Advanced Data Acquisition System for Wind Energy Applications

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Abstract

Today renewable energies, particularly wind energy are important to meet 24 hour energy demands while keeping carbon emissions low. As the cost of renewable energies are high, improving their efficiency is a key factor to reduce energy prices. High quality experimental data is essential to develop deeper understanding of the existing systems and to improve their efficiency.

This paper introduces an unmanned airborne data acquisition system that can measure properties around wind-turbines to provide new insight into aerodynamic performance and loss mechanisms and to provide validation data for wind-turbine design methods. The described system is a flexible and portable platform for collecting high quality data from existing full-scale wind-turbine installations. This allows experiments to be conducted without scaling and with real-world boundary conditions.

The system consists of two major parts: the unmanned flying platform (UAV) and the data acquisition system (DAQ). For the UAV a commercially available unit is selected, which has the ability to fly a route autonomously with sufficient precision, the ability to hover, and sufficient load capacity to carry the DAQ system. The DAQ system in contrast, is developed in-house to achieve a high quality data collection capability and to increase flexibility.

Keywords

UAV, renewable energy, wind turbine measurement, airborne measurement, digital data acquisition

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1 Introduction

Wind-energy is a sector with growing interest in Australia, currently wind farms produce over 33% of the country's clean energy. Between 30 and 50 large-scale wind and solar projects must be built by 2020 to meet the large-scale component of the Renewable Energy Target of the Australian government (Clean Energy Council, 2015). Wind energy is a key component of an electricity supply with high levels of solar power, currently the main renewable energy in Australia, as wind energy provides continued generation during periods with cloud cover and at night (Australian Renewable Energy Agency, 2016).

The aim of this paper is to show the current state of the development of a drone that carries a high quality data acquisition system, capable of 3-D mapping air properties such as pressures, wind speed, temperatures, acoustic noise, with additional expansion options if required. This drone can be used to measure properties around wind-turbines to provide new insight into aerodynamic performance and loss mechanisms and to provide validation data for wind-turbine design methods.

Researchers from the School of Mechanical and Mining Engineering at the University of Queensland already have pedigree in the area of turbo-machinery and turbine development, albeit in the context of closed cycles (Russel et al., 2016). A next step is to grow this expertise to include wind-energy. The transfer of simulation methods and numerical tools is reasonably straightforward, however experimental methods (particular collection of real world data) requires new approaches, such as the aerial data acquisition system described in this paper.

Traditionally the development of turbomachinery and wind-turbines has been carried out by sub-scale testing of simplified systems or sub-systems in wind-tunnels (Bartl, 2011). This approach is still important, particularly when analyzing fundamental effects under idealized conditions. However, this approach has limitations when trying to analyze performance under real life conditions or when trying to measure the effects of large scale interactions effects, such as non-ideal velocity profiles experience in real world applications or wind-turbine to wind-turbine interactions as shown in Fig. 1.
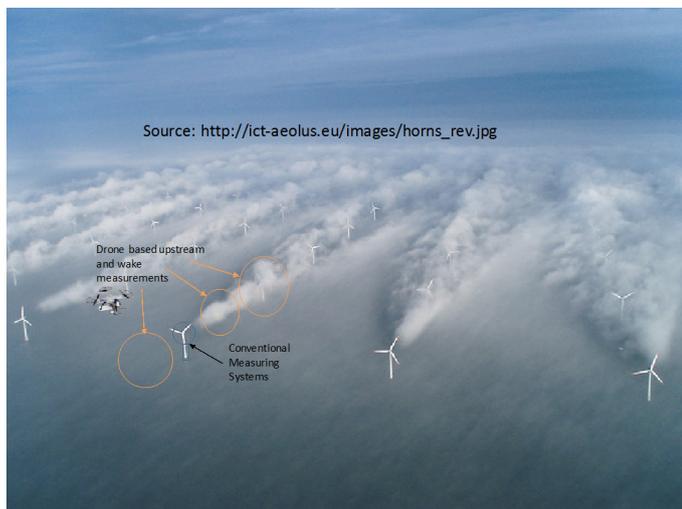
Source: http://ict-aeolus.eu/images/horns_rev.jpg

Drone based upstream
and wake measurements

Conventional
Measuring
Systems

Fig. 1 Improved data collection capabilities using a drone (Aeolus, 2016)

