# Gun Launched Micro Air Vehicle for the Observation

www.isl.eu

AGENCE NATIONALE DE LA RECHERCHE ANR

**"Concepts, Systèmes et Outils pour la Sécurité Globale"**


## Project coordinator

P. Gnemmi, ISL (patrick.gnemmi@isl.eu)

## Scientific responsible

S. Changey, ISL

sebastien.changey@isl.eu

M. Boutayeb, CRAN

R. Lozano, HEUDIASYC

R. Syriani, SBG Systems SAS


## Public end users

## Private end user

# Participants to the Project

www.isl.eu

L. Bernard – C. Berner – S. Changey – F. Christnacher - P. Gnemmi
R. Kauffmann – A. Koehl – B. Martinez – A. Matwyschuk
K. Meder – E. Pecheur – C. Rey – E. Roussel – S. Schertzer
E. Sommer – S. Theodoulis - P. Wernert - P. Wey

M. Boutayeb – A. Drouot – B. Grandvallet
H. Rafaralahy – M. Zasadzinski

P. Castillo - I. Fantoni - R. Lozano - C. Chauffaut

A. Guinamard – R. Syriani

# Introduction



- **Growing interest in several countries for Micro Air Vehicles (MAV)**
  - reports to the European Community:
    - "25 Nations for an Aerospace Breakthrough, European Civil Unmanned Air Vehicle Roadmap", 2005
    - Frost and Sullivan, "Study Analysing the Current Activities in the Field of UAV", 2007
  - use of these machines flying without any pilot particularly well adapted to surveillance and detection operations on sensitive sites or in hostile environments

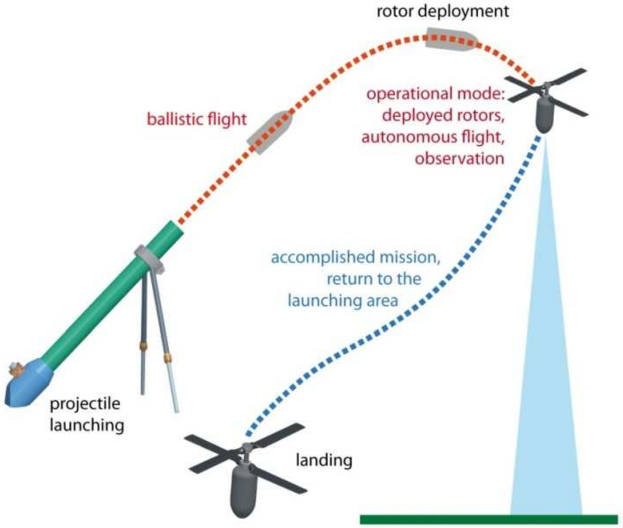
# Outline

- Concept of a Gun Launched Micro Air Vehicle
- State of progress of the project
- Conclusion
- Short-Term Future Work

# Concept of a Gun Launched Micro Air Vehicle (GLMAV)

- **What is the GLMAV ?**

- **GLMAV main characteristics**
  - 2 launching scenarios for an 80 mm projectile
    - 100 m of height, 100 m and 500 m of range
  - two coaxial contra-rotating rotors
    - rotor diameters: 25 cm
    - total mass: 0.6 kg expected → 1.1 kg presently
  - equipped with an autopilot
  - equipped with a system for detailed observation



# GLMAV Concept

www.isl.eu

- **Originality of the new ISL concept**
  - transformation of a projectile into a controlled vehicle
- **Advantages of a GLMAV compared to a classical MAV**
  - use of external energy
    - to bring the vehicle over the scene
  - very fast intervention
    - to be operational in a very short time
  - noiseless up to the operational mode (except the gun shot)
  - embedded equipment should resist to the launching acceleration
    - not comparable to a toy
    - rigid platform → hardening against wrong handling

# GLMAV Project

- **Conception, realization of a demonstrator for a hybrid projectile/MAV system**
  - 3 years from March 2010 up to March 2013
  - scientific/technical objectives
    - catching « stabilized » videos of an observed scene
  - scientific/technical hard points to be solved
    - resistance of the components to the acceleration
    - transient phase: transformation of the projectile into an MAV
    - autopilot: brain of the GLMAV
  - final product
    - demonstrator of a MAV launched from a dedicated tube and flying in real flight conditions

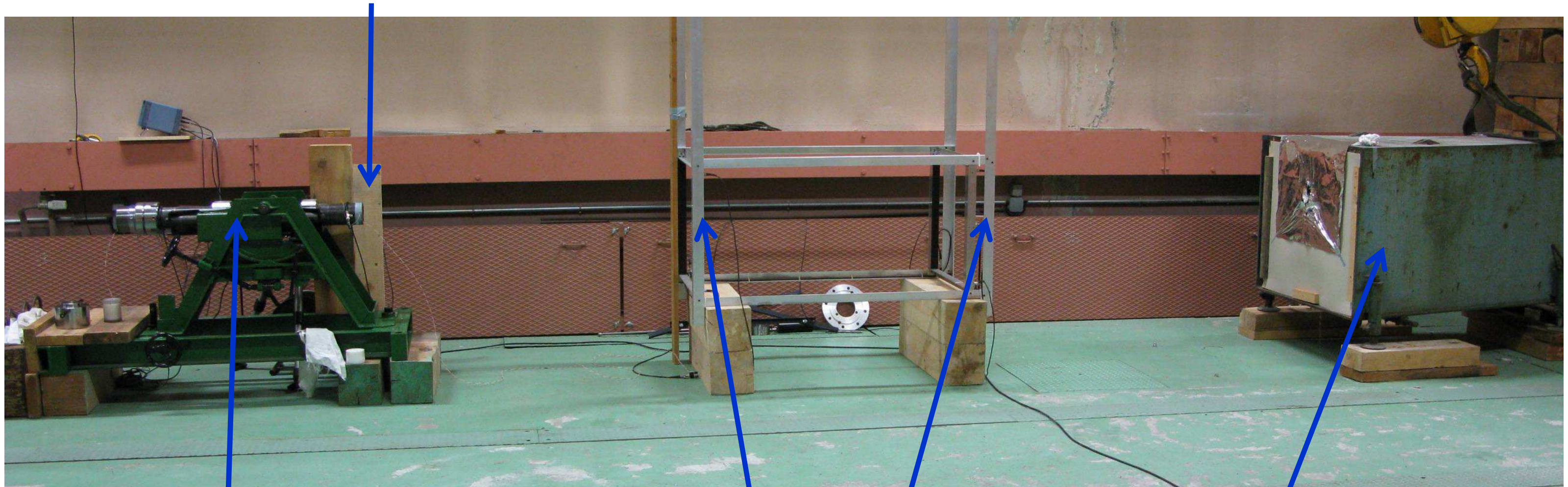
# Projectile Launcher

(WP 1, 1/10)

www.isl.eu

- **Laboratory launcher for acceleration tests**
  - design, preliminary tests, projectile recovery system

