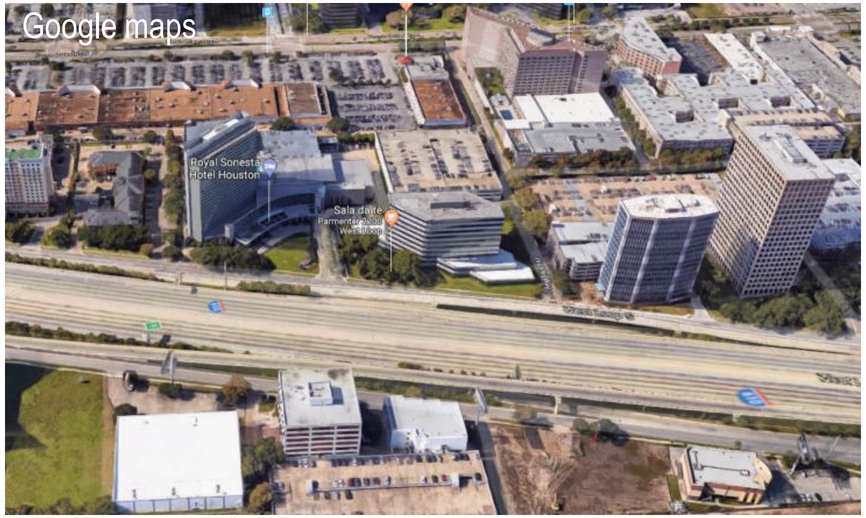
Research activity at the L.E.S.I.M. laboratory

The drone as mobile measurement platform

Introduction (1)

“**Reality capture**” is the process of digitizing the physical world by scanning it inside and out, from the ground and the air.



Industries have long sought data from above, generally through satellites or planes, but drones are better “**sensors in the sky**” than both.

Drones can provide “anytime, anywhere” access to overhead views with an **accuracy** that rivals laser scanning.

“Drones go to work” (1)

Introduction (2)

Drones have been recently proposed to map the scene of car accidents.

In all cases when economic transactions or legal issues are involved, it is fundamental to provide the uncertainty of the measurement result through structured and traceable procedures.

Image data collected during the drone flight can be used to produce a 3D point cloud and distance and size measurements, with **unofficial and approximate accuracy** of 2-5 cm.

"4 Reasons Drones will revolutionize accident scene response" (2)

Tutorial scope

A drone-based measurement instrument is a complex system:

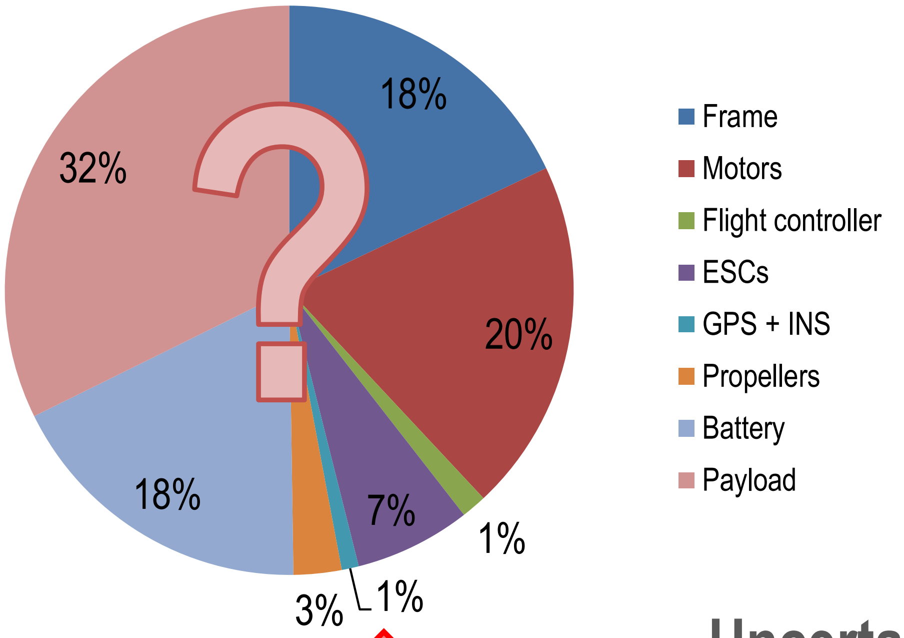
Several sub-systems (propulsion, flight control, power supply, etc.) contribute to define the overall system behavior;

The final measurement result is generally obtained by complex indirect methods operating on data from several sensors.

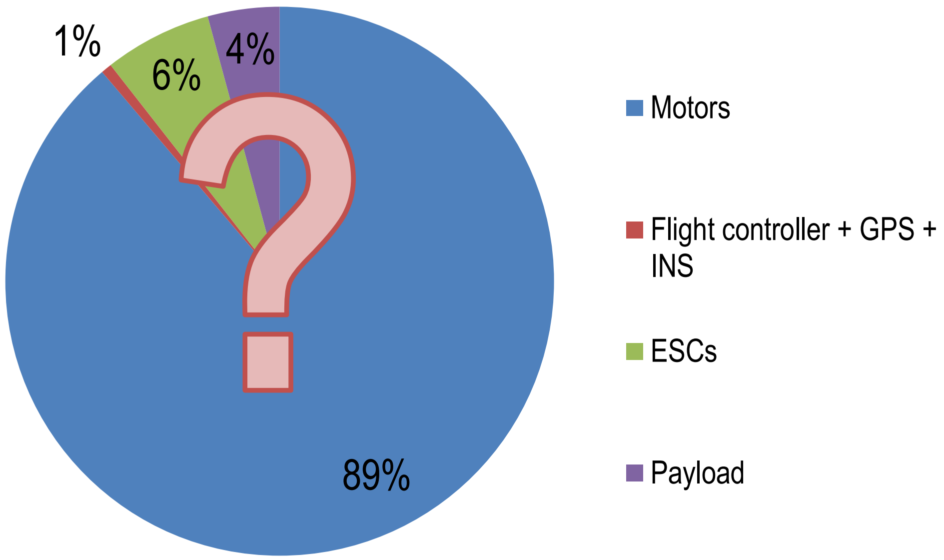
In the following, the designing steps and the testing procedures that are needed for implementing a drone-based measurement instrument.

