used to record flight data for each flight.



Figure 1

DJI Matrice 210

(This depicts the RTK version of the Matrice 210 – the accident aircraft did not have the two white external GPS antennas attached.)

Recorded information

The recorded data showed that at the start of the flight, both batteries had a voltage of 22.5 VDC but an erroneous SOC of 100% which is normally associated with a battery voltage of 26.3 VDC. Nine seconds before the end of the flight, with both battery voltages at about 18 VDC (but indicating a SOC of 77%), a battery low-voltage condition was detected by the aircraft causing it to go into an automatic landing mode three seconds later. The aircraft powered down and the motors stopped while it was still airborne at a height of 20 m above the ground. The manufacturer's initial analysis concluded that landing was initiated 'due to critically low voltage'. This was confirmed by the AAIB's separate analysis of the recorded data (Figure 2).

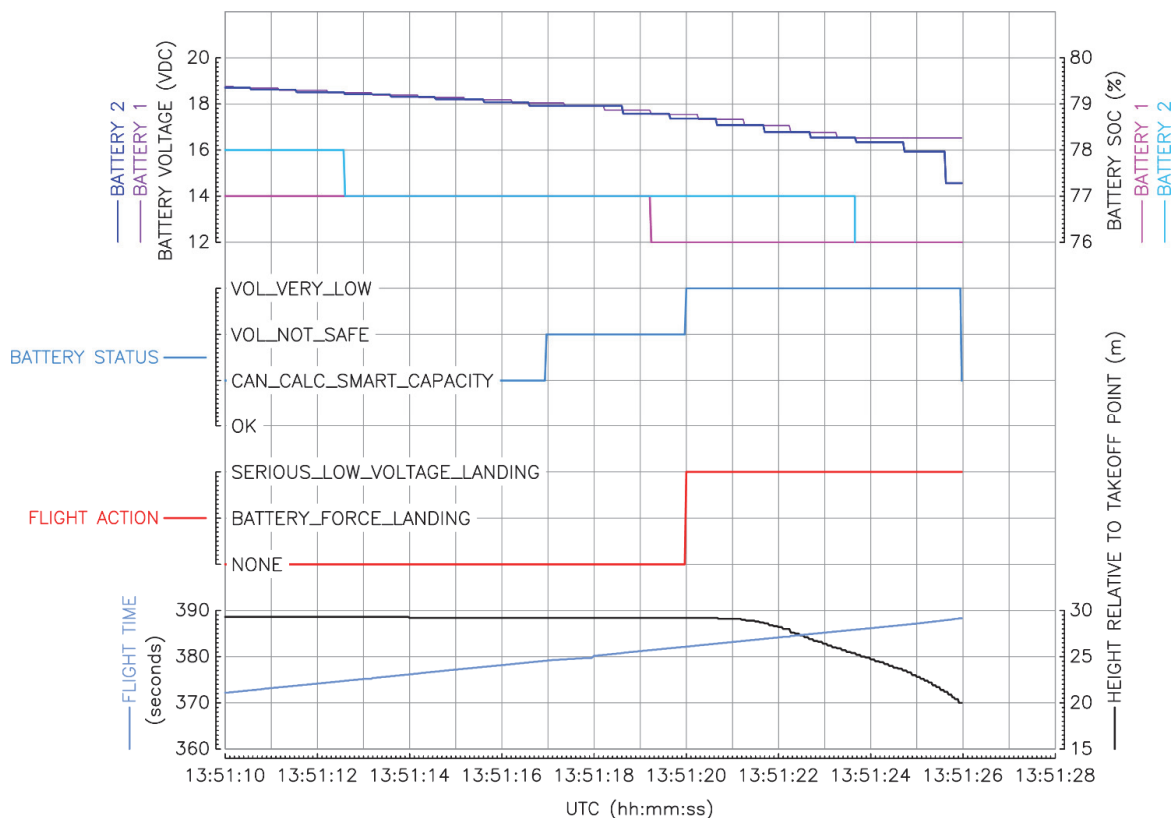


Figure 2

Plot of salient data for last 16 seconds of the recorded data

Similar Matrice 210 UK accidents

Between 9 July and 26 October 2018, the AAIB was made aware of another three Matrice 210 accidents, each of which crashed due to a loss of power, and which the manufacturer concluded were a result of landings being initiated due to critically low battery voltages. The batteries in these accidents (all TB55s) were indicating an erroneously high SOC. (See reports on DJI Matrice 210 RTK - EW/G2018/07/43, DJI Matrice 210 RTK - EW/G2018/10/09 and DJI Matrice 210 - EW/G2018/10/17 in this AAIB Bulletin 11/2019.)

Investigation by the UAS manufacturer

To understand the problem highlighted by these accidents and by a handful of similar cases worldwide, a comprehensive investigation, starting October 2018, was undertaken by the manufacturer to determine the root cause of the battery voltage and SOC mismatch of the smart batteries at fault.

Smart batteries and State of Charge

A smart battery is a rechargeable battery with a built-in management system that can monitor the battery status (such as current, voltage, charge level and state of health parameters). This information can then be used by a charger or UAS, for example, to intelligently manage their use.

Battery voltage is not an easy-to-interpret measure of the battery capacity remaining as voltage reduces non-linearly as current is drained. Therefore, the battery calculates a SOC which is a measure of its short-term (ie current charge) capacity and often called the 'gas gauge' or 'fuel gauge' function. The units of SOC are expressed as a percentage where 0% = empty and 100% = full. The SOC, rather than actual battery voltage, is used by the UAS to calculate battery 'fuel' trigger levels against which automatic actions such as Return to Home (RTH) or Automatic Landing can be set, so that these actions can be carried out safely.