Traditionally cup or ultrasonic anemometers, installed at a limited number of points in the flow field are used to provide accurate and precise data. However, as wind turbines continue to grow in size, masts for mounting these anemometers have become taller, more expensive and difficult to move. This limitation has driven the development of more advanced, remote sensing tools for the wind energy industry: The LIDAR and the SODAR (Lang and McKeogh, 2011), utilizing laser and ultrasonic technology respectively. The systems allow measurement of wind speed up to 200m away from the sensor in order to map the flow field. These instruments are good for sensing low wind speeds (1-70 m/s), giving better accuracies than the cup anemometers, with the LIDAR more accurate and the SODAR more precise. Limitations of both are low spatial and time resolution, and the high cost (Schneemann et al., 2014). Furthermore, the measurements are limited to localized bulk flow velocities.

Advances in technology, particularly drones, lightweight electronics and computational power, now allow an alternative approach which overcomes these limitations. Using an airborne vehicle accurate point measurements can be made. There are some out-of-the-box studies that provide idea of integrating UAV to commercial aviation. (Rohacs and Rohacs, 2012) In addition to bulk flow velocities this approach allows an extended suite of sensors, which can include local air temperatures, density and short length scale turbulence properties, which are important to characterize individual blade performance and blade aerodynamics. Traditionally these data are only available in lab-scale experiments. This paper presents the development of an airborne system.

Using the proposed airborne system, instead of simulating small scale components and validating these with wind-tunnel measurements it is possible to experimentally test complete wind-turbines (or portions of a wind-farm) and to validate simulations with full sets of measurements taken in the field. Effectively the traditional wind tunnel experiment is taken from the laboratory to the wind-farm site.

UAVs are used in many applications from emergency management (Rohacs et al., 2006) to education purposes (Baburin et al., 2013).

2 Unmanned flying platform

To perform the measurements and to carry the instrumentation, a robust UAV is required. The main requirements are as follows:

- Autonomous flying capability with on-board autopilot and GPS positioning system with a relative accuracy better than ±10 m
- Autonomous go home function
- Ability to carry the instrumentation package (design weight of 0.8 kg)
- Ability to hover
- Flight time greater 30 minutes
- Detection of mission ending conditions, like low-battery or loss of signal

These requirements can be satisfied using the popular quad rotor configuration, however more exotic configurations should not be discounted (Nagy and Rohacs, 2013). On-board camera mounts are not required, but they can facilitate a more accurate positioning of the UAV during measurements. A total of 24 UAVs were considered in the market analysis, encompassing a range of recreational and commercial systems, as well as considering quadcopters, hexacopters, octocopters, and helicopters. This analysis showed, that material selection is not a differentiator between the products, with carbon fiber widely used across the range. However, the ability to follow GPS waypoints for a flight is only provided by some systems. After considering the cost and required flight time, only products from Aeronavics (Aeronavics website, 2016), Australian Droid and Robot (ADR website, 2016) and Aibotix (Aibotix website, 2016) meet the requirements. Their products are summarized in Table 1.

Our choice is the Dropbear quadcopter from Australian Droid and Robot (Fig. 2), a local manufacturer. This ensures quick maintenance is readily available thereby minimizing downtime.

Table 1 Basic data of shortlisted UAVs

UAV Name	Payload (kg)	Endurance (mins)	Price	Autopilot
Aeronavics SkyJib	5	15	High	Yes
Aibotix Aibot X6	2	20	Average	Yes
ADR Dropbear	2	30	Average	Yes

Fig. 2 Dropbear quadcopter from Australian Droid and Robot (ADR)

This quadcopter has the following specification:
- Payload capacity: 0 - 2kg
- Endurance: up to 30 minutes
- Dimension: 680 x 600 x 280 mm
- Autopilot system: 3DR Pixhawk
- 915MHz telemetry system, 2.4GHz remote control system
- Double GPS for redundancy

2.1 Operating Modes

The airborne system is designed for two main operating modes. The first is a manual mode and the second is a fully automated mode. Hybrid operation will the possible also.

In the manual mode, the movement of the drone (position) is directly controlled by the operator, to freely explore the fluid flows. During flight a limited number of sensors outputs are available to the operator via the RF down-link. In addition, the operator will able to switch into station holding mode and to initiate the collection of data.