Design parameters

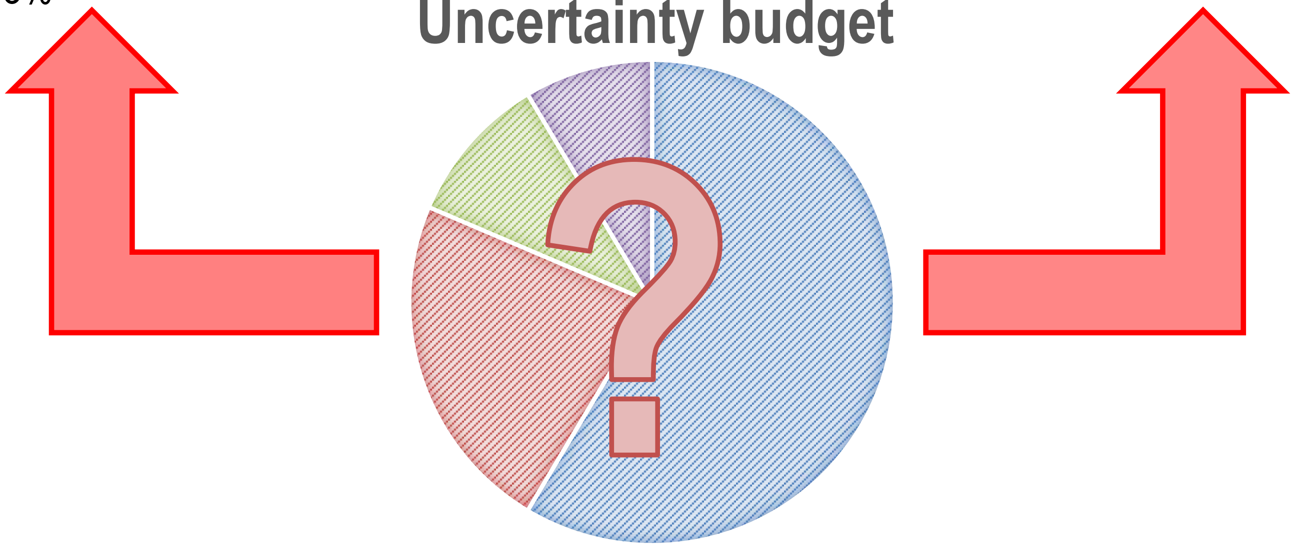
Weight budget



Power consumption budget

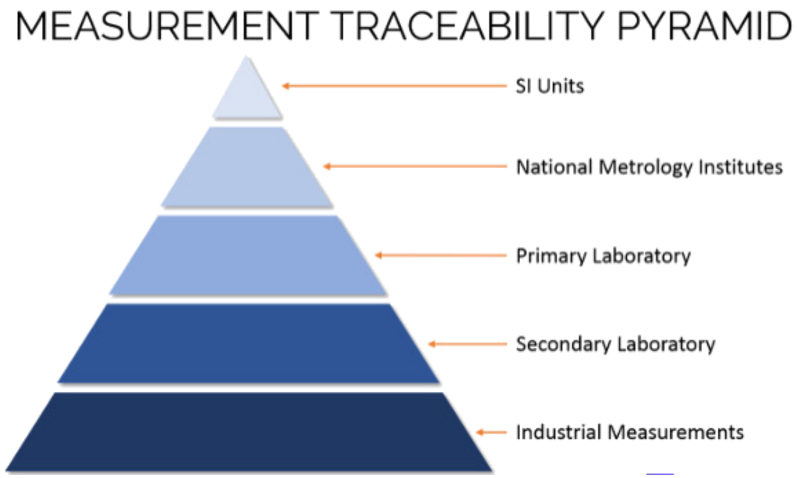


Uncertainty budget



Measurement uncertainty budget (1)

The on-board sensors must be chosen such that the measurement result complies with the target uncertainty.

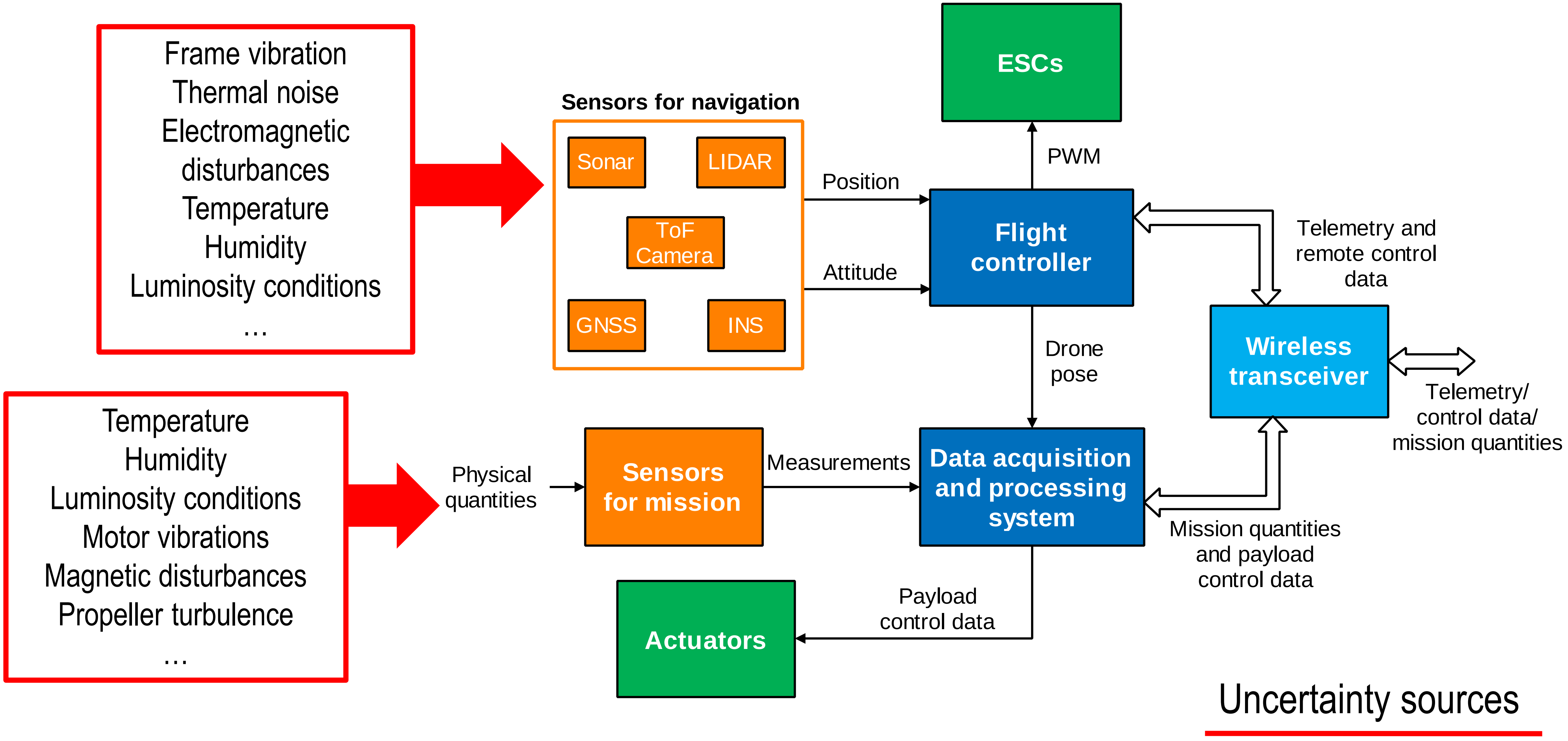


http://www.isobudgets.com/

Specific calibration methods must be defined, applied and documented in order to guarantee the measurement traceability.

https://bblsa.com/

Measurement uncertainty budget (2)



Measurement uncertainty budget (3)

To define the measurement uncertainty budget, the following steps are needed:

1. Identification of the uncertainty sources affecting mission measurements;
2. Evaluation of an uncertainty model according to the identified uncertainty sources;
3. Uncertainty sensitivity analysis.

The outputs of the uncertainty budget analysis are:

- The feasibility of the system according to the target uncertainty;
- The definition of the sensor specifications in terms of uncertainty for both the pose and the mission measurements.

