Educational for Drone (eDrone)
574090-EPP-1-2016-1-IT-EPPKA2-CBHE-JP

Educational for Drone
(eDrone)

Design of a drone-based measurement instrument
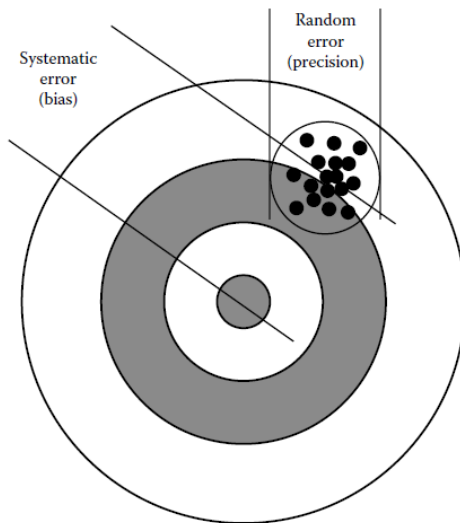
Prof. Francesco Picariello, Ph.D.

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Università
degli Studi
del Sannio

Accuracy and errors

- The **accuracy** of an instrument is defined as the difference between the true value of the measurand and the measured value indicated by the instrument. Typically, the true value is defined in reference to some absolute or agreed upon standard.

- For any particular measurement, there will be some error due to **systematic** (bias) and **random** (noise) error sources.

- There are a variety of factors that can result in systematic measurement errors. One class of cause factors are those that change the input–output response of a sensor resulting in miscalibration.

Calibration

Sensitivity = $\dfrac{\mathrm{d}S}{\mathrm{d}X}$
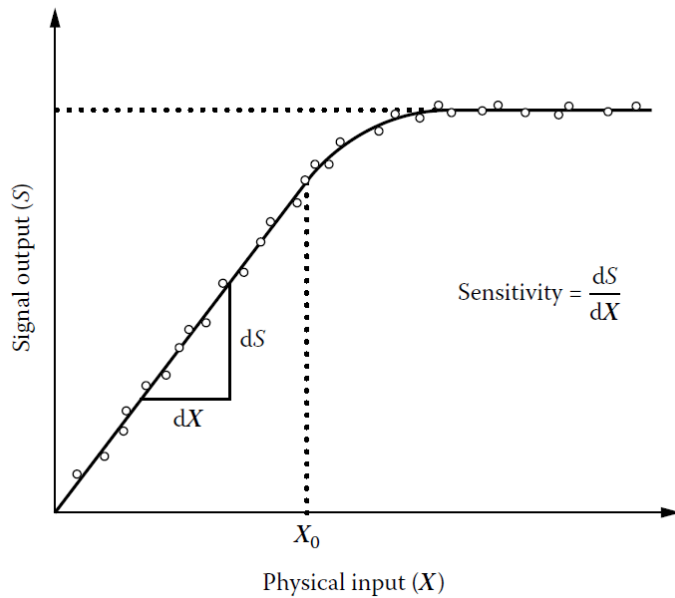
- The relationship between the physical measurement variable input and the signal variable (output) for a specific instrument is known as the calibration of the instrument.

Precision and Random error sources

- In many cases, if the systematic error source is known, it can be corrected for by the use of **compensation methods**.

- **Random error** is sometimes referred to as noise, which is defined as a signal that carries no useful information.

- **Precision** indicates the closeness of agreement between measured quantity values obtained by replicate measurements
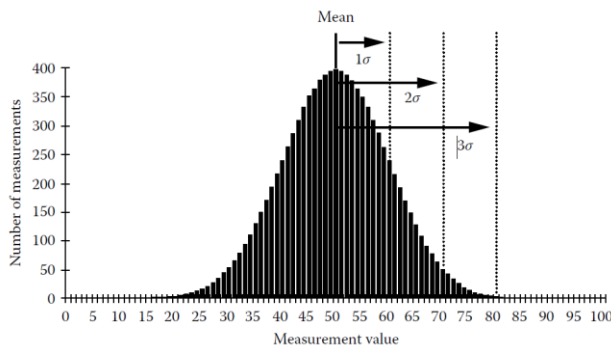
In case of random error **Gaussian distributed**, the precision of the measurement is normally quantified by the standard deviation (σ).