In the second mode, the automatic mode, the operator is able to predefine a number of way-points and or grid of locations which will be visited by the drone. At each point the drone then proceeds to collect a pre-defined set of measurements.

3 Data acquisition system

The DAQ system is designed and built in-house to ensure high quality data collection. It is a modular design, consists of several re-configurable modules, allowing easy adaptation of the system to the requirements of different investigations.

The core of the DAQ system is a central controller, which interacts with the flight control system of the drone and manages the sensor payload (see Fig. 3).

The reconfigurable sensor payload is able to measure the following parameters:
- Ambient temperature, humidity, pressure
- Wind speed and direction
- Spatial position with high accuracy
- Range sensor

Off-the-shelf sensors are used to obtain these measurements, apart from wind speed and wind direction. A bespoke sensor system will be designed in-house. This system is required as the air around the drone (quadcopter) is affected by the drone. The carefully designed sensor systems with appropriate positioning and in-situ calibration gives the required high accuracy. Calibration of the system will be conducted using a tethered drone in one of UQ's wind tunnels using the final configuration of the sensor arrangement.

3.1 Overall system layout

The overall system layout is shown in Fig. 3. The core of the system is a low-power, high performance microcontroller, that coordinates the system and that has several integrated peripherals, including the A/D converter and digital interfaces used in this application.

The system consists of:
- Sensors
- Signal conditioners
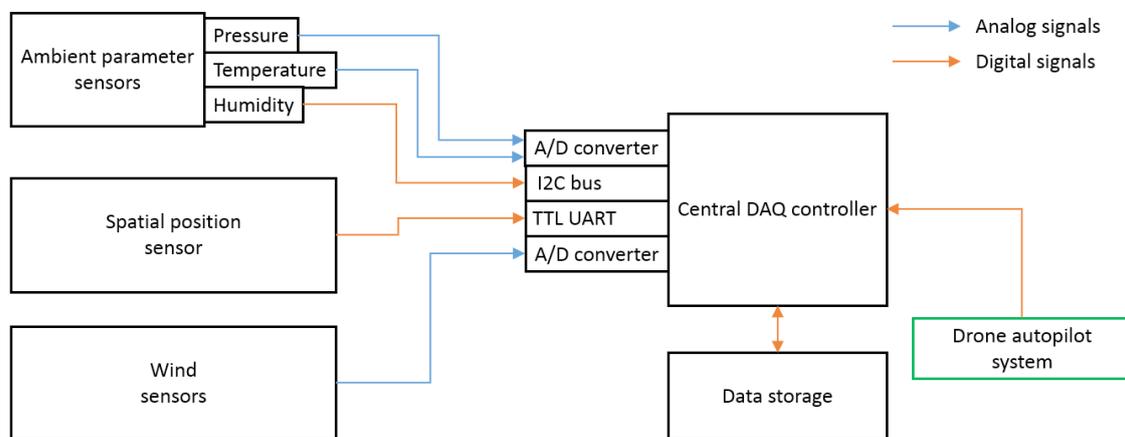- A/D converters
- Digital microcontroller

Fig. 3 DAQ system overview

- Non-volatile memory for data storage
- Power supply

The collected data are stored on a micro SD card that provides long term, nearly infinite, reliable data storage. Communication with the memory card is through the relatively simple SPI protocol.

The system (including all modules in Fig. 3 except the drone systems shown as green box) is intended to be realized on a single 4 layer PCB to ensure industry standard design, better noise attenuation and small size (Texas Instruments, 1999).

The physical arrangement of the sensors can be seen in Fig. 4. To maintain undisturbed flow field for sensitive sensors, the wind speed and direction sensors, and the pressure sensors are mounted on both side of a carbon rod and duplicated. Using two sets of sensors provides better accuracy and a more detailed spatial resolution. The DAQ system and the remaining sensors are mounted near the Centre of Gravity of the quadcopter.