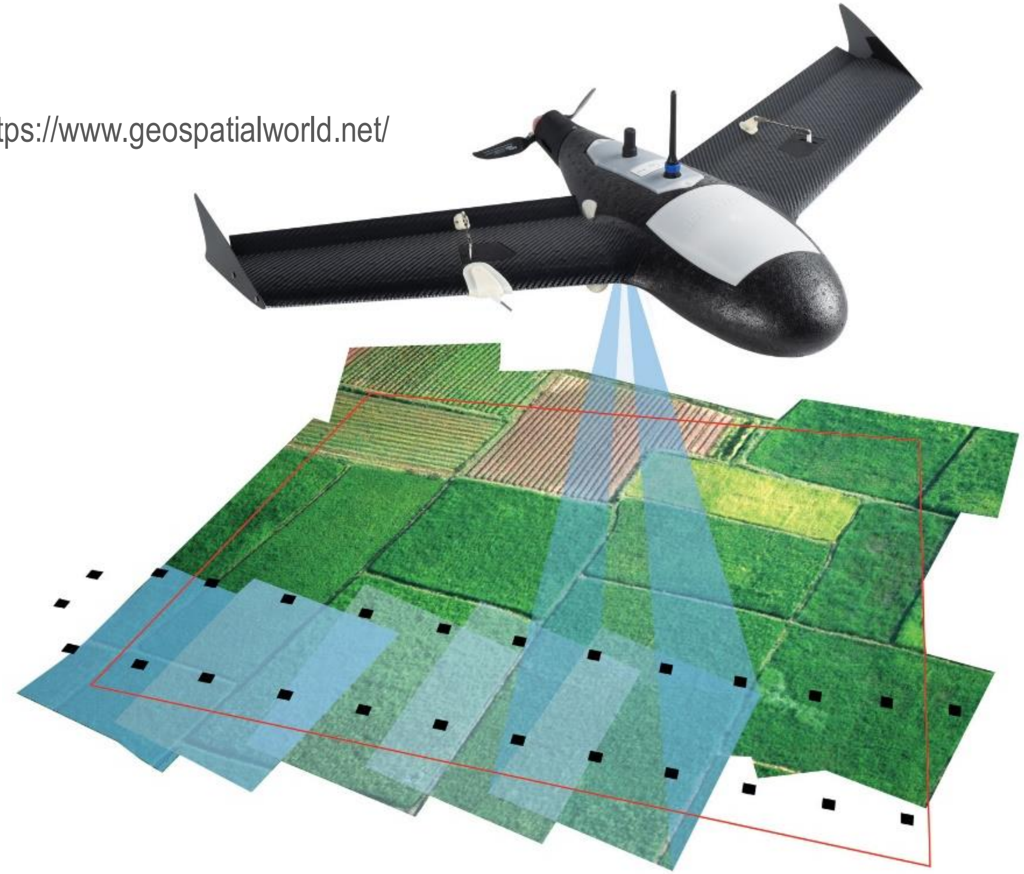
Drone-based measurement instrument design steps

1. Definition of the measurand (mission measurement);
2. Definition of the target uncertainty and measurement range;
3. Uncertainty budget analysis;
4. Definition of the requirements related to the sensors for navigation and for mission;
5. Definition of the communication link;
6. Definition of the drone platform according to the weight and power consumption budgets.

Case study: aerial photogrammetry for 3D reconstruction

In aerial photogrammetry, the 3D reconstruction is implemented by means of structure from motion.

https://www.geospatialworld.net/



The structure from motion consists of observing objects from different positions.

In aerial photogrammetry, the structure from motion is implemented acquiring two consecutive images during the flight mission.

P. Daponte, L. De Vito, F. Picariello, S. Rapuano, M. Riccio, "An uncertainty model for height measurement based on aerial photogrammetry", Proc. of 1st International Conference on Metrology for Archaeology, Benevento, Italy, October 22-23, 2015 (5)

1. Definition of the measurand - 2. Definition of the target uncertainty, and measurement range

The **measurands** are the geometrical dimensions (height, width, and length) of each object in the surveyed area.

The **target uncertainty** is in the order of 10 cm.

The **measurement range** depends on the maximum height of the object in the surveyed area (e.g. 3 m).

3. Uncertainty budget analysis

$$u_h^2 = \underbrace{\left(\frac{dh}{dc_{rm}}\right)^2 \cdot u_{c_{rm}}^2 + \left(\frac{dh}{dc_{lm}}\right)^2 \cdot u_{c_{lm}}^2 + \left(\frac{dh}{dc_{rg}}\right)^2 \cdot u_{c_{rg}}^2 + \left(\frac{dh}{dc_{lg}}\right)^2 \cdot u_{c_{lg}}^2}_{1} + \underbrace{\left(\frac{dh}{d\theta}\right)^2 \cdot u_\theta^2 + \left(\frac{dh}{db}\right)^2 \cdot u_b^2 + \left(\frac{dh}{df}\right)^2 \cdot u_f^2}_{2}$$

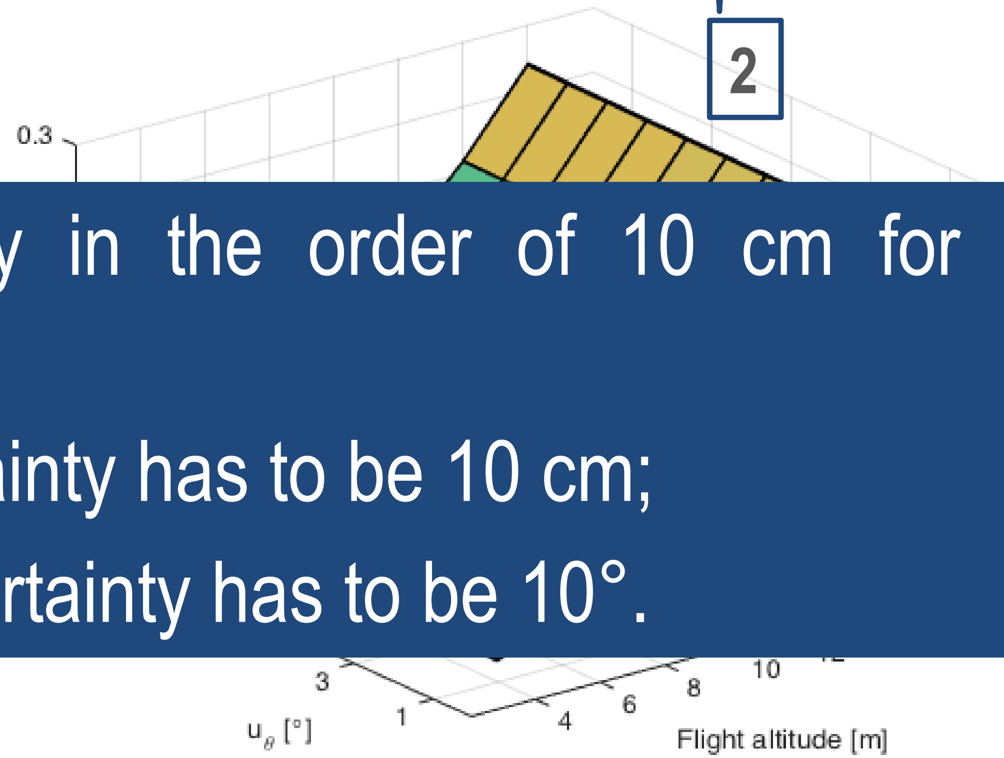
This

1.

2.

For achieving a target uncertainty in the order of 10 cm for a maximum flight altitude of 14 m:

- The maximum baseline, b, uncertainty has to be 10 cm;
- The maximum orientation, ϑ, uncertainty has to be 10°.