Terma radar
10.511 GHz, 0.3 W



launcher 80 mm, 12 calibers long

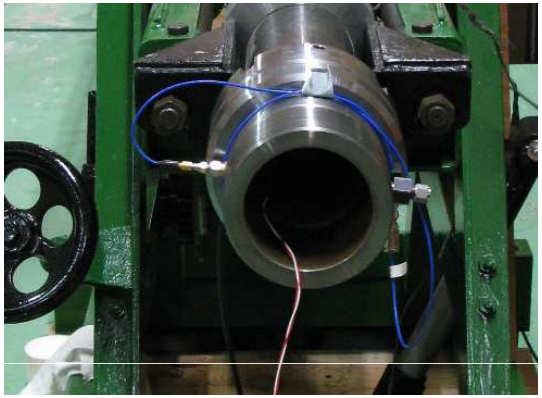
projectile recovery system

optical barriers

# Projectile Launcher (WP 1, 2/10)

www.isl.eu

- **Laboratory launcher for acceleration tests**
  - measurements
    - velocity
      - by radar and optical barriers
    - pressure
      - by Kistler 601H (0-1000 bar)
    - acceleration
      - by accelerometer PCB Piezotronics M350A13 (±10000 g's)

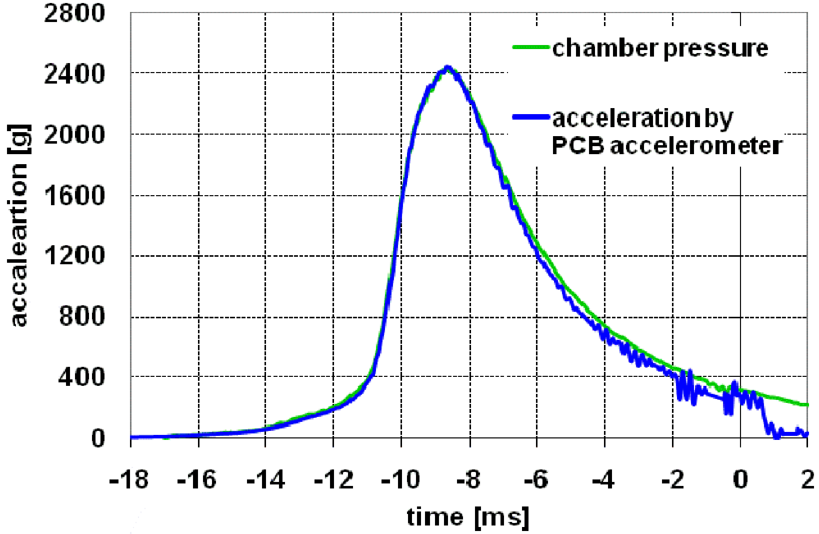


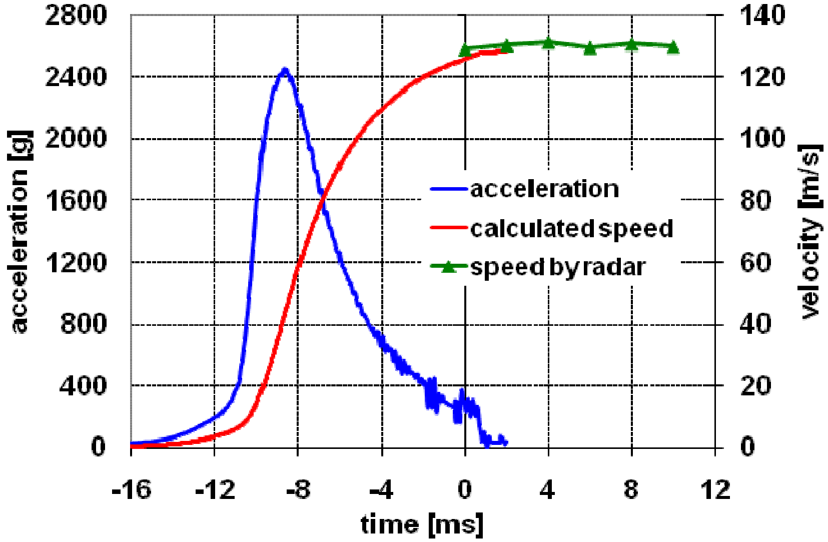
# Projectile Launcher

(WP 1, 3/10)

www.isl.eu

- **Laboratory launcher for acceleration tests**
  - performances



# Acceleration Tests

(WP 1, 4/10)

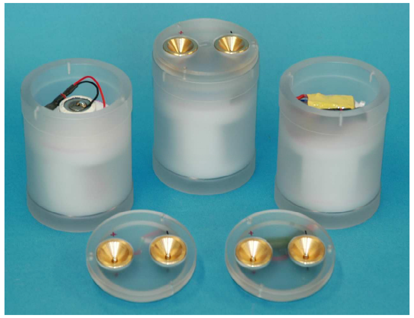


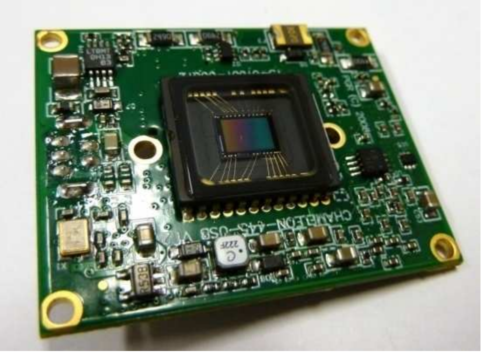
- **Status up to March 10$^{th}$, 2011**
  - a total of 36 acceleration tests
  - approach
    - 3 successive tests of all components for validating their robustness
    - no particular packaging due to the low acceleration level
  - acceleration range: 1710 to 3470 g's
  - velocity range: 97 m/s to 150 m/s

# Acceleration Tests (WP 1, 5/10)



- **Successful acceleration tests**
  - 3 different batteries, electronic boards (transmission and on-board computer), brushless motor and its regulator, servo-motor, camera without optical lens

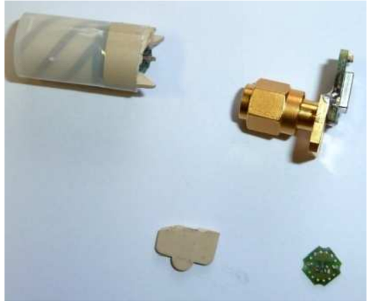



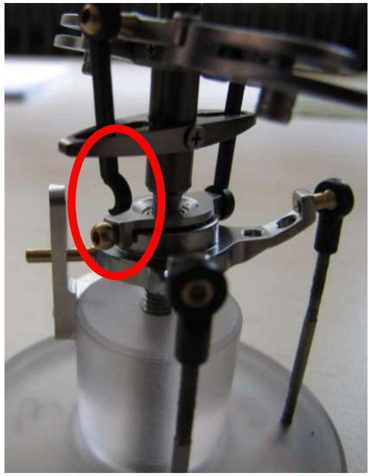
# Acceleration Tests

(WP 1, 6/10)



- **Not completely successful acceleration tests**
  - SBG Systems IMU
    - default on an accelerometer
    - enhancement in progress
  - GPS antenna
    - necessity of moulding
    - 1 satisfactory test
  - 1 connecting rod
    - broken at 3rd test
    - to be reconsidered