Such value is then called **standard uncertainty.**

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General architecture of a digital measurement instrument
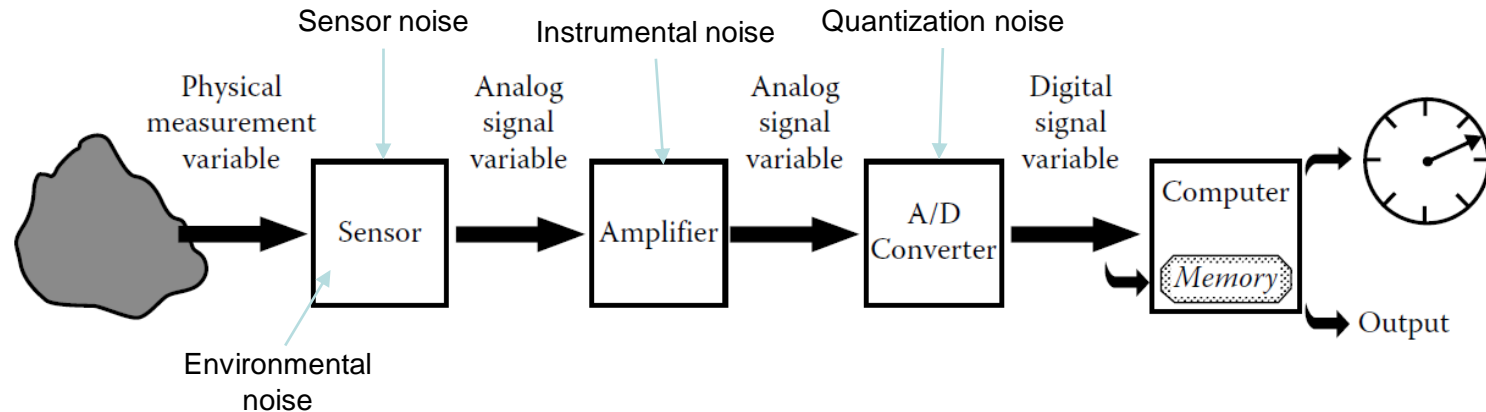
- The design of an instrument involves the evaluation of the **uncertainty budget**, by assessing the different components of the measurement uncertainty and their combination.

Indirect measurements

- Many physical quantities are indirectly measured, by exploiting functional relations (**a model**) that connect them to other directly measured quantities.

$$Y = F(X_1, X_2, ..., X_n)$$

- In this case the uncertainty of the measurement result is obtained from the combination of the uncertainties of the directly measured quantities (if the measured quantities are all independent):

$$u_Y = \sqrt{\left(\frac{\partial F}{\partial X_1}\right)^2 u_{X_1}^2 + \left(\frac{\partial F}{\partial X_2}\right)^2 u_{X_2}^2 + \cdots + \left(\frac{\partial F}{\partial X_n}\right)^2 u_{X_n}^2}$$

Drone-based measurement instrument

- 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.
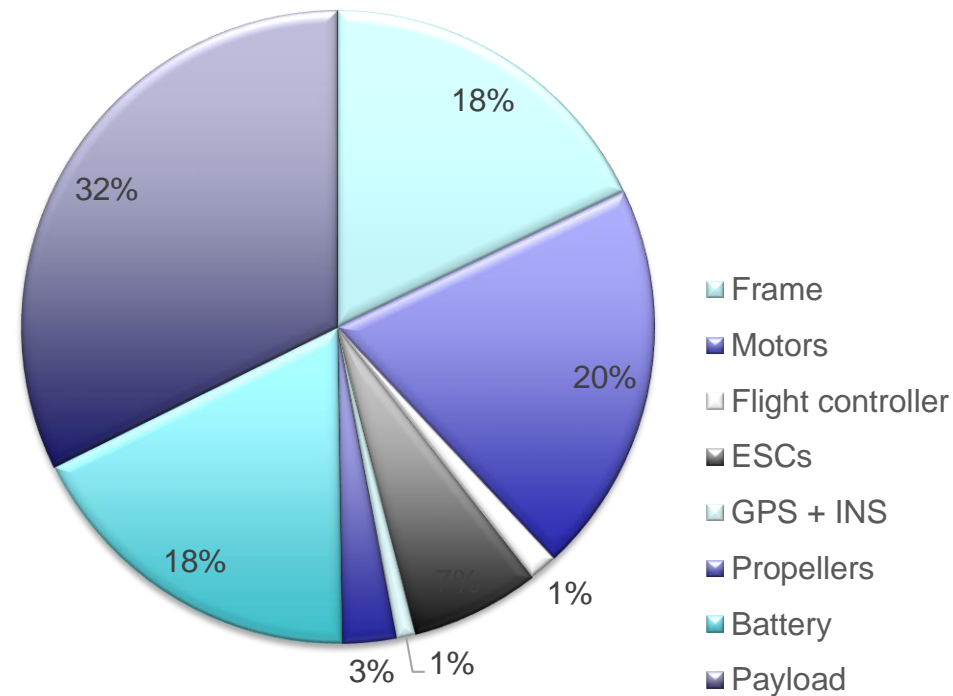
Design parameters

- The main parameters to be considered for designing a drone-based measurement instrument are:

1. Weight;

2. Power consumption;

3. Communication link;

4. Measurement uncertainty.

- Those parameters strictly depend on the mechanical and electrical parts of the drone.