Uncertainty [m] vs. flight altitude [4, 16] m and pitch angle uncertainty **[1°, 10°]**, for different baseline uncertainties **[1.5, 10] cm**

P. Daponte, L. De Vito, G. Mazzilli, F. Picariello, S. Rapuano, "A height measurement uncertainty model for archaeological surveys by aerial photogrammetry", J. of Measurement, Feb. 2017 (6)

4. Definition of the requirements related to the sensors for navigation and for mission

For the measurements of the baseline b, distance between two waypoints, and the angle ϑ, drone elevation angle of drone in the second waypoint referred to the first, mainly two techniques can be considered:

- The payload includes a RGB camera with a gimbal;
- The sensors for navigation are GPS and INS.

GNSS-based technique (e.g. D-RTK)

- The baseline uncertainty is 1 cm (max. target 10 cm);
- The orientation uncertainty is 0.2° (max. target 10°).

Image-based pose estimation

- Luminosity conditions;
- Wind conditions;
- Gimbal stability;
- Background texture conditions.

5. Definition of the communication link

	FHSS		S-FHSS		Wi-Fi IEEE 802.11			AM/FM (First-Person View FPV)		COFDM (FPV)	
	2.4 GHz		2.4 GHz		2.4/5 GHz			900 MHz/1.2 GHz/2.4 GHz/5.8 GHz		900 MHz/1.2 GHz/2.4 GHz/5.8 GHz	
	Bit rate [Mbit/s]	Distance [m]	Bit rate [kbit/s]	Distance [m]		Bit rate [Mbit/s]	Distance [m]	Bandwidth [MHz]	Distance [m]	Bit rate [Mbit/s]	Distance [m]
	3	1500	128	5000	b	11	140	16 (FM)	5000	5	10000
					g	54	140				
					n	300	250				
Remote control data	X		X		X					X	
Telemetry data	X		X		X					X	
Payload data					X			X (camera)		X	

6. Definition of the drone platform according to the weight and power consumption budgets.

Aerial photogrammetry
Weight budget

Gimbal + camera (Zenmuse X4S)	253 g
Quadrotor Frame (F	[illegible]
Flight controller + GPS + I	[illegible]
4 ESCs (DJI - E30	[illegible] g
4 Propellers (Z-BLADE 9450)	52 g
4 Motors (DJI – 2312E)	224 g
Battery 4500 mAh 4S LiPo	375 g
Tot.	1300 g

Takeoff weight 400 g/rotor with 4S LiPo
Max. total weight = 1600g.

Cost: $ 1,500 – $ 2,000

Estimated uncertainty: 0.16 m

Aerial photogrammetry
Power consumption budget

Gimbal + camera (Zenmuse X4S)	5 W
er + GPS + IMU (N3 DJI)	5 W
s (DJI - E305)	200 W
4 Motors (DJI – 2312E)	
Tot.	210 W

By considering a flight time of 20 min, the capacity of the battery has to be about 4600mAh (4S-LiPo).

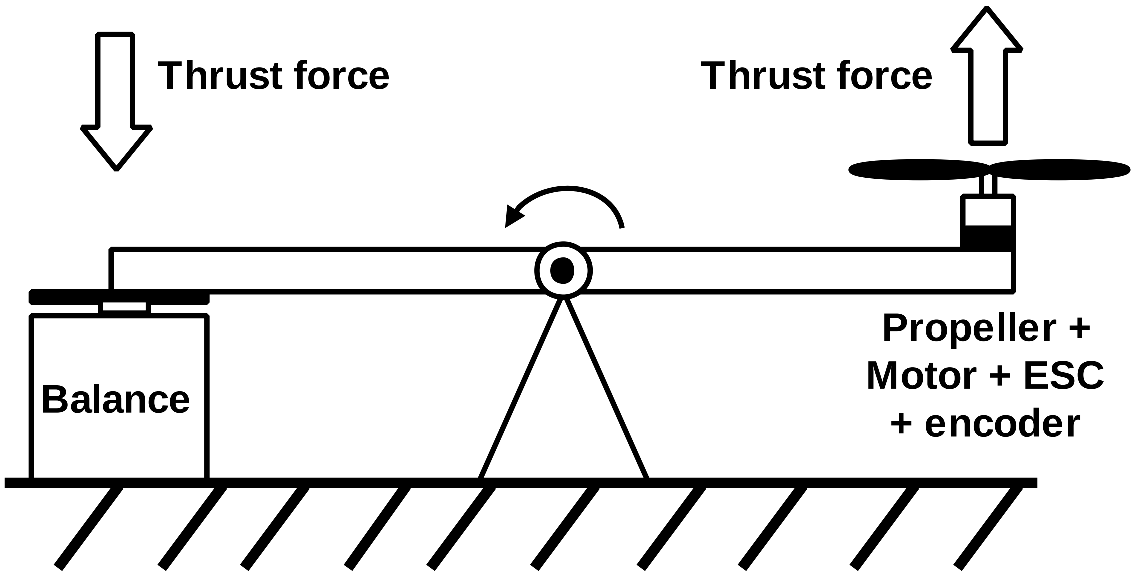
Overview of characterization methods

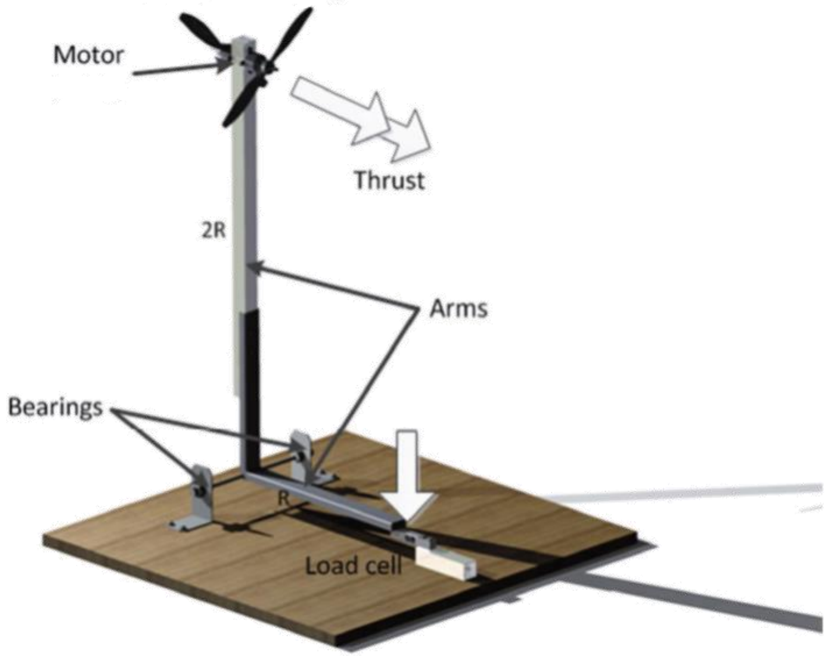
The characterization methods for a drone-based measurement instrument can be classified into:

Characterization performed on test bench, the aim is to measure the parameters related to each drone's component for the following subsystems: (i) propulsion subsystem, and (ii) INS-control board.

Characterization performed during flight, the aim is to characterize the mission measurements provided by drone.

Characterization performed on test bench





- The most important parameters to be measured are: (i) the thrust forces in relation to the motor speeds, (ii) the motor speed response time, and (iii) the power efficiency in terms of Newton per Watt, [N/W].
- A common test bench used for measuring the static thrust force is implemented using an electronic weight balance.
- A characteristic speed versus thrust force can be obtained and it can be used for optimizing the mechanical and the electrical drone design and the control method.