3.2 Central DAQ controller

To control the entire system and to process the analogue and digital signals from different sensors, a mixed data acquisition system is being developed. It handles the analogue voltages, as well as digital I2C and UART communication. The controller has the following tasks:

- receive synchronization signals from the autopilot system of the UAV and control the DAQ process accordingly
- collect analogue signals and convert them with A/D converter
- maintain digital communication with digital sensors
- ensure proper timing of the data acquisition process
- save collected data on board into non-volatile storage
- append time stamp for every data line stored in memory
- transfer portion of collected data to ground station for monitoring

The controller firmware flowchart can be seen in Fig. 5. There are 3 main loops: one is timed by the positioning system at a 10 Hz update rate. The other 2 loops are controlled by internal timers, allowing free definition of update intervals. The first loop measures the ambient parameters at a rate of 100 Hz. The second loop operates at 25Hz, and is used for sensors with medium refresh rate such as range sensor. Each loop saves the data into one of the two internal memory buffers 512 bytes long. While one buffer (the active one) is being filled with data, the other one (already full) is written to the SD card. This topology requires that the time to fill the buffer is less than the time required for the SD card write in order to ensure data integrity. Preliminary calculations show, that in this DAQ scenario, the 100 Hz loop has data rate of 1200 byte/s, the 10 Hz loop has 160 byte/s and the 25 Hz loop has 100 byte/s, meaning a total of 1460 byte/s. According to application note from Microchip, the data transfer rate of an SD compliant memory card in SPI mode is about 25 Kbits/s, which is equal to 3125 byte/s (Microchip, 2008). However, according to other sources, up to 117 Kbit/s can be achieved with optimized code, even in 1 byte transfer mode with microSD card (FatFs website, 2016). It can be seen, that even in the worst case the data transfer speed of SD card is about 2 times higher, that the data collection speed.

At the current stage of the design process the PIC24EP128GP206 microchip has been selected as the heart of the DAQ controller. It has 60MIPS performance, 128kB program memory, 16kB data memory and 6 channel 12 bit A/D converter along with several digital communication modules and DMA channels (Microchip, 2016). This or other comparable 16-bit PIC microcontrollers are suitable for the application.

3.3 Measurement of ambient parameters

The ambient temperature and humidity are measured using sensors located on the bottom side of the quadcopter to avoid the heating effect of direct sunlight. The sensors are listed in
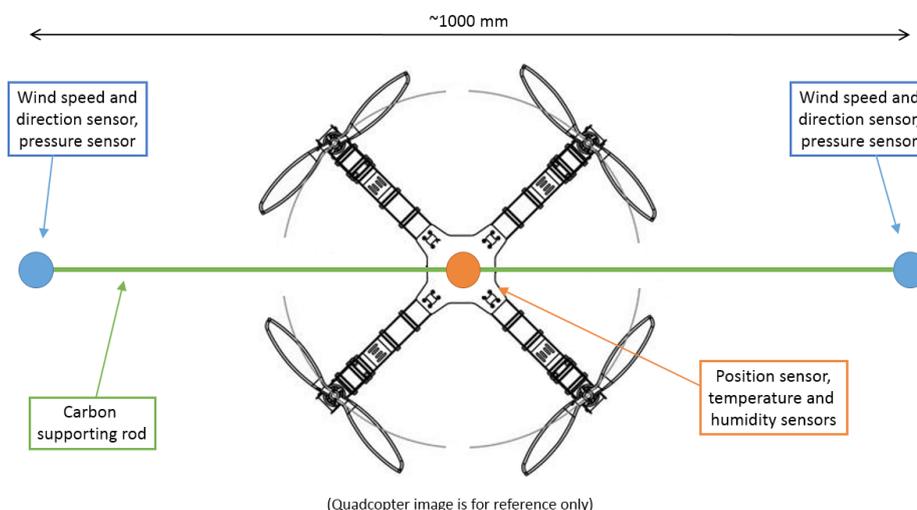

~1000 mm

Wind speed and direction sensor, pressure sensor

Wind speed and direction sensor, pressure sensor

Carbon supporting rod

Position sensor, temperature and humidity sensors

(Quadcopter image is for reference only)