Weight budget

- The weight is the main parameter for sizing the motors, the propellers, and the frame of the drone.

The main contributors to the drone weight are:

1. The payload that depends on the application (usually it contains at least a gimbal and a camera);

2. The frame. Its contribution on the total weight can be reduced using carbon fiber frames;

3. The brushless motors;

4. The battery.

Pie chart legend:
- Frame
- Motors
- Flight controller
- ESCs
- GPS + INS
- Propellers
- Battery
- Payload

Pie chart values: 18%, 20%, 1%, 1%, 3%, 18%, 32%

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Power consumption budget

The battery of the drone is sized according to its power consumption and the required flight time for a mission.

The power consumption shares have been estimated considering the maximum power consumption values exhibited by each drone sub-system.

For the payload, a gimbal with a camera and the transmitter have been considered.

Usually, the main contributors to the drone power consumption are the motors.

Legend:
- Motors
- Flight controller + GPS + INS
- ESCs
- Payload

Pie chart values: 1%, 6%, 4%, 89%
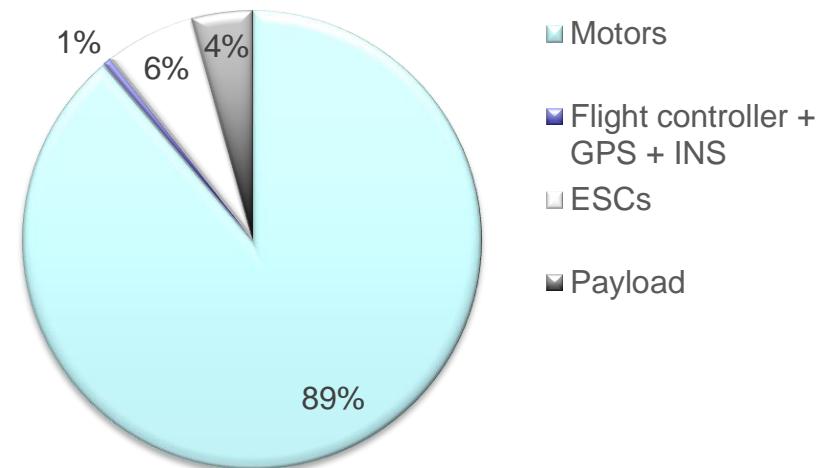
The capacity of the battery is estimated as:

$$C = 16.67 \cdot \frac{P}{V_b} \cdot t_f \quad [mAh]$$

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Communication link budget

	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	X		X		X					X	
Telemetry	X		X		X					X	
Payload					X			X (camera)		X (camera)	

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Measurement uncertainty budget (1)