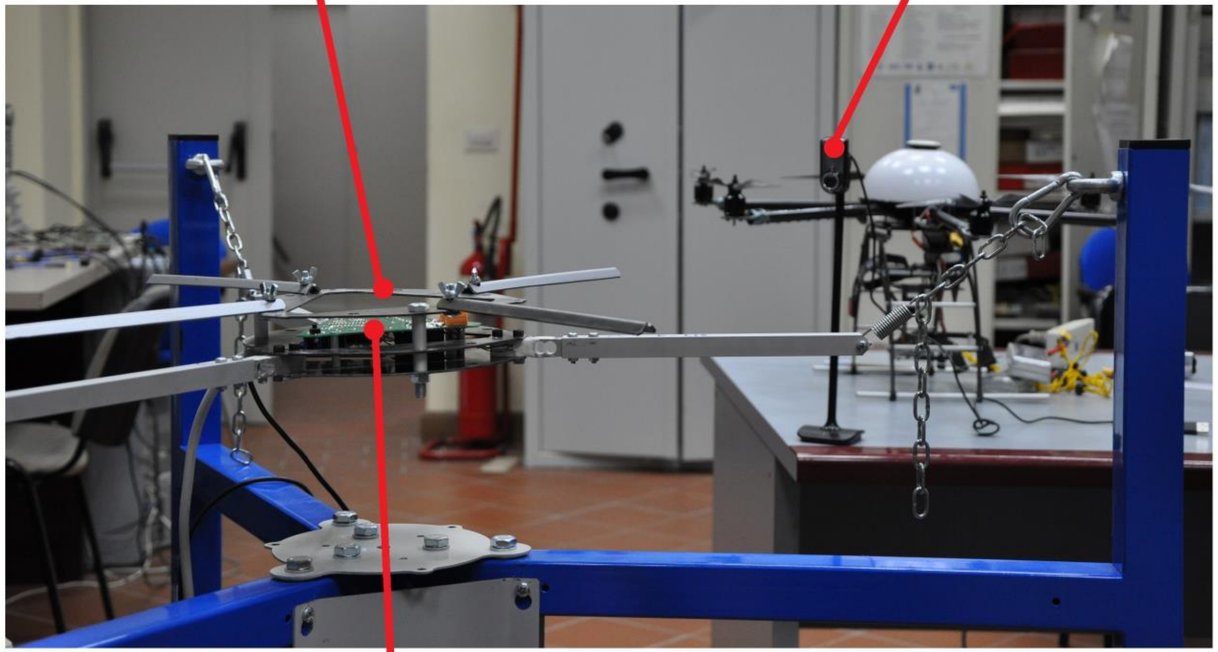
Open issue

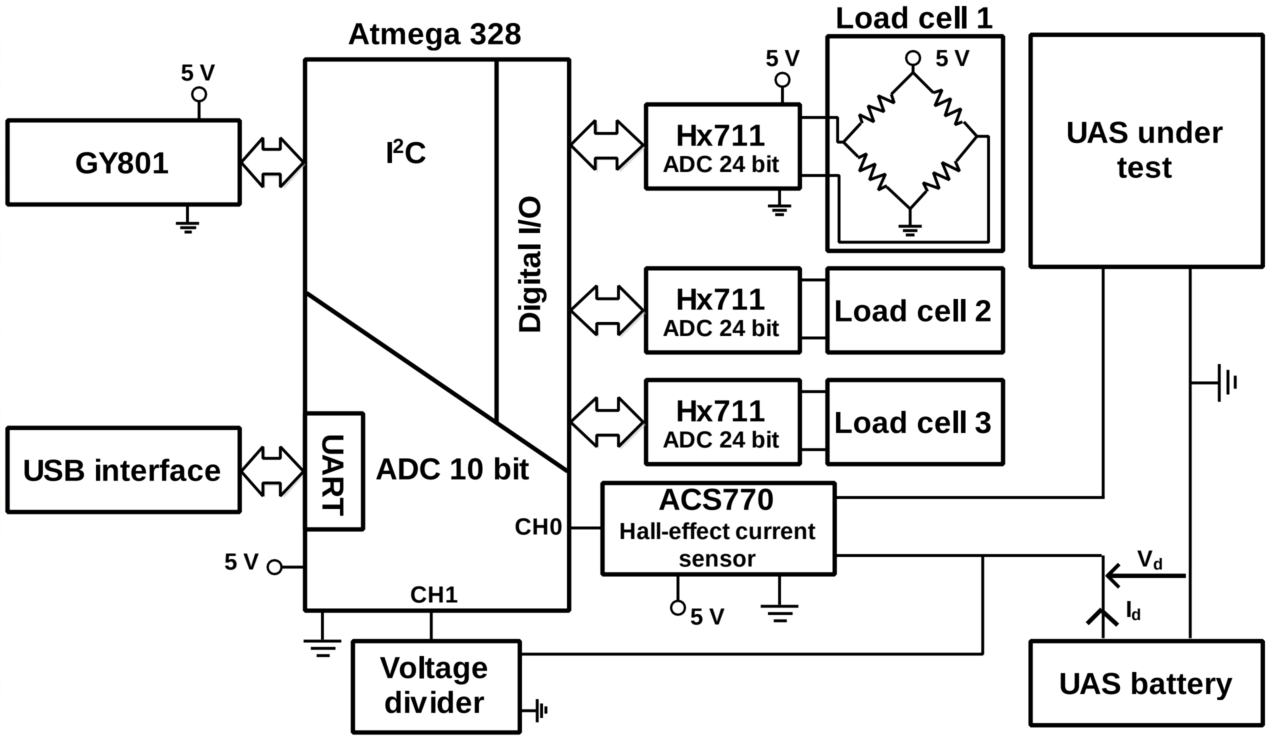
In literature, the systems used for testing drones are mainly used for measuring parameters related to each component of the drone itself (such us control board, propeller, motor, and so on).

These measurement systems are designed for testing each drone subsystem and they do not allow assessing the reliability of a drone as a whole system.

B. Brzozowski, P. Daponte, L. De Vito, F. Lamonaca, F. Picariello, M. Pompetti, I. Tudosa, K. Wojtowicz, “A remote controlled platform for UASs testing”, AESS Magazine

DronesBench (1)





The system consists of: (i) the accommodation plane, where the drone is inserted, (ii) the monitoring board, which is used for acquiring the data of the sensors, and (iii) the video camera for online visualization and recording of the testing scenario.