# Acceleration Tests



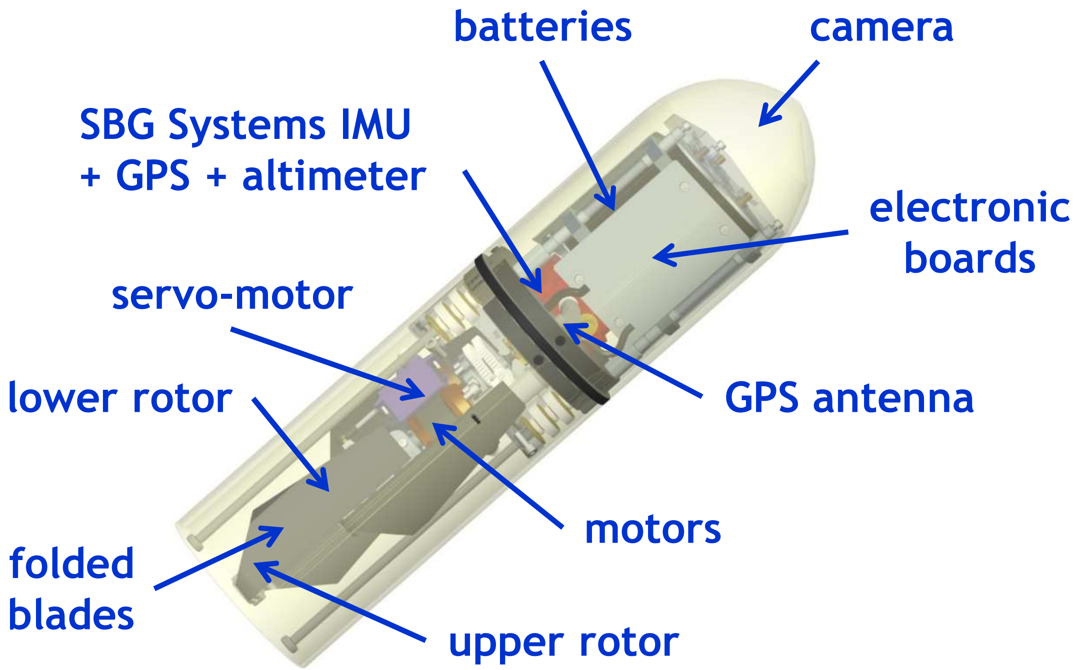


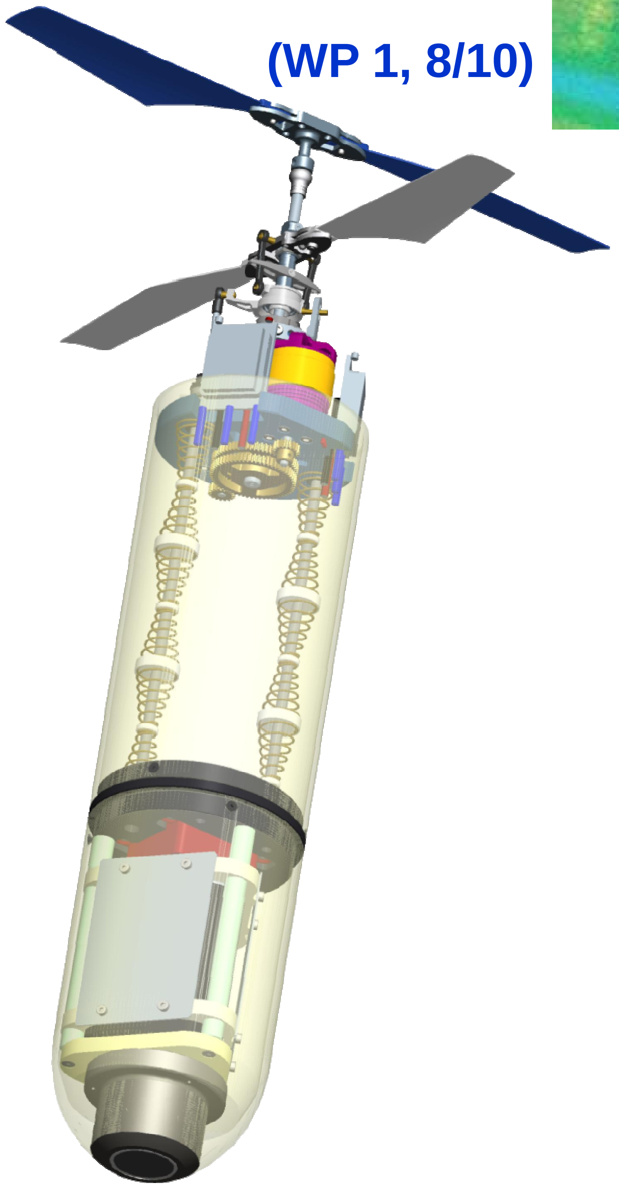
- **Main problems have been solved**
- **To be validated**
  - SBG Systems IMU
  - 2 tests for the GPS antenna
  - some supports
  - deployment system
  - complete mounted rotors

# Platform Design

(WP 1, 8/10)

- **Version V1.1**
  - will be tested in March 2011



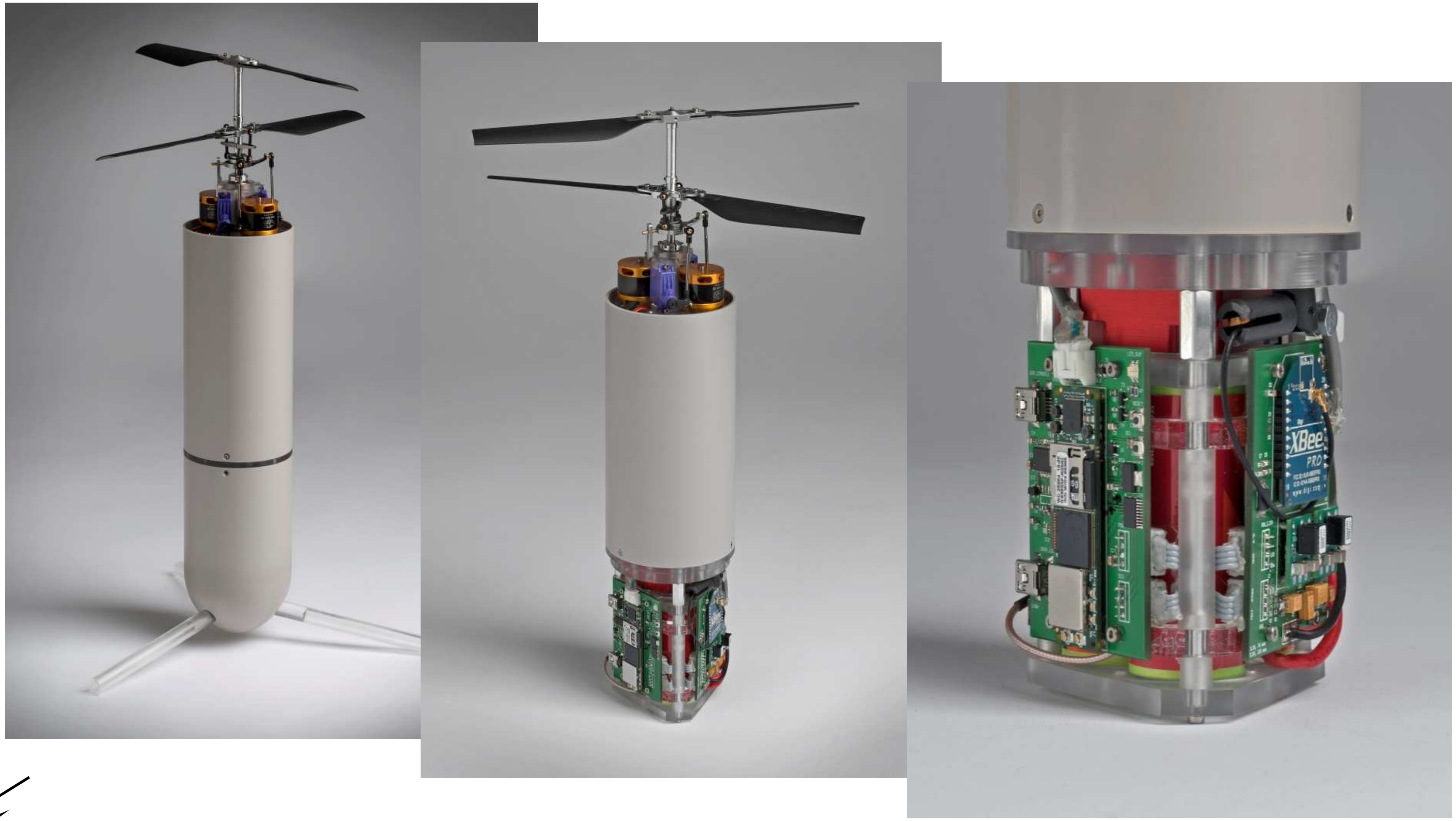



# Platform Design

(WP 1, 9/10)