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

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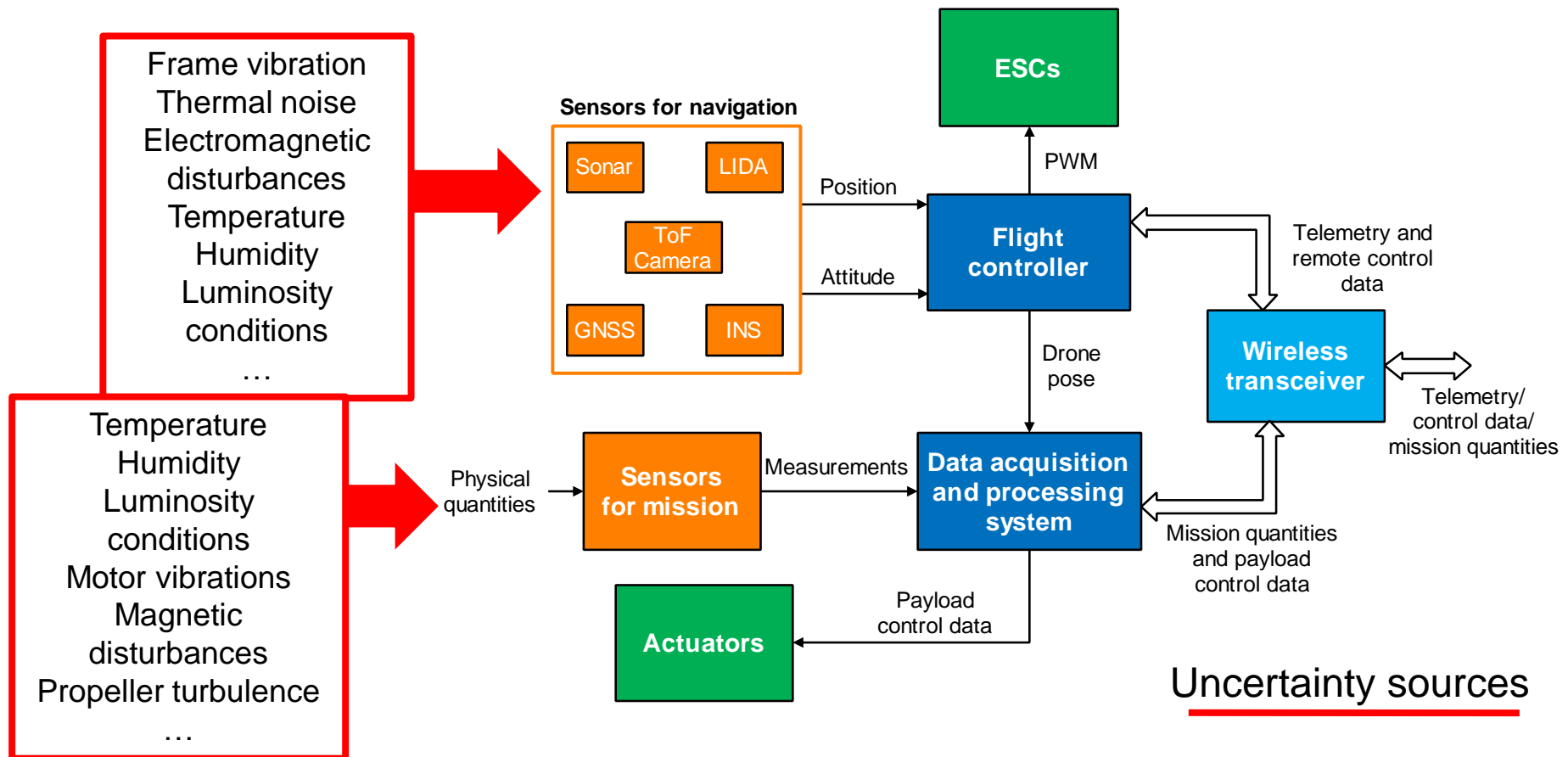
MEASUREMENT TRACEABILITY PYRAMID

- SI Units
- National Metrology Institutes
- Primary Laboratory
- Secondary Laboratory
- Industrial Measurements

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Measurement uncertainty budget (2)

Frame vibration
Thermal noise
Electromagnetic disturbances
Temperature
Humidity
Luminosity conditions
…

Temperature
Humidity
Luminosity conditions
Motor vibrations
Magnetic disturbances
Propeller turbulence
…