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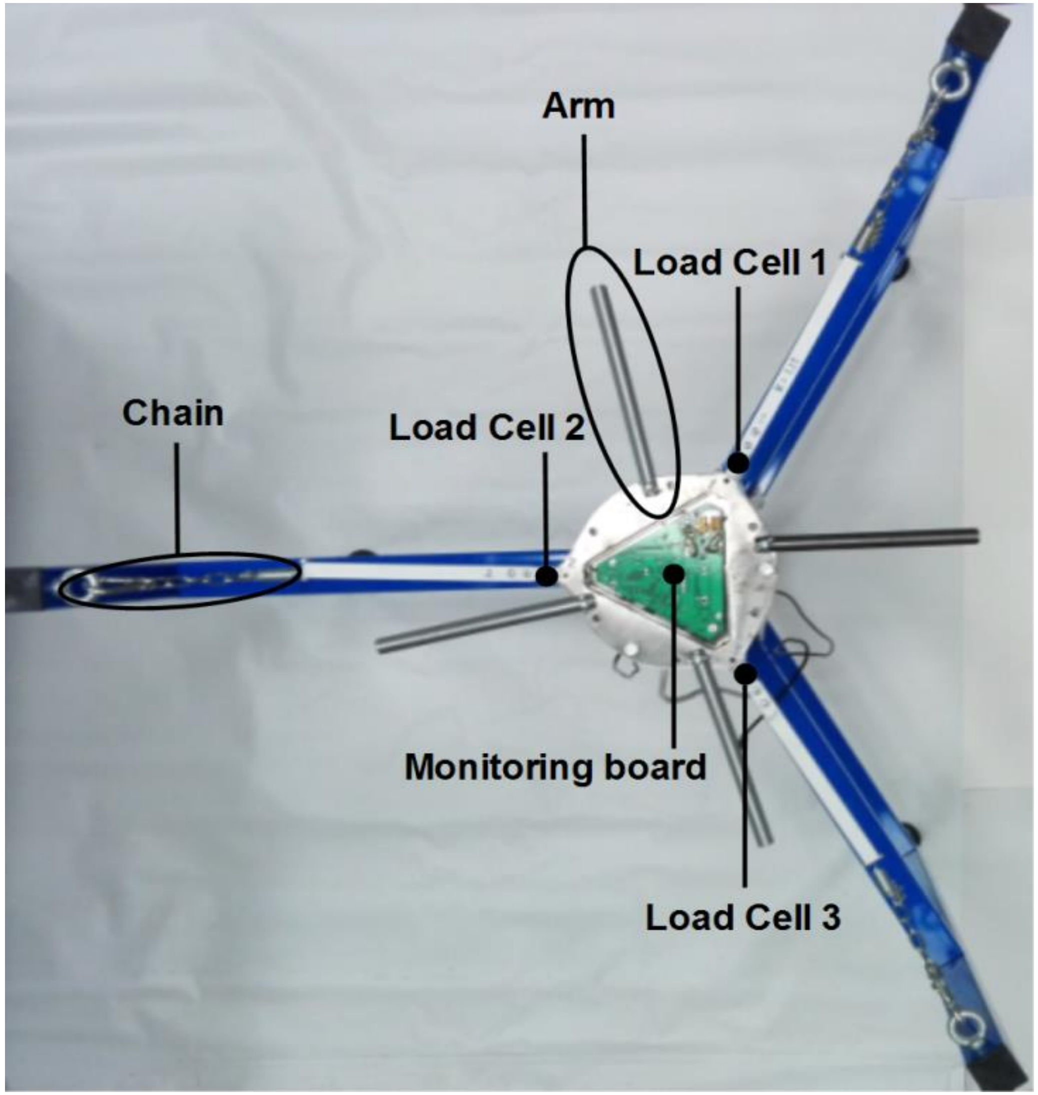
DronesBench (2)



- The sensing tips of the three load cells are attached to the accommodation plane, while the other fixture tips are connected through the chains to the test bench frame.
- The load cells are placed at 120° to each other on the accommodation plane.
- The drone under test is fixed through the four arms that are attached on the accommodation plane and the monitoring board is placed under the accommodation plane.
- The measurements are acquired in real-time, from the monitoring board, on a PC by using a LabVIEW application.

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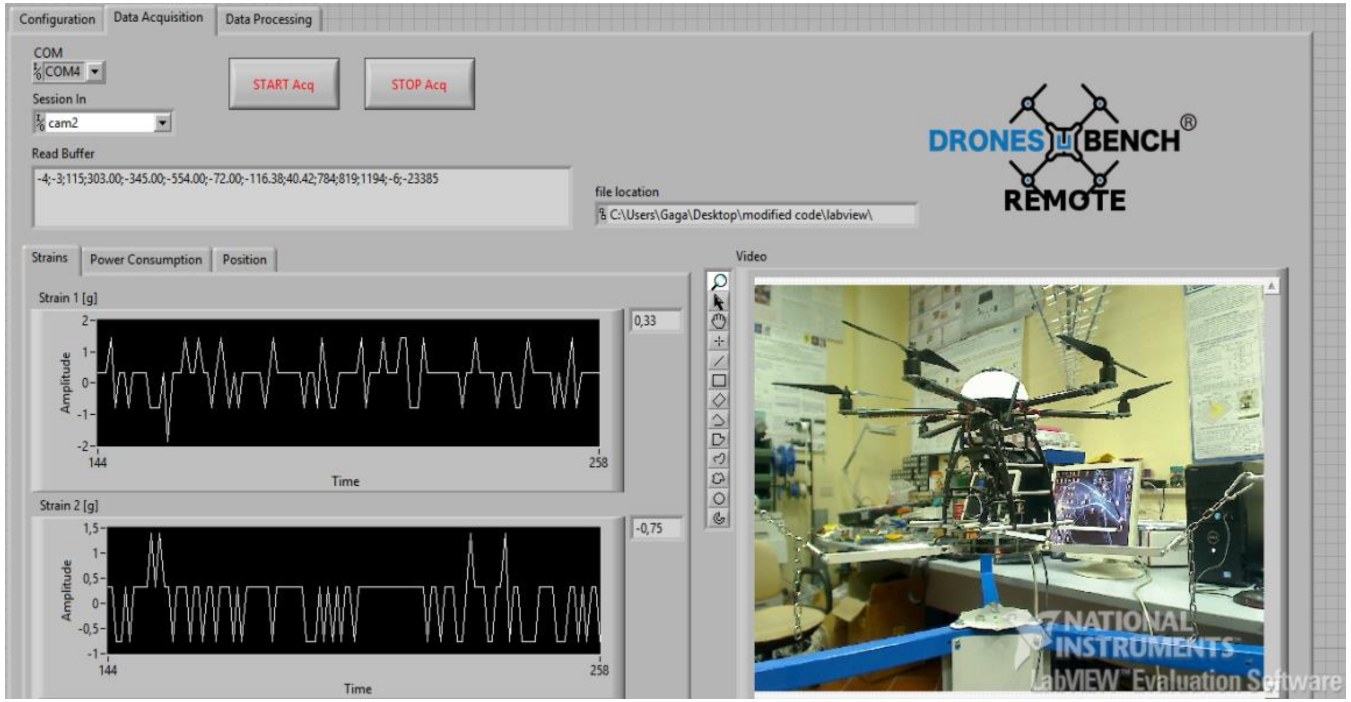
DronesBench (3)



By acquiring the data provided by each load cell and by considering the z-axis of the three load cells aligned, at each sampling instant the thrust force exerted by drone along the z-axis is evaluated as follows:

$$F = F_{z,1} + F_{z,2} + F_{z,3}$$

The thrust force values, acquired at each sampling instant, are stored in the vector:

$$\boldsymbol{F} = [F(0), \ldots, F(N)]$$

The power consumption values, acquired at each sampling instant, are stored in the vector:

$$\boldsymbol{P} = [P(0), \ldots, P(N)]$$

A linear regression, based on least square fitting between vectors ***F*** and ***P***, is performed, and the obtained slope (*FoM*) is associated to the drone efficiency in terms of Newton per Watt, [N/W].