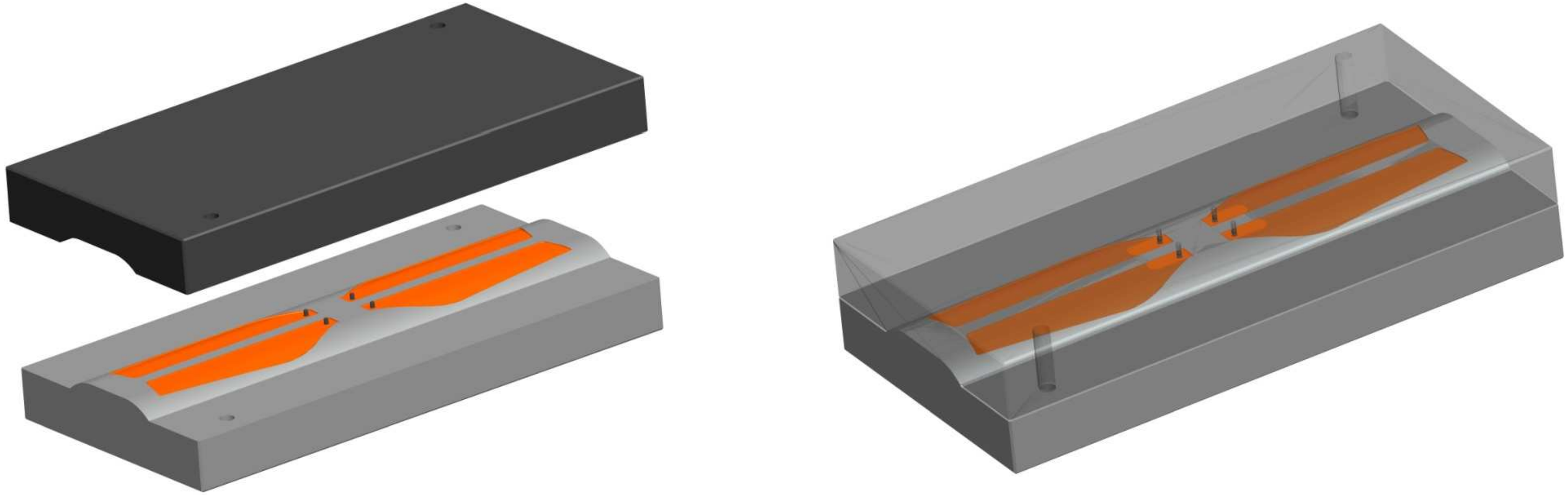
- **Realization of version V1.1**



# Platform Design

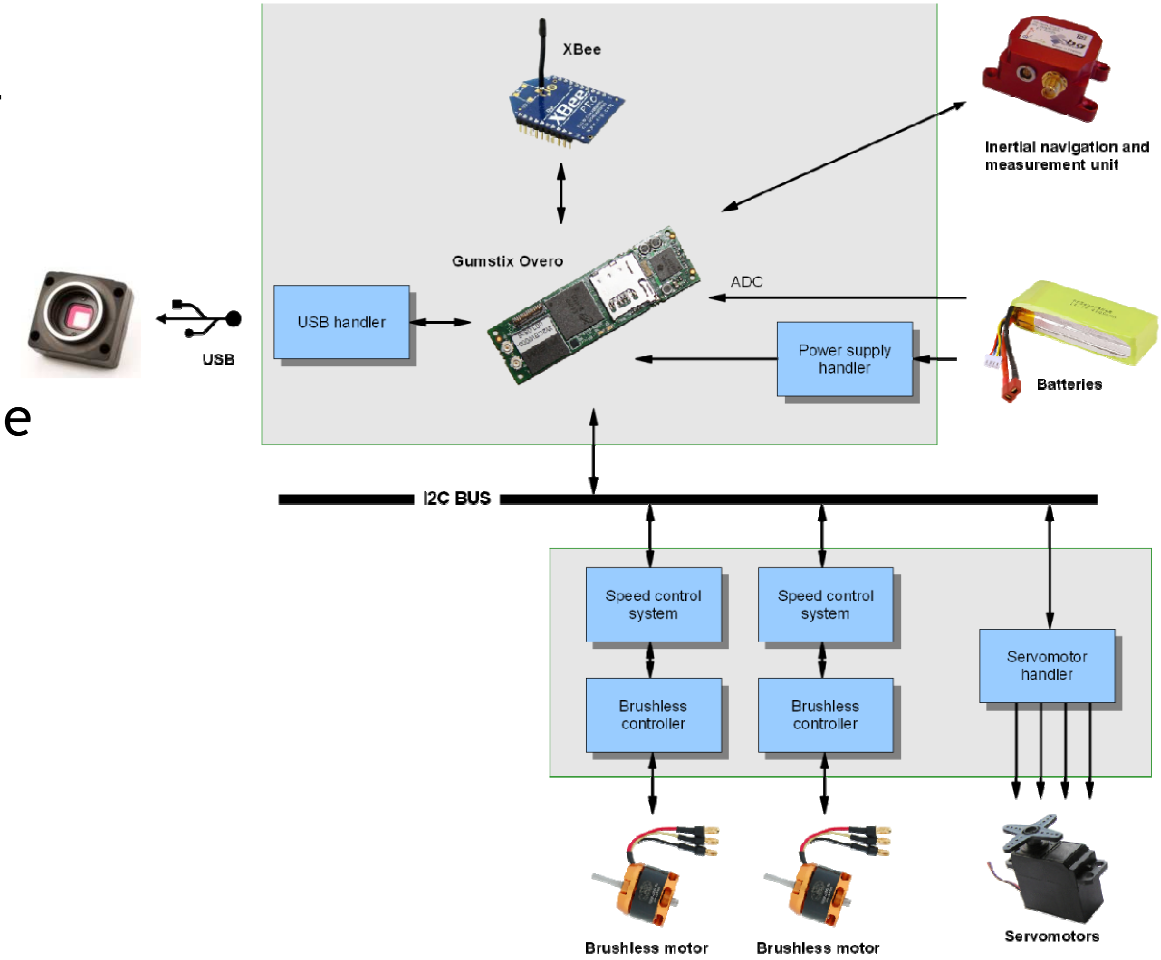
(WP 1, 10/10)

- **Mould for carbon-araldite composite blades**
  - design in progress
  - cooperation with HUNTSMAN — Enriching lives through innovation