Sensors for navigation

Sonar   LIDA

ToF Camera

GNSS   INS

ESCs

Position
Attitude

PWM

Flight controller

Telemetry and remote control data

Drone pose

Wireless transceiver

Telemetry/ control data/ mission quantities

Physical quantities

Sensors for mission

Measurements

Data acquisition and processing system

Mission quantities and payload control data

Payload control data

Actuators

Uncertainty sources

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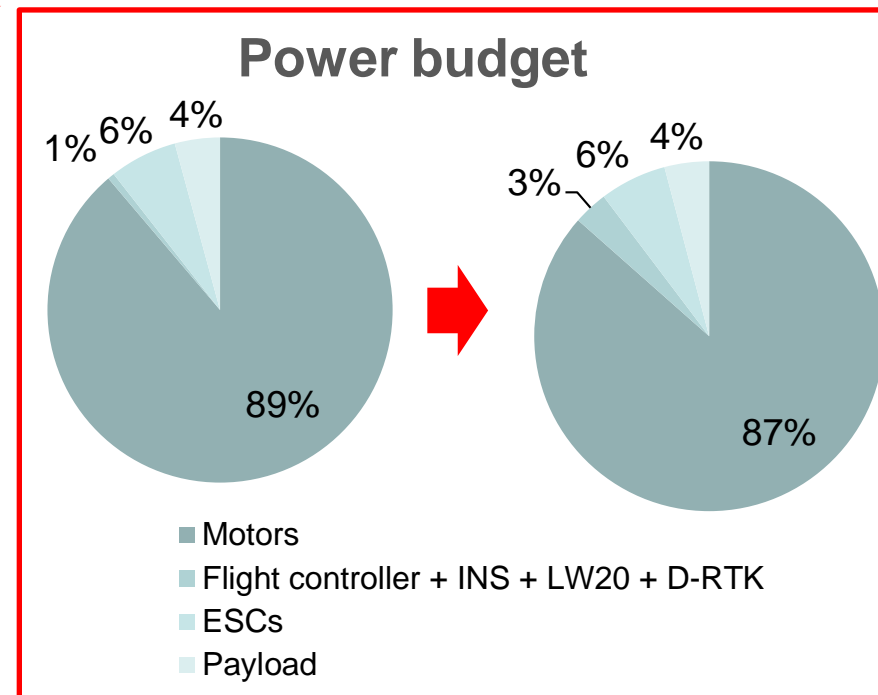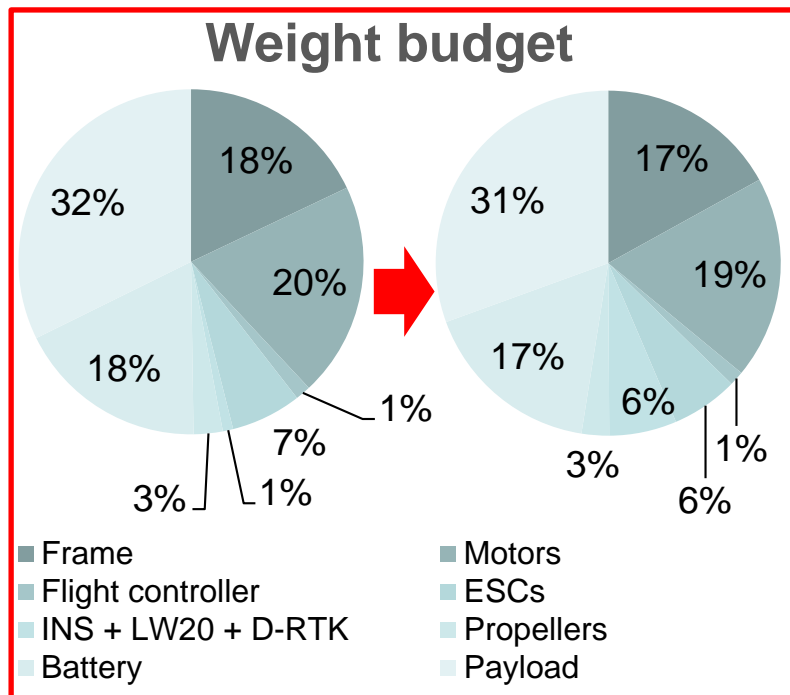
Measurement uncertainty budget (3)

- 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.
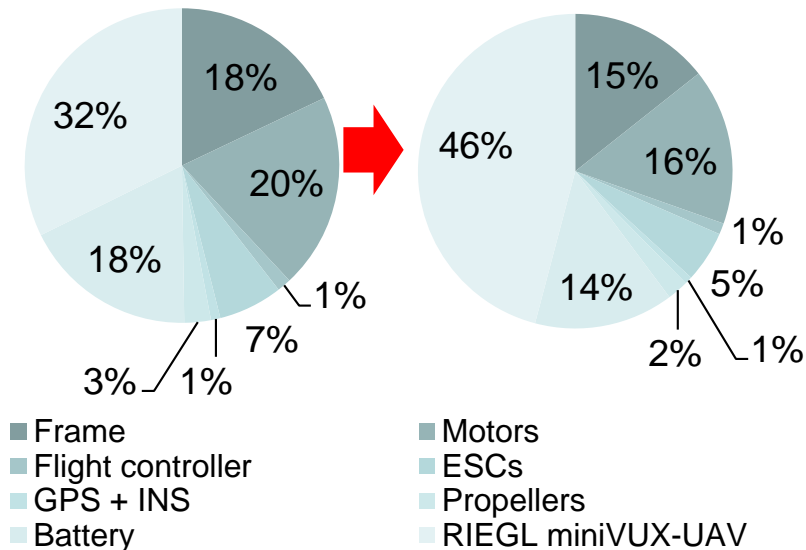
Balance among budgets (1)

What?	How?	Effect
Reduction of the drone pose measurement uncertainty	Integration of a LIDAR altimeter (LW20) and GNSS (D-RTK)	Change of frame and motors