For the SOC to be calculated, a battery capacity algorithm is used that integrates the total current flowing in and out of the battery to obtain the battery net charge. Batteries in storage, however, can generate an infinitesimal voltage which the battery capacity algorithm will detect and interpret as an apparent 'ghost' current. Over time, this can result in the battery SOC increasing even though the actual capacity has not changed. To stop this happening, an Open-Circuit Voltage (OCV) correction in the algorithm is used to compensate for any 'ghost' currents detected.

Investigation findings

The TB50 and TB55 batteries have a battery capacity calculation register that is used to configure the algorithm. One of the bits of the register (the 'DoDWT' bit¹) is used for turning on the OCV correction in the algorithm. The battery manufacturer's default setting for the 'DoDWT' bit is 1 which disables the OCV correction (this setting is needed for batteries with different chemical compositions to the Li-ion composition of the TB50 and TB55 batteries). The aircraft manufacturer was aware of this setting and made the decision to not change it as it was not expecting the 'ghost' current of these batteries to be very high, and therefore not to be an issue.

The investigation found, however, that for some batteries the 'ghost' current was higher than expected but within the design variance of the battery. When these batteries were subsequently subject to long-term storage (such as new batteries shipped and then stored

Footnote

¹ Depth of Discharge WeighTing, Depth of Discharge (DOD) of a battery is the inverse of SOC (so 100% = empty and 0% = full).

by a retailer), the capacity algorithm slowly summed up the 'ghost' current as a charge, resulting in the generation of the false high SOC value. When the batteries were then recharged for use, the charging would have stopped once the SOC value reached 100%, but essentially before the batteries had reached their maximum charge capacity.

Battery firmware updates

Battery firmware version v01.00.00.71 was released by the manufacturer in August 2018 to set the 'DoDWT' bit to 0. For the update to work correctly, an internal flag was monitored to confirm that the new firmware had been installed; however, it was later realised that for some batteries, this flag was not being set even though the firmware was installed correctly.

Battery firmware version v01.00.00.77 was subsequently released in November 2018 that forcibly set the 'DoDWT' bit to 0 to enable OCV correction in the battery capacity algorithm for all TB50 and TB55 batteries.