# Embedded Autopilot Hardened Against Acceleration (WP 2-3, 1/4)

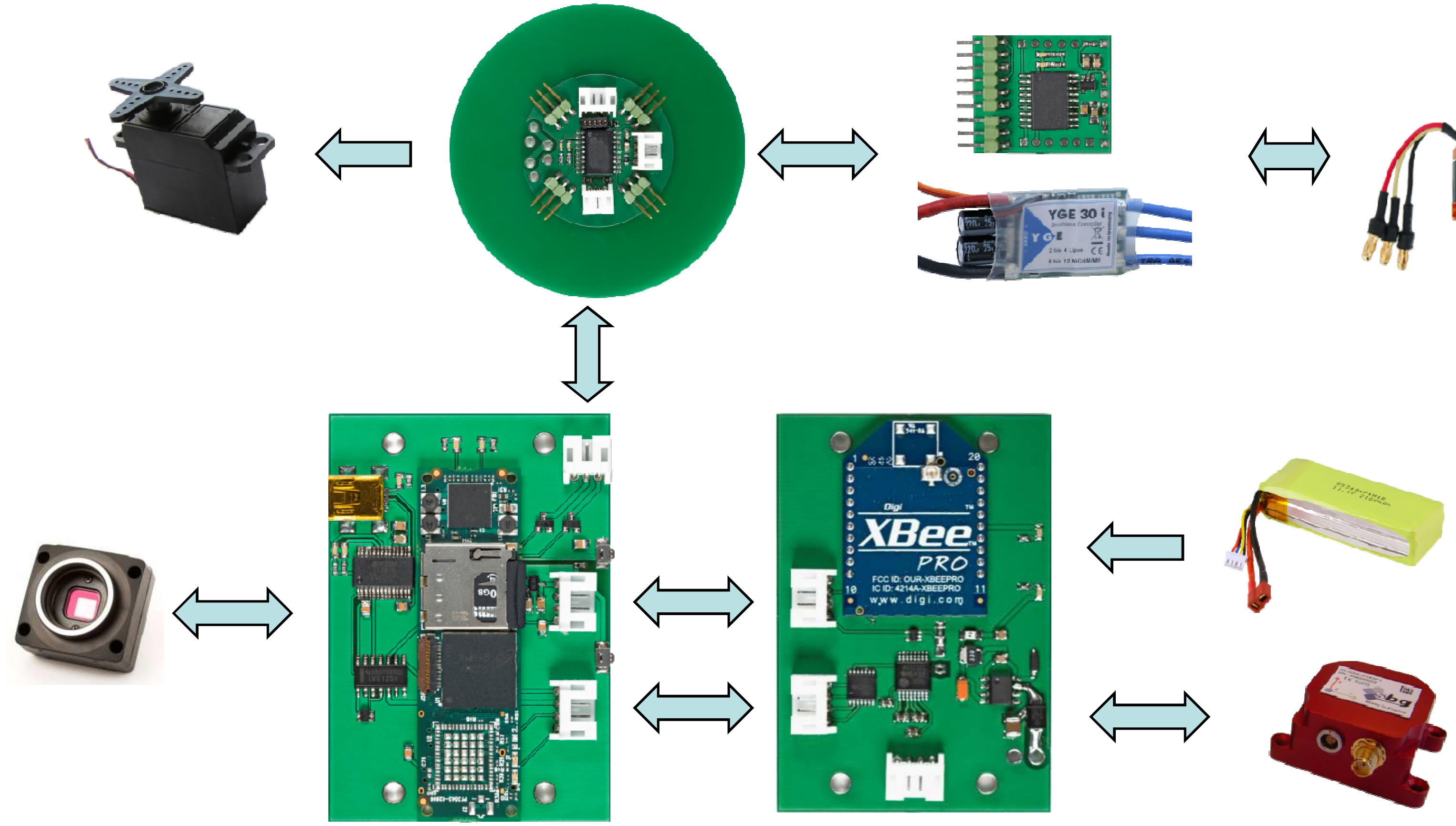
- **Man in the loop**
  - by remote control
  - by PC interface
- **Principle scheme**
  - on-board computation of the command laws



# Embedded Autopilot Hardened Against Acceleration (WP 2-3, 2/4)



- **Design of the electronic system**

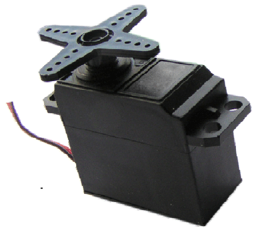


# Actuator Control

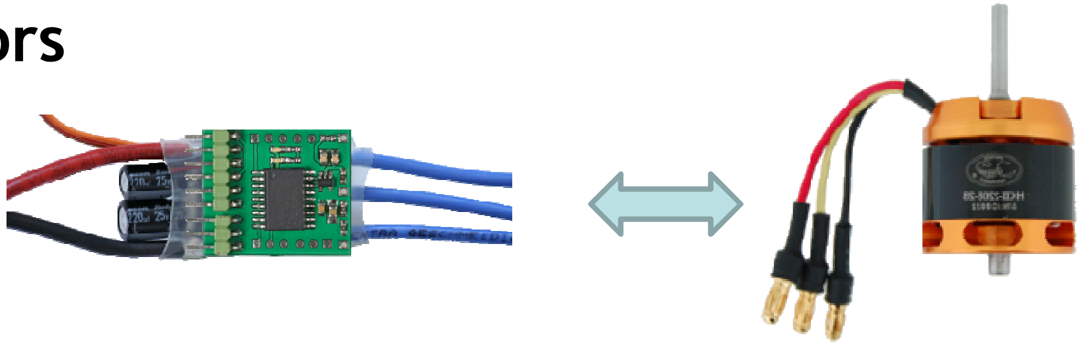
(WP 2-3, 3/4)