Weight budget
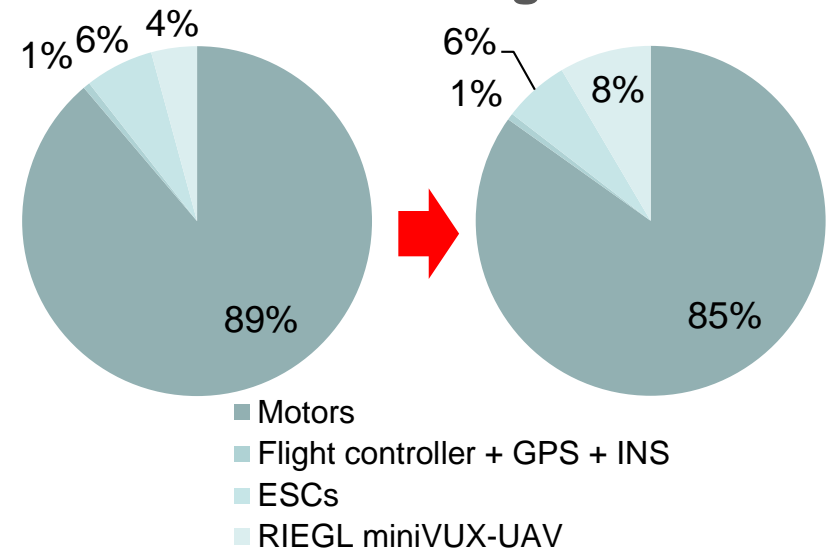

Legend:
- Frame
- Motors
- Flight controller
- ESCs
- INS + LW20 + D-RTK
- Propellers
- Battery
- Payload

Power budget

Legend:
- Motors
- Flight controller + INS + LW20 + D-RTK
- ESCs
- Payload

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Balance among budgets (2)

What?	How?	Effect
Reduction of the uncertainty related to mission measurement	Using of a LIDAR for 3D mapping (RIEGL miniVUX-UAV) against RGB camera	Change of frame and motors

Weight budget

Power budget

Legend (Weight budget):
- Frame
- Flight controller
- GPS + INS
- Battery
- Motors
- ESCs
- Propellers
- RIEGL miniVUX-UAV

Legend (Power budget):
- Motors
- Flight controller + GPS + INS
- ESCs
- RIEGL miniVUX-UAV

Drone-based measurement instrument design steps

According to the presented budgets, it is possible to define the steps for designing a drone-based measurement instrument:

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.
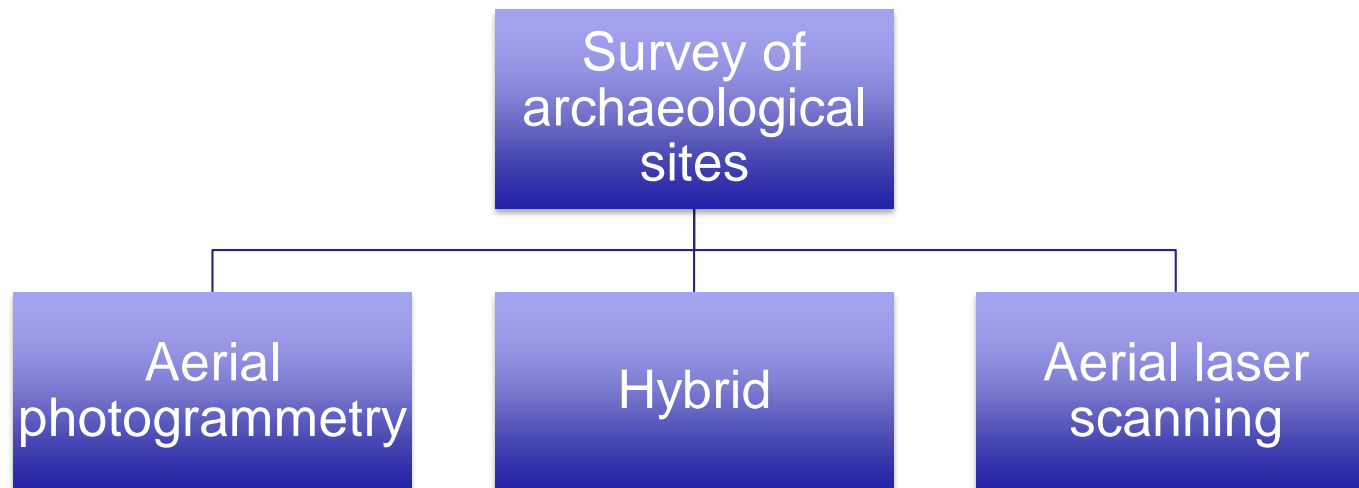
Case study: 3D mapping of archaeological sites

- The aim is to provide a 3D map containing geometrical measurements related to wide archaeological sites or archaeological sites with difficult access.

```
Survey of archaeological sites
├── Aerial photogrammetry
├── Hybrid
└── Aerial laser scanning
```