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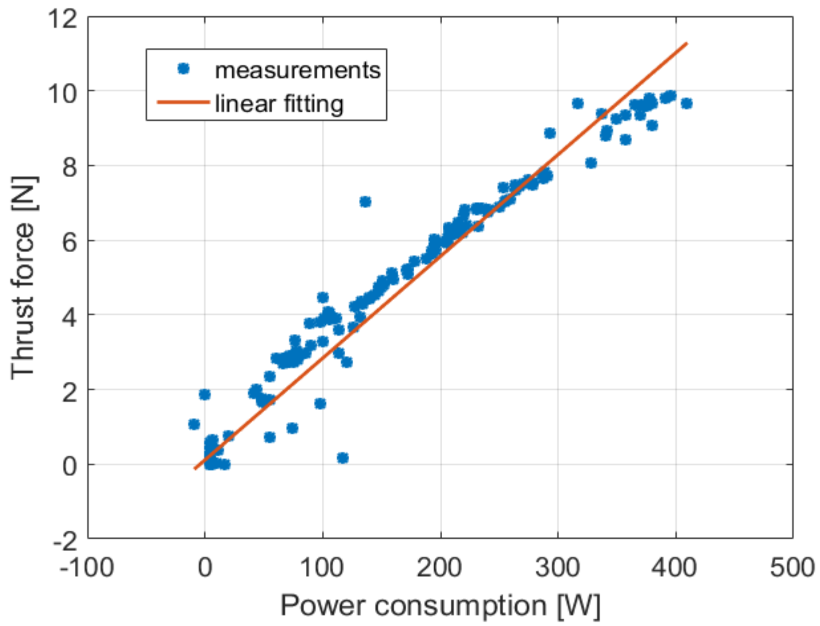
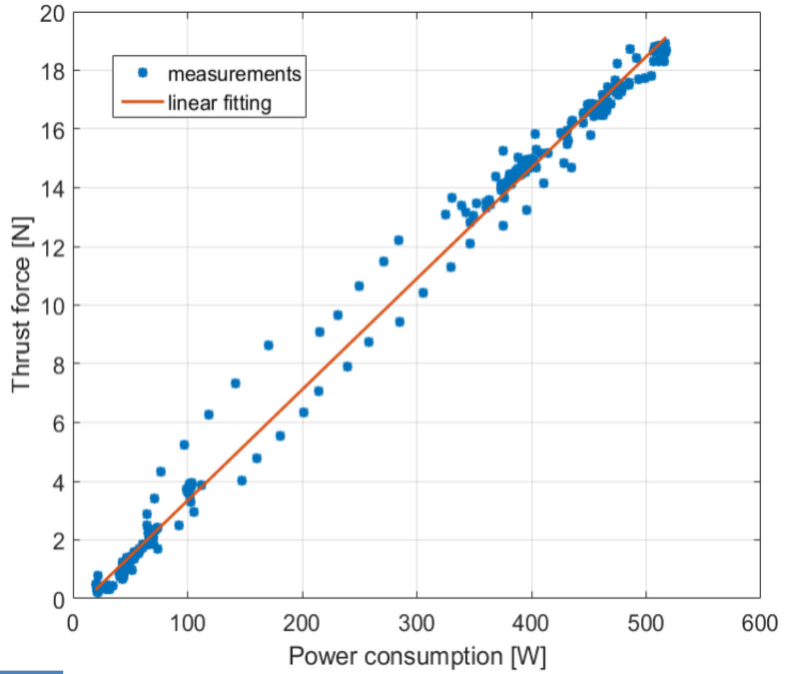
Preliminary results (1)

Quadrotor
FoM = 0.027 N/W



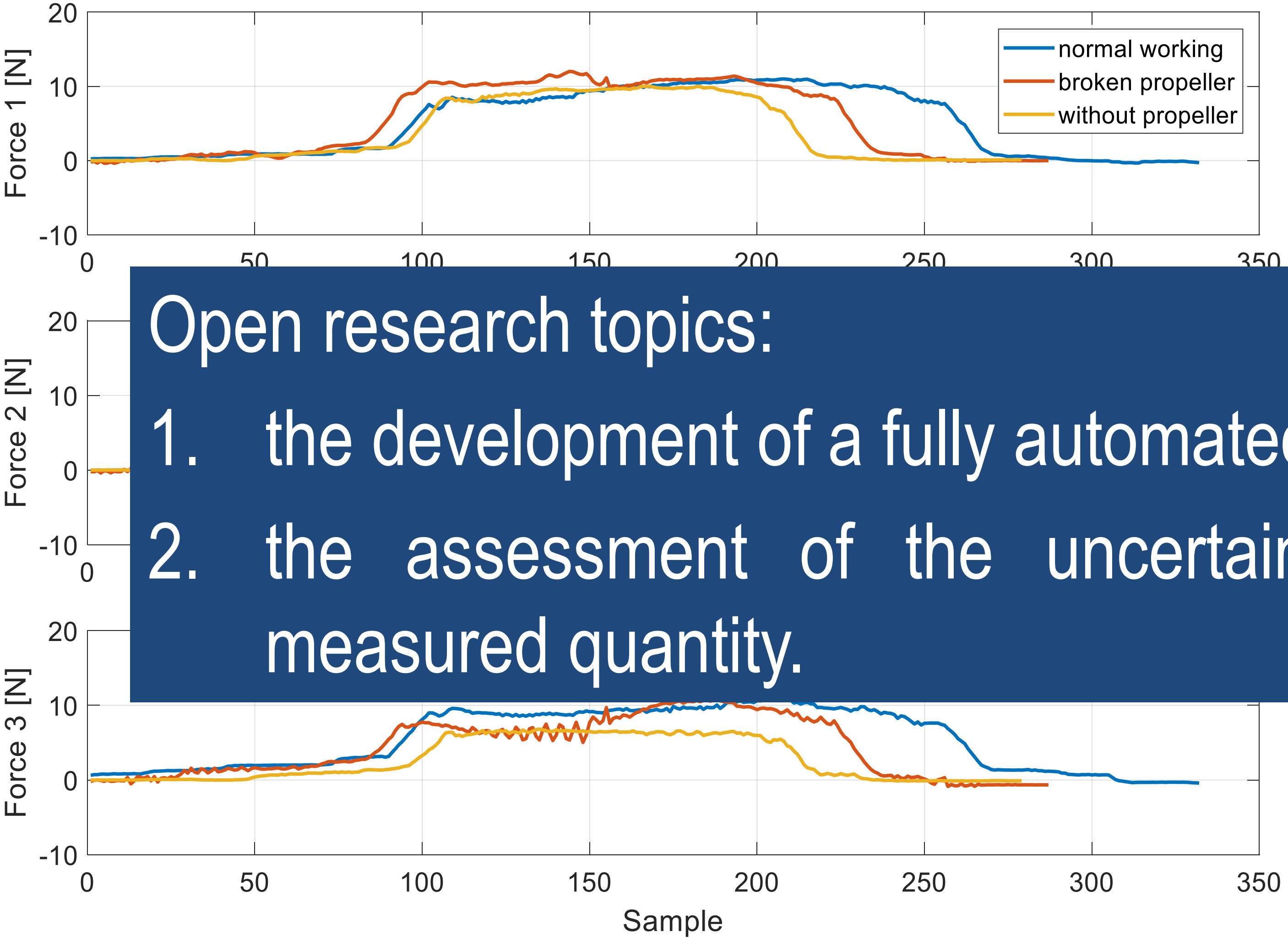


Hexarotor
FoM = 0.038 N/W

	Quadrotor	Hexarotor
Motor	Sunnysky V3508	Pulso U22 M
Propeller	(28 × 12.5) cm	(28 × 12.5) cm
ESC	Opto 30 A	Opto 30 A
Control board	Pixhawk V2.4.8	DJI NAZA-M V2
Battery	Turnigy 3S, 5000 mAh	Fullpower 4S, 5000 mAh
Frame	wheelbase length 495 mm	wheelbase length 670 mm

The testing procedure consists of driving the drone manually by using the ground control station. In particular, the test has been performed for about 45 s where the pilot executed one throttle variation from the minimum to the maximum values allowed by the drone.