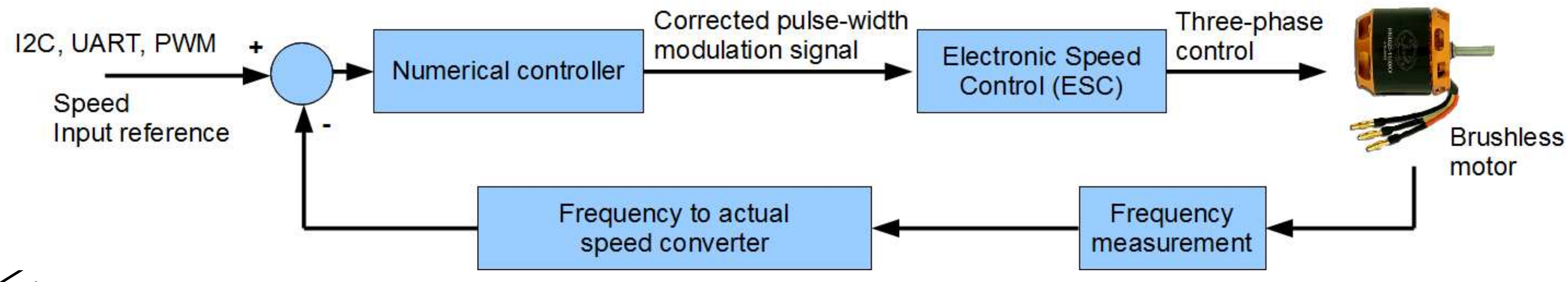
- **Servo-motors**
  - PWM signal



- **Brushless motors**
  - PWM signal

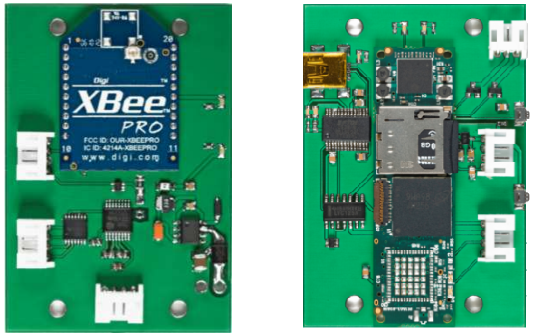


  - **automatic control of the motor speeds**

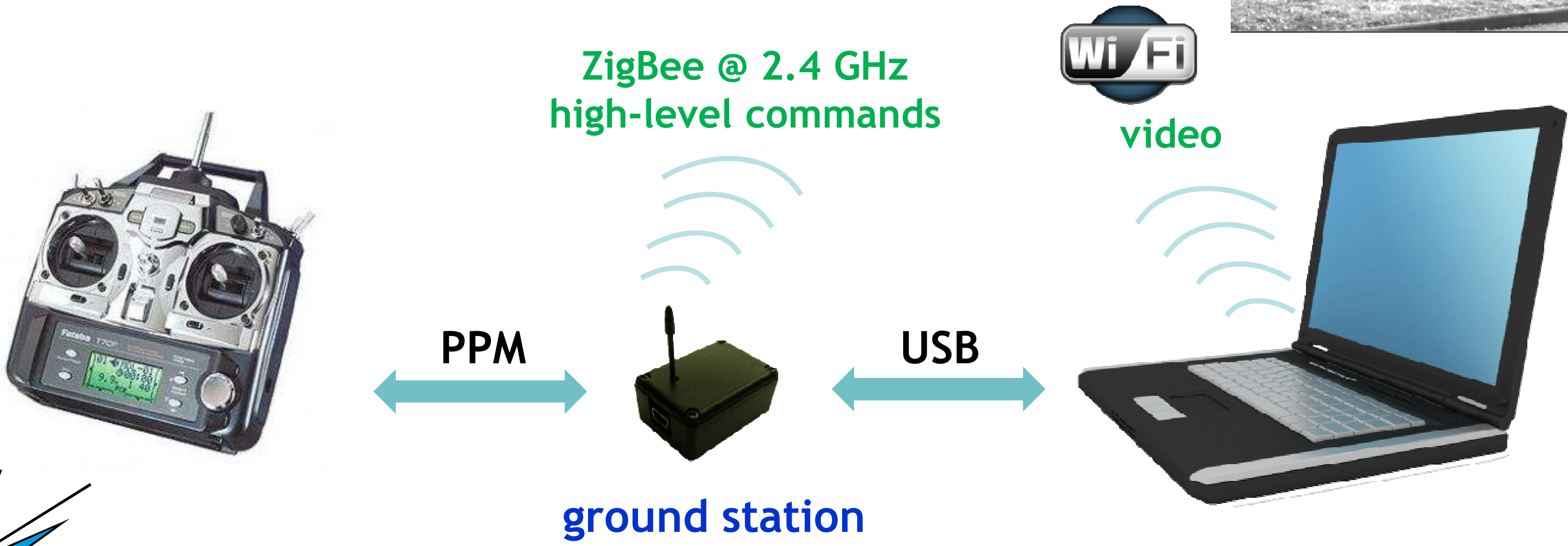


# Communication Interface (WP 2-3, 4/4)

- **Design of the ground station**
  - USB
  - Wireless



on-board modules

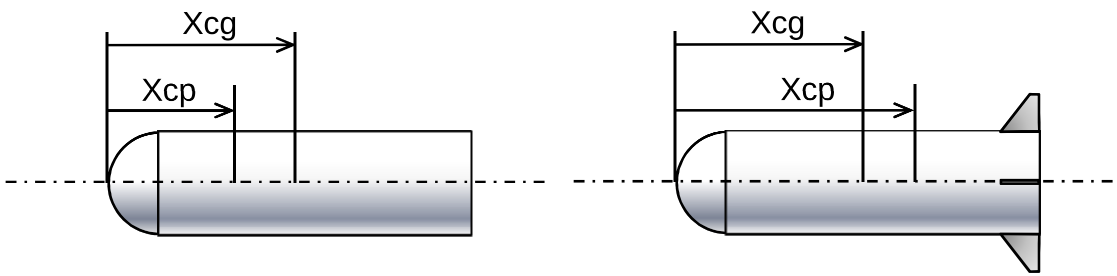



# Ballistic Flight Phase

- **Projectile data**

Pro-Engineer model

| spin-stabilized projectile | fin-stabilized projectile |
|---|---|




| body alone: | | |
|---|---|---|
| | D | 80 mm |
| | L | 309 mm |
| | m | 0.957 kg |
| | Xcg | 1.725 cal |
| | Ix | 6.68e-04 $kg.m^2$ |
| | It | 4.57e-03 $kg.m^2$ |

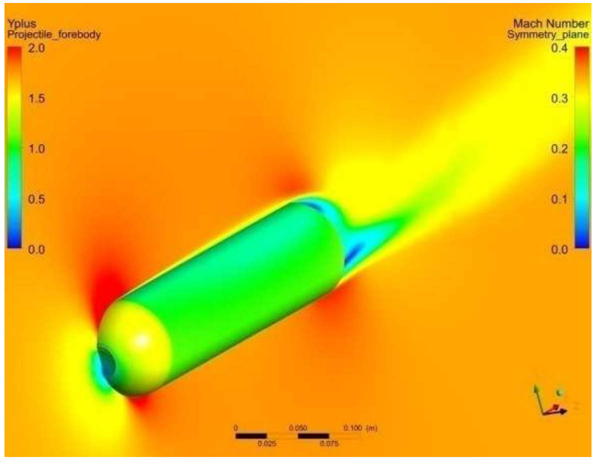
# Ballistic Flight Phase



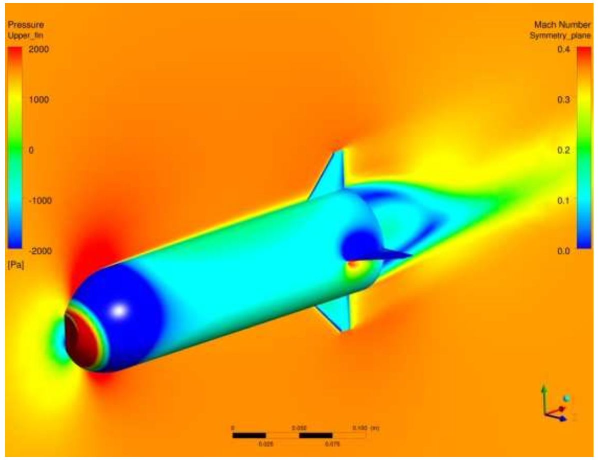


- **RANS numerical simulation, ANSYS CFX**

spin-stabilized projectile




fin-stabilized projectile




| M = 0.357 | spin-stabilized projectile | | | | fin-stabilized projectile | | | |
|---|---|---|---|---|---|---|---|---|
| AOA° | CD | CLα | Xcp | CMα | CD | CLα | Xcp | CMα |
| 0 | 0.231 | | | | 0.237 | | | |
| 3 | 0.250 | 2.087 | 0.942 | 1.831 | 0.251 | 4.055 | 2.101 | -1.612 |
| 6 | 0.296 | 1.983 | 0.891 | 1.895 | 0.287 | 4.037 | 2.104 | -1.623 |