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Aerial photogrammetry

- In aerial photogrammetry, the 3D reconstruction is implemented by means of structure from motion.
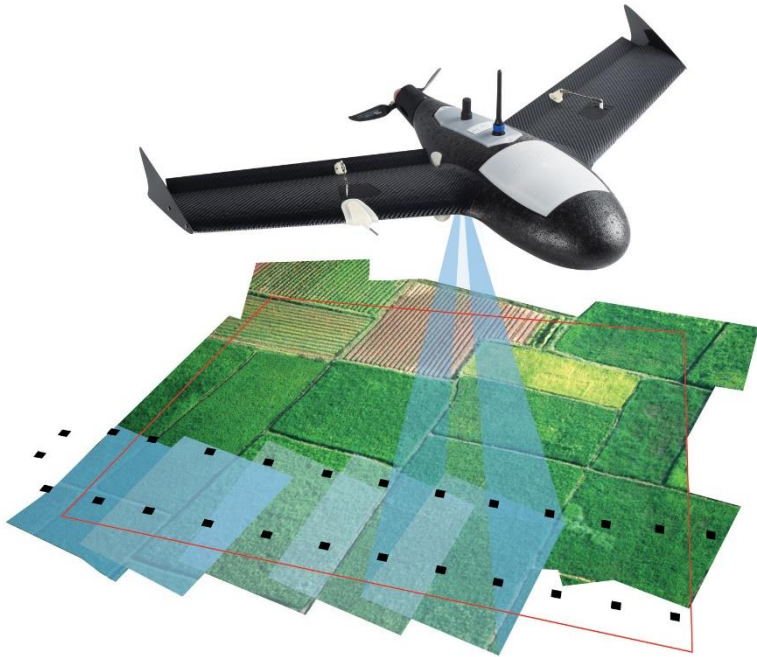
The structure from motion consists of observing objects from different positions.

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

Aerial laser scanning

An aerial laser scanning (ALS) system consists of a drone with embedded a LIDAR system.
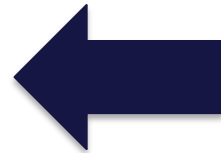
Hybrid

- This technique combines aerial, terrestrial photogrammetry and terrestrial laser scanning.
- In order to define the reference coordinates, several targets for each acquisition method are placed in the archaeological site and localized through a total station.
- The acquisition and processing steps are: (i) localization of the targets by means of total station, (ii) acquisition of the images with aerial photogrammetry, (iii) acquisition of the images with terrestrial photogrammetry, (iv) generation of the 3D models, and (v) 3D models integration.

3D models integration

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Comparison

	Accuracy	Sensing time	Processing time	Cost
Aerial Photogrammetry	Low	Low	Medium	Low
Hybrid technique	High	High	High	High
Aerial laser scanning	High	Medium	Low	Medium

- 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).

- Another important parameter for this specific application is the time required for the survey (**sensing time**).

3.a Uncertainty budget analysis (aerial photogrammetry)

- In case of aerial photogrammetry height has a higher uncertainty than the other dimensions.
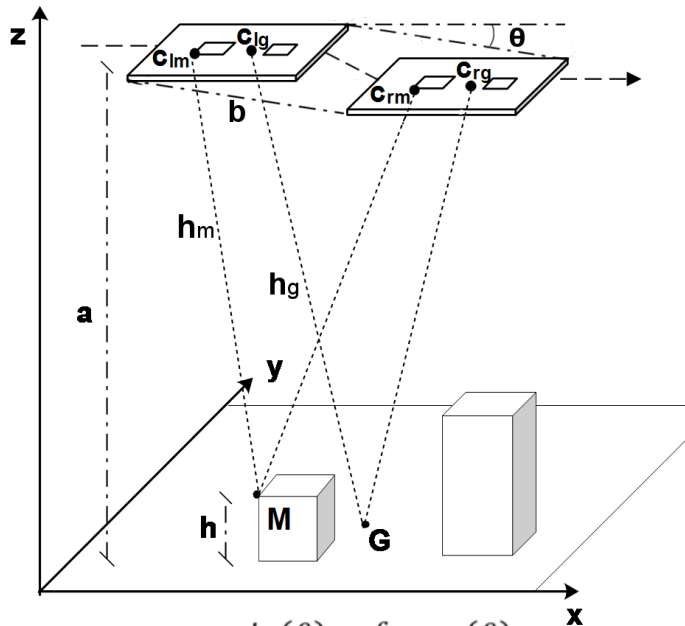
$$h_m = \frac{c_{rm} \cdot sin(\theta) - f \cdot cos(\theta)}{f \cdot (c_{rm} - c_{lm})} \cdot \left(f \cdot cos(\theta) - c_{lm} \cdot sin(\theta) \right) \cdot b$$