Preliminary results (2)



Open research topics:

1. the development of a fully automated system for faults detection;
2. the assessment of the uncertainties associated with each measured quantity.

Test 1: the hexarotor was tested with all the propellers working (called normal working).

Test 2: the hexarotor was tested with one propeller damaged, missing about 1 cm of

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The obtained results show that the force measurements can be used for detecting and identifying faults or damages of drones.

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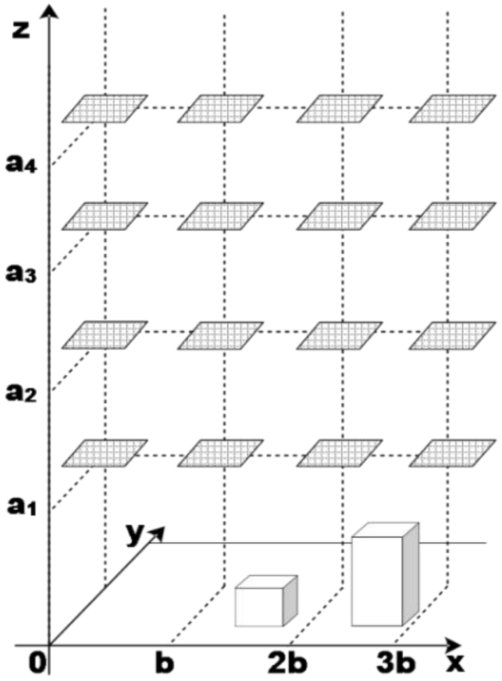
Characterization performed during flight: aerial photogrammetry



Camera parameters	Value
Number of effective pixels	12.4 megapixels
Field Of View	94° at 20 mm
Image Max Size	4000 x 3000 pixels
Sensor wide	6.16 mm
Sensor high	4.62 mm
Focal length	4 mm
Diagonal pixel sensor size	21.8 μm
ISO 5800:1987 range	100-1600

- For each position, 20 images have been acquired to evaluate the uncertainty related to each measurement.
- As target, a box has been used and its height of 0.418 m has been measured with the Leica Disto D3a infrared distance meter.
- Two averages of 6 distances camera-topside box (h_m) and 6 distances camera-ground level point (h_g) have been considered.
- The difference between these averaged values provides the object height measurement.
- An image scaling operation is performed in order to compensate systematic effects.

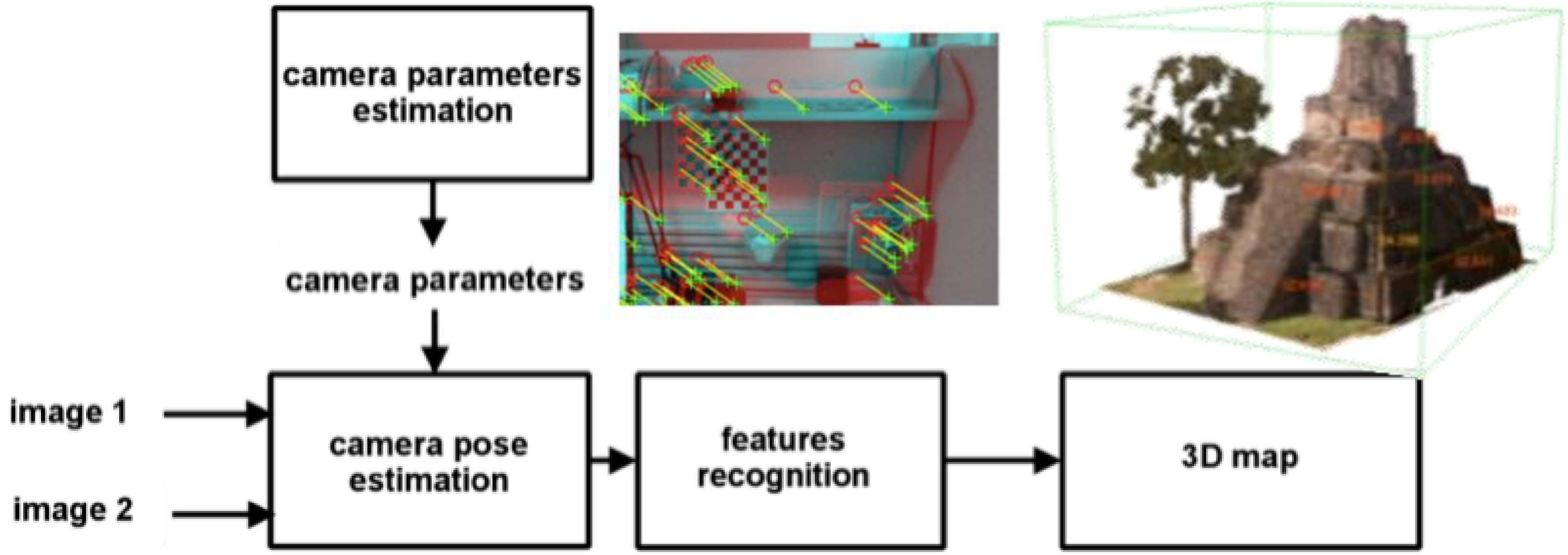
P. Daponte, L. De Vito, G. Mazzilli, F. Picariello, S. Rapuano, "A height measurement uncertainty model for archaeological surveys by aerial photogrammetry", J. of Measurement, Feb. 2017 [6]

3D reconstruction applications

Pix4Dmapper Pro:

- Initial Processing, Pix4Dmapper Pro computes key points on the acquired images and provides a preliminary 3D map of the scene;
- Point Cloud and Mesh step increases the density of 3D points on the 3D map realized in Initial Processing step;
- Digital Surface Model (DSM) and Orthomosaic step provides a digital surface model and orthomosaic of the 3D map points. The 3D map can be scaled according to a reference size.

The developed 3D reconstruction application (MATLAB):



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Results

Flight altitude [m]	MATLAB-based 3D application [m]	Proposed model [m]	Uncertainty of stereovision geometry parameters [m]	Pix4D [m]	Proposed model [m]	Uncertainty of stereovision geometry parameters [m]
3	0.20	0.20	0.20	0.25	0.24	0.24
7	0.12	0.11	0.10	0.45	0.44	0.44
9	0.17	0.16	0.13	0.43	0.43	0.42
11	0.23	0.22	0.18	0.30	0.29	0.26

- The main uncertainty sources for both the 3D reconstruction applications are due to the estimation of the stereovision geometry parameters;
- The uncertainties related to the estimation of these stereovision parameters are higher for low flight altitudes than for the high ones. This is due to the fact that for low flight altitudes more details of the background are in the acquired images;
- The camera pose estimation algorithm is confused by the presence of more similar details on the background texture.

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