# Ballistic Flight Phase



- **Stability analysis**
  - gyroscopic stability condition: $S_g > 1$

$$S_g = \frac{2}{\pi}\left(\frac{p}{V}\right)^2 \frac{I_x^2}{I_t} \frac{1}{\rho_a D^3 C_{M\alpha}}$$

**where the spin p is determined by the rifling twist of the launcher**

  - dynamic stability condition: $S_g > \dfrac{1}{S_d(2 - S_d)}$

$$S_d = \frac{2\left(C_{L\alpha} + \frac{mD^2}{I_x} C_{Mp\alpha}\right)}{C_{L\alpha} - C_D - \frac{mD^2}{I_t} C_{Mq}}$$

→

**$S_g$ = 1.48**
**rifling twist = 15 calibers / revolution (11.83°)**
**V = [ 50, 100, 150 ] m/s → p = [ 42, 83, 125 ] Hz**

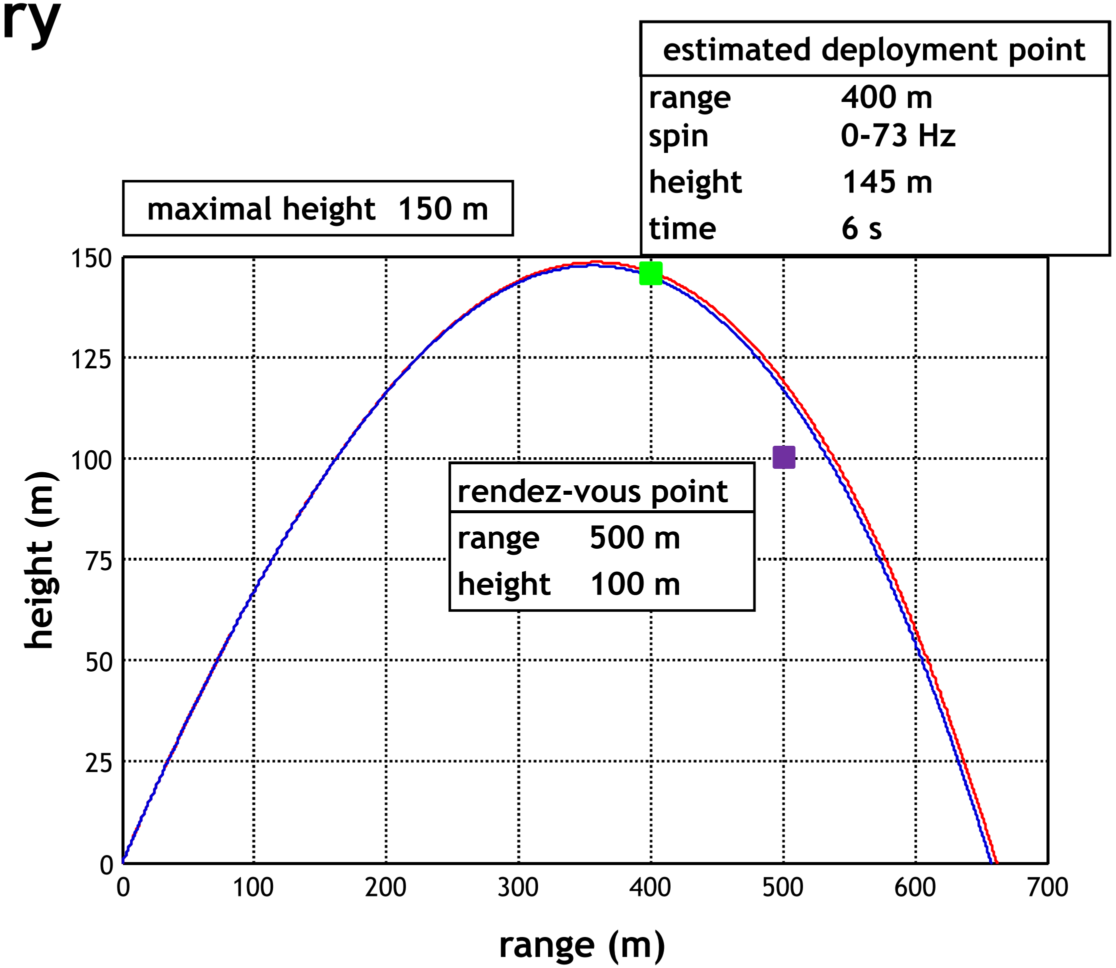
# Ballistic Flight Phase



- **Nominal trajectory**

## Initial conditions

| | | |
|---|---|---|
| | velocity | 100 m/s |
| | launching angle | 37 ° |
| ■ (red) | spin-stabilized | |
| | lateral deviation | 1.25 ° |
| | spin | 83 Hz |
| ■ (blue) | fin-stabilized | |
| | lateral deviation | 0 ° |
| | spin | 0 Hz |




trajectory in the vertical plane

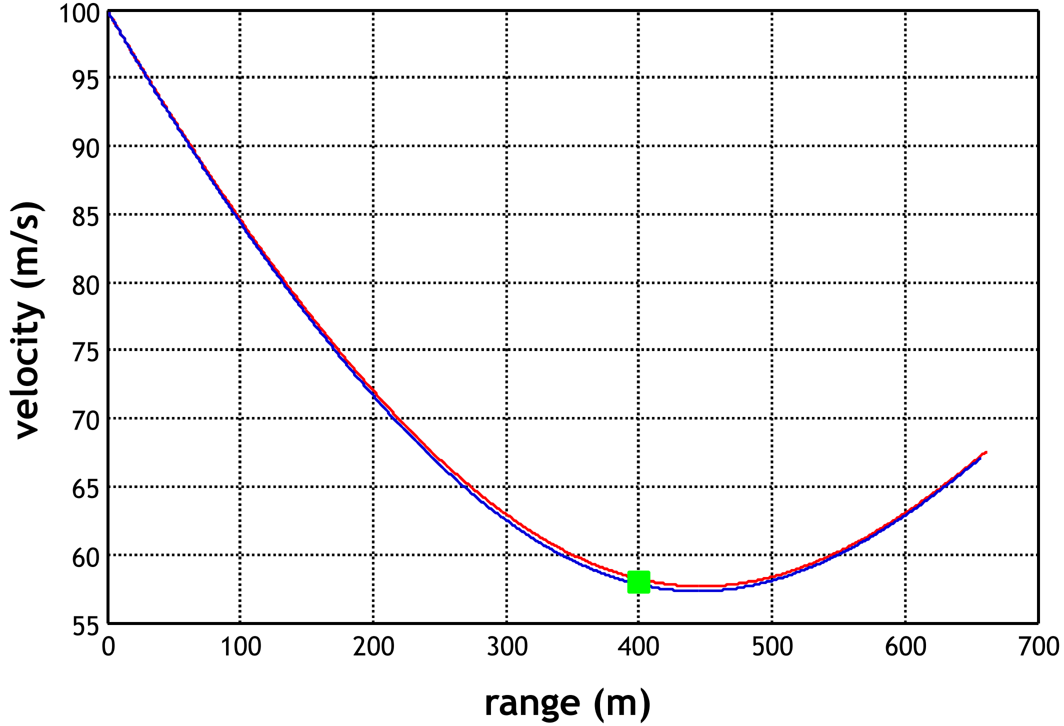
# Ballistic Flight Phase



- **Nominal trajectory**

**Initial conditions**

| | | |
|---|---|---|
| | velocity | 100 m/s |
| | launching angle | 37 ° |
| ■ (red) | spin-stabilized | |
| | lateral deviation | 1.25 ° |
| | spin | 83 Hz |
| ■ (blue) | fin-stabilized | |
| | lateral deviation | 0 ° |
| | spin | 0 Hz |