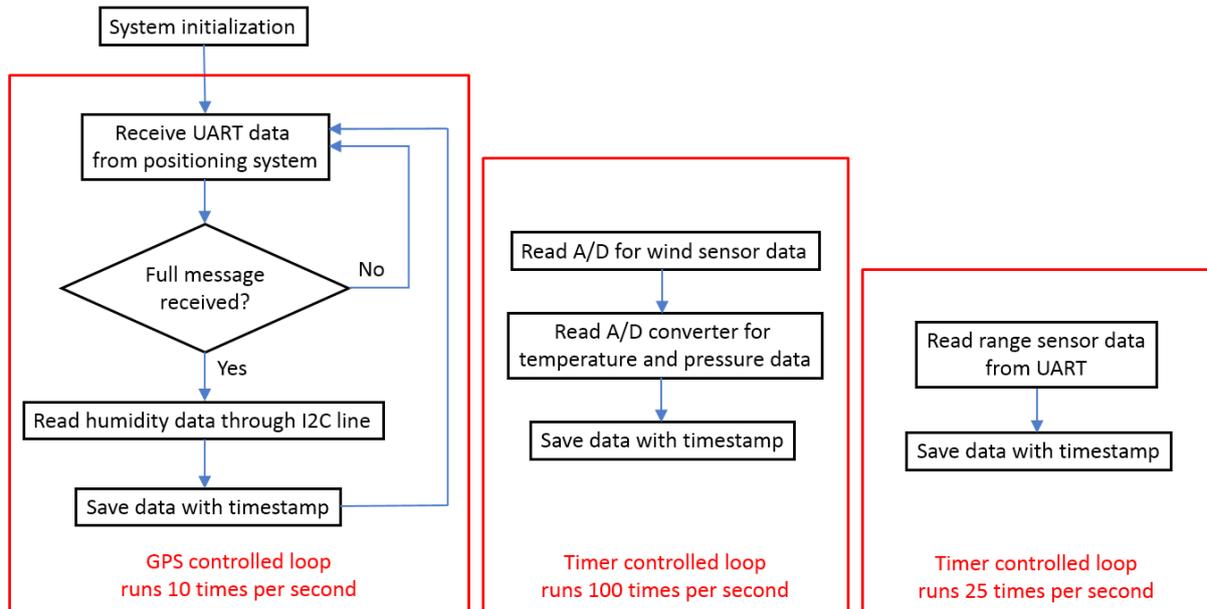**Fig. 4** Preliminary physical layout of sensors

Fig. 5 Basic flowchart of DAQ controller firmware

Table 2 Sensors for ambient parameters

Sensor	Parameter measured	Interface / Output	Range	Accuracy	Response time
LMT70	temperature	Analog voltage	-20 - +90 °C	0.1°C	1.5 s
MPXHZ6116A	pressure	Analog voltage	20-115 kPa	1.5%	15 ms
SHT25	humidity	Digital / I2C	0-100 %	1.8%	5-30 s

Table 2. The pressure sensor is intended to measure both mean ambient pressure and small scale pressure disturbances that are generated by the wind turbine blades passing in front of the drone. Thus to correctly measure these small changes and so that the measurements are not affected by the flow induced by the quad copter rotors, the pressure sensors are positioned at the end of the carbon rod as shown in Fig. 4. All the sensors are surface mount miniature sensors. Signal amplification and conversion to digital signal will be conducted by the central DAQ controller.

3.4 Measurement of wind speed and direction

Measuring the wind speed and direction is a challenge on-board of a quadcopter due to the proximity to the rotors and their induced air flows. To limit the influence of the rotors the sensors are spatially separated from the quadcopter using the carbon rod (see Fig. 4). Furthermore, in-situ calibrations will be performed to further characterize any disturbances and to correct for effects where one sensor is on the lee side of the UAV. Furthermore, the quadcopter itself is sensitive for atmospheric turbulence, therefore the movement of the UAV should be taken into account also (Zudov et al., 2014) to allow high accuracy wind speed measurement.

Possible sensor options are hot wire sensors or ultrasonic anemometers with good spatial resolution. However, while 3D ultrasonic anemometers, which would suit our application are readily available, they are too heavy and have too large in size to be mounted on the drone.

The most suitable sensor is a 3D hot wire sensor, like the Gold-plated tri-axial probe: 55P95 by Dantec Dynamics (Dantec webshop, 2016). It is a constant temperature sensor that measure wind speed from 0.2 m/s to 200 m/s, at a refresh rate of up to 400 kHz. Lower cost alternatives with comparable performance are currently being investigated.