Aircraft firmware updates

As an additional redundant safety mechanism to the v01.00.00.77 battery firmware update, aircraft firmware v01.02.0000 was also released in November 2018 that introduced within the aircraft's flight controller a method to estimate the SOC. With the updated firmware, the software compared the controller-estimated SOC at the trigger points for an RTH or Automatic Landing with that calculated by the battery and, in the event of a difference of greater than 10%, trigger an RTH or Automatic Landing.

Aircraft firmware v01.02.0301 was then released in December 2018, which introduced within the flight controller a current integration method to estimate the SOC with better accuracy to the method used in the v01.02.0000 update.²

Issues with the user manual and the apps used to control the Matrice

The Matrice 210 user manual (current version November 2018) does not specify that the batteries have their own firmware. It only describes the aircraft firmware and remote controller firmware. The aircraft firmware does not automatically install the latest battery firmware into a battery pair that is connected to the aircraft. If an operator has multiple sets of batteries, they might not have known that they needed to install each set of batteries into the airframe and conduct a firmware update on each set³. The manufacturer is planning an update to the user manual which will state:

'The battery firmware is included in the aircraft firmware. Be sure to update all the batteries' firmware.'

Footnote

² The release was in conjunction with the release of battery firmware v01.00.00.84 that added a battery heating safeguard to ensure that the temperature of the batteries is higher than 61°F (16°C) before takeoff. This was to prevent cold battery use when the battery performance is sub-optimal due to decreased chemical activity in the battery.

³ If an operator had consulted the firmware release notes on the manufacturer's website, then from August 2018 onwards they would have seen a note referring to updating all batteries with the firmware. However, it was not until December 2018 that the manufacturer included the battery firmware version in the release notes.

The Matrice 200 series aircraft can be controlled using the DJI Pilot app or the DJI Go 4 app. The DJI Pilot app is only available on Android whereas the DJI Go 4 app is available on Android and iOS. The user manual does not specify which app should be used but it states that the DJI Pilot app needs to be used to control two cameras. At the time of this accident and until 14 November 2018 the DJI Pilot app was in beta release⁴. For this reason, some operators chose to use the DJI Go 4 app. However, the DJI Go 4 app⁵ cannot display the battery firmware version. Operators needed to know to use the DJI Pilot app to check the battery firmware version, but this was not specified in the user manual or the firmware release notes. Both apps had a system to warn the user if the battery firmware was not up-to-date. However, if after opening the apps, the user made a quick selection to enter flight mode, these messages would not appear; and once within the app it appeared that the firmware was up to date.

The manufacturer has made improvements to the DJI Pilot app (Android V1.1.0) to address these issues and is also planning improvements to the DJI Go 4 app. The planned update to the user manual will also specify that the DJI Pilot app is the recommended app to use (it is no longer in beta release).

The manufacturer stated to the AAIB that it is considering and designing 'push notifications' to users to notify them of emergency firmware upgrades without the user needing to upgrade the app first.

CAA Safety Notices

To raise awareness of the battery issues and firmware updates to DJI Matrice 200 series users, and introduce operational limits depending on the version of firmware installed, the CAA issued the following Safety Notices:

<i>Reference:</i>	<i>SN-2018/008 (dated 26 October 2018)</i>
<i>Title:</i>	<i>Small Unmanned Aircraft - DJI Matrice 200 Series In-Flight Power Failures</i>
<i>Description:</i>	<i>The purpose of this Safety Notice is to raise the awareness for DJI Matrice 200 series users of a small number of in-flight power failures which have led to a complete power loss and the aircraft have fallen to the ground. The SN gives guidance on how to complete the latest firmware update and also suspends any permissions based on an Operational Safety Case.</i>

<i>Reference:</i>	<i>SN-2018/009 (dated 31 October 2018)</i>
<i>Title:</i>	<i>Small Unmanned Aircraft - DJI Battery TB50 and TB55 In-Flight Power Failures</i>
<i>Description:</i>	<i>This SN gives guidance on DJI Battery TB50 and TB55 In-Flight Power Failures that supersedes SN-2018/008. Version 2 has been issued to clarify queries from industry relating to the suspension of permissions and exemptions issued to operators of the affected DJI platforms until further notice by the CAA</i>

Footnote

⁴ Android V0.6.3 (beta) until 14 November 2018. Beta release implies that there might be some bugs in the app.