- h_m is the distance between the camera in the first waypoint and the point M;
- C_{lm} and C_{rm} are the pixel projections of the point M on the camera sensor array in both left and right positions;
- C_{lg} and C_{rg} are the pixel projections of the ground level point G on the camera sensor array;
- ϑ is the drone elevation angle of drone in the second waypoint referred to the first;
- b is the distance between the positions related to image acquisitions;
- f is the camera focal length.

$$h = h_g - h_m = \frac{c_{rg} \cdot sin(\theta) - f \cdot cos(\theta)}{f \cdot (c_{rg} - c_{lg})} \cdot \left(f \cdot cos(\theta) - c_{lg} \cdot sin(\theta) \right) \cdot b - \frac{c_{rm} \cdot sin(\theta) - f \cdot cos(\theta)}{f \cdot (c_{rm} - c_{lm})} \cdot \left(f \cdot cos(\theta) - c_{lm} \cdot sin(\theta) \right) \cdot b$$

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

1

2

This

tern

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

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

In case of aerial laser scanning, the LIDAR provides the distance of each point respect to its z-axis. This measurement has to be aligned to

For achieving a target uncertainty in the order of 10 cm for a maximum flight altitude of 25 m:

- The maximum uncertainty related to the distance measurements has to be 10 mm;

- The maximum orientation, ϑ, uncertainty has to be 1° .

The uncertainty sources affecting measurements are:
- The uncertainty related to the distance measurements provided by laser;
- The uncertainties related to the measurements of the pitch and roll angles.

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

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

Image-based pose estimation

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

- Luminosity conditions;

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

- Wind conditions;

- Gimbal stability;

- The orientation uncertainty is 0.2° (max. target 10°).

- Background texture conditions.

In case of aerial laser scanning, the system provide in real-time at each waypoint the point cloud acquired by the LIDAR system.

https://www.lidarusa.com/

	RIEGL miniVUX-
Measurement distance uncertainty	3.5 cm @ 50 m
Scan rate	100 scans/s
Points per second	100 kpt/s

- The payload includes a LIDAR;
- The sensors for navigation are GPS and INS.

RIEGL mini VUX - UAV

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	X		X		X						X	
Telemetry	X		X		X						X	
Payload					X				X (camera)		X (camera)	

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6.a 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 (F330)	156 g
Flight controller + GPS + IMU (N3 DJI)	132 g
4 ESCs (DJI - E305)	108 g
4 Propellers (Z-BLADE 9450)	52 g
4 Motors (DJI – 2312E)	224 g
Tot.	925 g

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

Aerial laser scanning
Weight budget

LIDAR (RIEGL miniVUX-UAV)	1500 g
Hexarotor Frame (F550)	478 g
Flight controller + GPS + IMU (N3 DJI)	132 g
6 ESCs (DJI – E800)	258 g
6 Propellers (Z-BLADE – E800)	114 g
6 Motors (DJI – E800)	636 g
Tot.	3118 g

Takeoff weight 800 g/rotor with 4S LiPo
Max. total weight = 4800g.

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

Aerial photogrammetry
Power consumption budget

Gimbal + camera (Zenmuse X4S)	5 W
Flight controller + GPS + IMU (N3 DJI)	5 W
4 ESCs (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).

Aerial laser scanning
Power consumption budget

LIDAR (RIEGL miniVUX-UAV)	16 W
Flight controller + GPS + IMU (N3 DJI)	5 W
6 ESCs (DJI – E800)	400 W
6 Motors (DJI – E800)	
Tot.	421 W

By considering a flight time of 20 min, the capacity of the battery has to be about 9200mAh (4S-LiPo): 2 x 4600mAh (4S-LiPo).

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

Aerial photogrammetry

Gimbal + camera (Zenmuse X4S)	253 g	5 W
Quadrotor frame (F330)	156 g	
Flight controller + GPS + IMU (N3 DJI)	132 g	5 W
4 ESCs (DJI - E305)	108 g	200 W
4 Motors (DJI - E305)	224 g	
4 Propellers (Z-BLADE 9450)	52 g	
Battery 4500 mAh 4S LiPo	375 g	
Tot.	1300 g	210 W

Cost: $ 1,500 – $ 2,000
Estimated uncertainty: 0.16 m

Aerial laser scanning

LIDAR (RIEGL miniVUX-UAV)	1500 g	16 W
Hexarotor frame (F550)	478 g	
Flight controller + GPS + IMU (N3 DJI)	132 g	5 W
6 ESCs (DJI – E800)	258 g	400 W
6 Motors (DJI – E800)	636 g	
6 Propellers (Z-BLADE – E800)	114 g	
2 Batteries 4500 mAh 4S LiPo	750 g	
Tot.	3868 g	421 W

Cost: $ 15,000 – $ 20,000
Estimated uncertainty: 0.05 m

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