3.5 Spatial position determination

The quadcopter controller is equipped with GPS positioning system to enable the fully autonomous flight. However, this system, has consumer-grade accuracy, which means 7 meters horizontally (Wing, 2011). This is sufficient for flight planning, but does not provide the higher position accuracy that is required for the reconstruction of 3-D maps of measured data. To keep the autopilot of the UAV as is, a separated position system consisting of a type uINS-2 sensor, supplied by InertialSense (InertialSense, 2016) is considered for the high accuracy measurement. The uINS-2 consists of a GPS receiver,

a barometric sensor and an inertial system that are integrated using sensor fusing algorithms.

The main features are:

- 1kHz update rate
- Built in magnetometer, L1 GPS, barometric altimeter and accelerometer
- Calibrated INU for bias, scale factor and cross-axis alignment
- Size: 16x13x7 mm, Weight: 2 grams
- Power consumption: 340mW @ 3.3V

This single module sensor system interacts with the central DAQ controller using TTL level UART protocol. This sensor provides high accurate position readings globally, however for our application local coverage is sufficient, therefore other, lower cost solution is also considered.

The lower cost alternative based on differential GPS technology is the real time kinematic GPS systems (E. Gakstatter, 2009). It consists of two GPS receiver, one for the base station, a GPS receiver for the moving object called "rover" and an RF link between them. The base station is stationary, its exact position with respect to the object defining the measuring domain (e.g. wind turbine) is known with high accuracy. This base station is used to measure the actual deviation of the GPS signals. Using this deviations, which is send to the rover through the RF communication link the rover's measured position can be corrected to achieve high accuracy. These systems are traditionally high cost systems (E. Gakstatter 2014), however thanks to the mass production of high performance digital electronics, these systems are available in more cost effective forms. One of them is the Piksi from Swift navigation, which provides cm level accuracy and a 10 Hz update rate (Swift website, 2016).

3.6 Range measurement

In some cases, direct distance measurement is useful to determine the exact situation or position of the measurement.

For example, when the airflow is measured just behind the wind turbine propeller disk, sensing the time when the propeller blade is passing front of the actual measuring point is important. This can be performed by using a range sensor. Such sensors can measure if there is a blade in front of the UAV and can measure the accurate distance also.

Another application for the 1D range sensor is when improved positon accuracy is required. For example, when taking measurements at cooling tower outlet the sensor can measure the exact distance from the top edge of the cooling tower, giving an absolute and accurate 1D range, that way making the position sensing more precise and giving a way to validate the position data.

This sensor can be based on laser or ultrasonic technology, and a final choice will be made based on future investigations. The ultrasonic technology has a lower range (up to 10m), but is independent of the target surface. However, the measurement accuracy depends on atmospheric conditions. In contrast distance sensors based on laser technology have a longer range (up to 100m), which (sometimes highly) depends on the color and reflectivity of the target. These sensors also have a higher directionality.

The output of these sensors are typically digital, in some cases PWM, but most commonly a serial communication line such as I2C, SPI or UART.

Since our application requires a measuring range of at least 30-40m, the ultrasonic sensors are considered inadequate. Therefore, the SF02 laser rangefinder sensor is selected (Parallax website, 2016). It has a 50 meter range for natural targets, is lightweight and has several digital output. Its resolution is 10 mm, the accuracy is 0.1 m + 1%, and the update rate is 32 Hz. This laser sensor is mounted on a dual axis gimbal on the quadcopter, making possible to measure range in any direction regardless of the heading of the UAV.

4 Conclusion, summary

In this paper, the preliminary design of an unmanned aerial measurement system, intended to be used in renewable energy applications (e.g. wind turbines or wind farms) is shown. The system is divided to 2 main parts: the measuring system and the flight system (quadcopter) that carries the measuring system. The quadcopter selected from the market is the Dropbear from Australian Droid and Robot, equipped with a fully functional autopilot and up to 30 minutes of flight time. The measurement system is capable to accurately map 3D flow field at wind farms, making it possible to investigate wind turbine losses and interactions. The sensor set consists of temperature, pressure, humidity, wind speed and direction, and spatial position sensors, integrated with a mixed signal data acquisition system.

For the preliminary design a set of commercially available sensors has been selected for the instrumentation payload. Further sensor options will be investigated during the detailed design and during commissioning and calibration tests.

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