⁵ iOS V4.2.24, Android V 4.2.21 up to latest versions iOS V4.3.3 and Android V4.3.2 (19 December 2018).

Reference:	SN-2018/010 (dated 9 November 2018)
Title:	Small Unmanned Aircraft - DJI Battery TB50 and TB55 In-Flight Power Failures
Description:	<i>This Safety Notice provides updated instructions and guidance regarding the DJI TB50/55 series of batteries and supersedes SN-2018/009 version 2. While a number of the previous suspensions relating to operational authorisations remain in place, those relating to operations within congested areas and EVLOS flights have now been lifted.</i>

Reference:	SN-2018/011 (dated 21 November 2018)
Title:	Small Unmanned Aircraft - DJI Battery TB50 and TB55 In-Flight Power Failures
Description:	<i>This Safety Notice provides updated instructions and guidance regarding the DJI TB50/55 series of batteries and supersedes SN-2018/010. The text highlights the updated battery firmware that has been released by the manufacturer on 16 November to correct previous instances where power has been unexpectedly lost. The aircraft operating restrictions that must now be observed are dependent on whether or not the manufacturer's recommended updates have been successfully installed.</i>

In addition, the CAA have published two alerts on its Skywise website⁶, Alert SW2019/067 on 22 March 2019 which stated:

'The CAA has received six Mandatory Occurrence Reports in the last three months affecting the DJI Matrice 210 series drone.'

The reports have indicated that on each occasion the DJI M210 has malfunctioned resulting in rapid uncontrolled descent and consequent damage to the airframe upon impact with the ground. Reports suggest the issue may lie with one of the airframe's motors. We are working with the manufacturer and monitoring the situation.

All users of the DJI M210 series are advised to consider their obligations under Art. 241 of the ANO⁷ and avoid flying over people or property until further notice.'

This was superseded by Alert SW2019/116, published on 30 May 2019 which said:

'On 22 March 2019 the CAA released a Skywise update regarding the DJI M210 series drone and a number of reported failures.'

The manufacturer has been unable to identify a common root cause and continues to investigate whether the failures are related. The CAA has received no further similar reports.'

Footnote

⁶ <http://skywise.caa.co.uk/dji-matrice-210-series-drone/> [accessed September 2019]

⁷ Article 241 of the Air Navigation Order 2016 (ANO), amendment 28 September 2018, states: 'A person must not recklessly or negligently cause or permit an aircraft to endanger any person or property.'

No additional restrictions beyond those in the Air Navigation Order 2016 are in place for the use of a DJI M210.

However, the CAA reminds operators to have appropriate mitigation's in place if flying over persons or property in accordance with the Air Navigation Order, as was the case prior to this reported issue.'

Previous Matrice 210 AAIB investigation

In October 2018, the AAIB reported on another DJI Matrice 210 accident⁸ that occurred on 20 December 2017 where power to the motors were cut when the system calculated that the battery levels were too low. Although the manufacturer could not explain the anomalies seen in the behaviour of one of the batteries (and different to the battery issue discussed in this report), it was aware of a battery firmware issue that resulted in the actual battery levels being ignored and power to the motors being cut because the system considered the battery level too low. It subsequently released a battery firmware update on 29 December 2017 (DJI Matrice 200 Series Release Notes for the 'Optimisation of battery level display') to resolve this issue.

Other Matrice 210 AAIB investigations

In addition to the accidents discussed in this report, the AAIB has investigated seven Matrice 210 accidents that occurred in the UK between 14 January 2019 and 18 March 2019. All involved the aircraft falling to the ground for technical reasons; some relating to electronic speed controller failures and motor failures, but none relating to the battery issue discussed in this report.

Analysis

The manufacturer's investigation into this accident and the three others described in this report revealed that some TB50 and TB55 batteries could generate erroneously high SOCs when left in long-term storage.

For the affected batteries, it was found that they were generating higher than expected (but within the design variance) 'ghost' currents, which the battery capacity algorithm slowly summed up as an apparent charge. As these higher 'ghost' currents had not been anticipated, the manufacturer decided that the OCV compensation was not needed.

This resulted in the batteries registering a higher charge than they actually had, such that, when taken out of storage and subsequently recharged for use, the charging would stop before their maximum charge capacity had been reached.

When these batteries were then used, the aircraft was monitoring and seeing what it thought was sufficient charge capacity in the batteries for continued flight with enough reserve to fly back home. However, the charge capacity was actually less than this, allowing the

Footnote

⁸ AAIB Bulletin 10/2018 pages 81-82: Accident to DJI Matrice 210 – EW/G2017/12/017 <https://www.gov.uk/aaib-reports/aaib-investigation-to-dji-matrice-210-registration-n-a> [accessed September 2019]

aircraft to continue flying until the battery low-voltage condition was detected triggering an RTH quickly followed by an Automatic Landing command. There was, however, insufficient voltage to continue powering the aircraft as the low-voltage RTH condition was set too low. At this point the motors stopped and the aircraft fell to the ground.

For this accident, the operational procedures meant that the aircraft was being operated in a cordoned-off area clear of people, vehicles, vessels and structures not under the operator's control, so that when it fell to the ground, there was no danger of it falling on someone. However, this is just one of 12 Matrice accidents with a similar outcome mentioned in this report that the AAIB has investigated, which highlights the potential danger, following a technical failure, for an unmanned aircraft to fall uncontrollably to the ground.

Ballistic recovery parachute systems

The Matrice 210 which has a maximum takeoff mass of 6.14 kg could cause a serious injury or a fatality if it fell on someone. The best way to mitigate the risk to people from an unmanned aircraft falling uncontrollably to the ground is to avoid flying over people. An alternative or additional way to mitigate against the risk of an unmanned aircraft falling to the ground is to install a ballistic recovery parachute system (BRPS). After-market BRPS are available for the Matrice 200 series aircraft.

There is a standard, ASTM F3322⁹, which specifies requirements for the design, manufacturing and testing of Small Unmanned Aircraft System parachutes¹⁰.

Safety actions

A number of safety actions have been made by the aircraft manufacturer and UK regulator. These are summarised as follows:

The manufacturer issued a number of firmware updates for the batteries, aircraft and controller apps as follows:

- Provided battery firmware updates to correct the erroneously high SOC issue.
- Provided aircraft firmware updates to perform a gross check of the batteries' SOC and trigger a RTH or Automatic Landing if a difference of greater than 10% is detected at specified trigger points.
- The DJI Pilot app has been updated to provide a clear warning when the battery firmware is out of date. The manufacturer is also planning improvements to the DJI Go 4 app.
- A planned update to the Matrice 200 series user manual will specify that the DJI Pilot app is the recommended app to use, and will specify that the batteries contain firmware that must be individually updated.

Footnote

⁹ <https://www.astm.org/Standards/F3322.htm> [accessed September 2019]

¹⁰ Compliance with this specification is intended to support an applicant in obtaining permission from a national aviation authority (NAA) to fly a small UA over people.

The CAA issued four safety notices and Skywise Alert SW2019/067 to raise awareness of the battery issues and firmware updates to DJI Matrice 200 series users, as well as introducing operational limits depending on the version of firmware installed. These limitations have now been removed with the publication of Skywise Alert SW2019/116 which also reminded operators to have appropriate mitigations in place if flying over persons or property.