velocity versus range

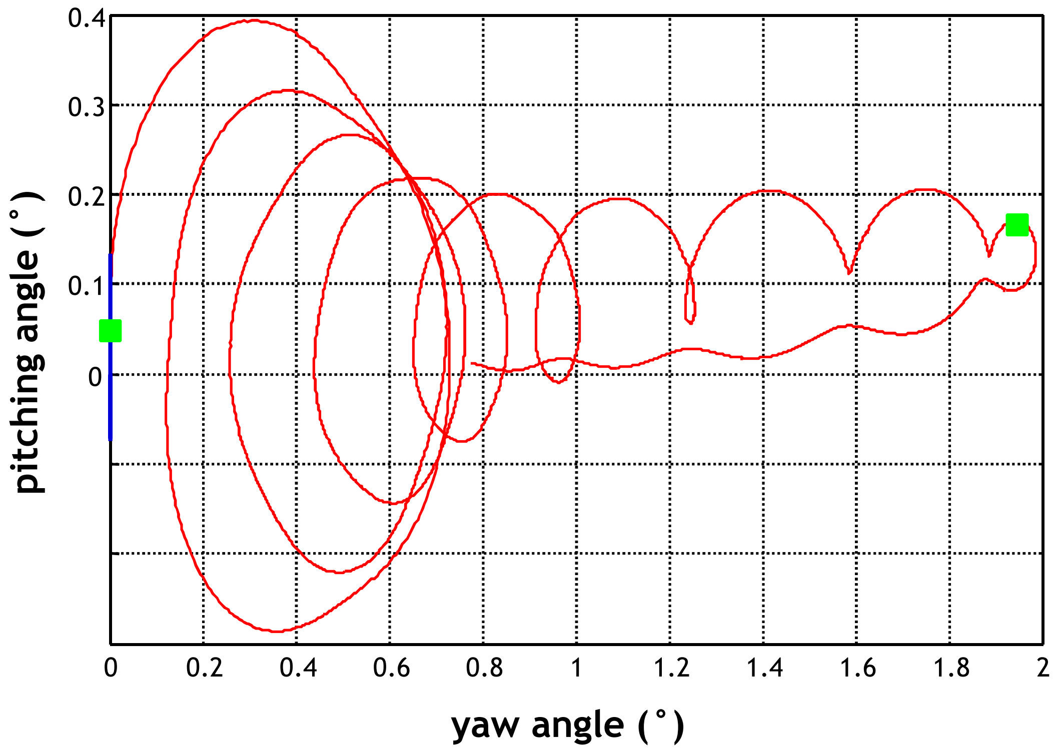
# Ballistic Flight Phase



- **Nominal trajectory**

**Initial conditions**

| | | |
|---|---|---|
| | velocity | 100 m/s |
| | launching angle | 37 ° |
| ■ (red) | spin-stabilized | |
| | lateral deviation | 1.25 ° |
| | spin | 83 Hz |
| ■ (blue) | fin-stabilized | |
| | lateral deviation | 0 ° |
| | spin | 0 Hz |




polar diagram of angle of attack

# Ballistic Flight Phase

(WP 4, 7/8)

www.isl.eu

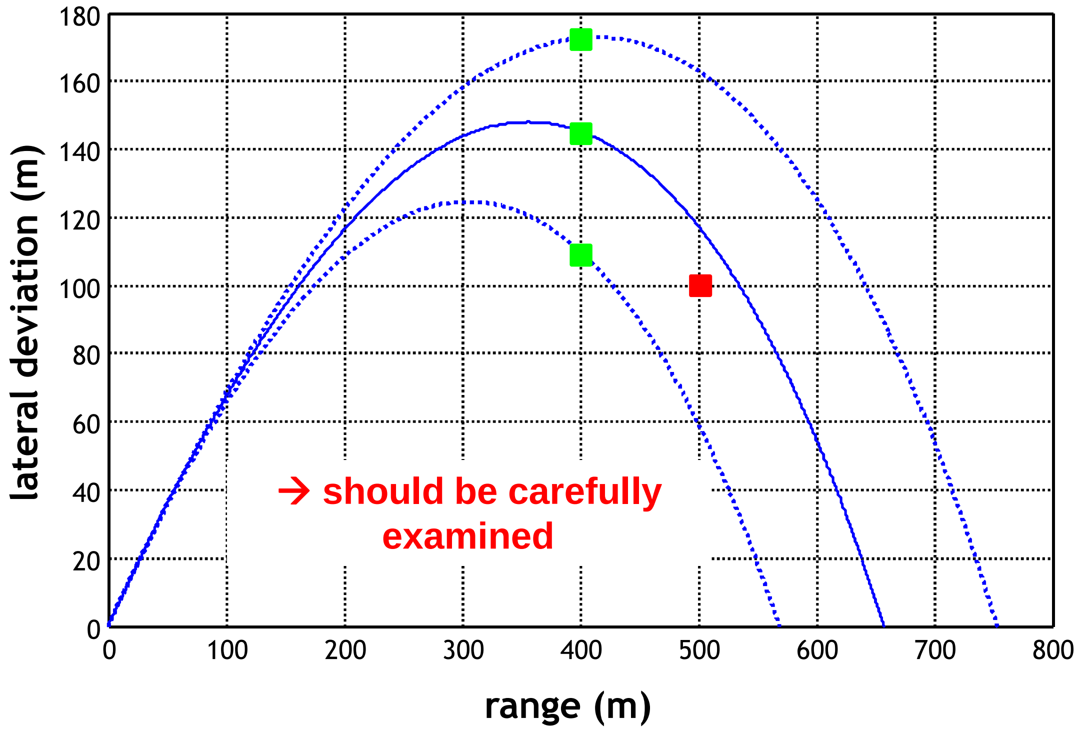
- **Perturbed trajectory**

## Initial conditions

| | |
|---|---|
| velocity | 100 m/s |
| launching angle | 37 ° |

| | |
|---|---|
| ■ fin-stabilized | |
| lateral deviation | 0 ° |
| spin | 0 Hz |

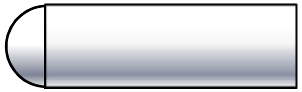
initial velocity: ± 10 m/s




trajectory in the vertical plane

# Ballistic Flight Phase (WP 4, 8/8)

- **Choice of the projectile**

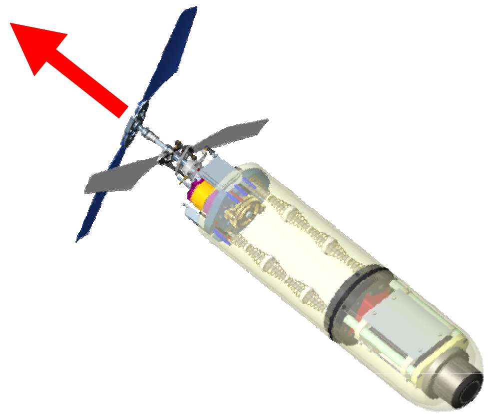


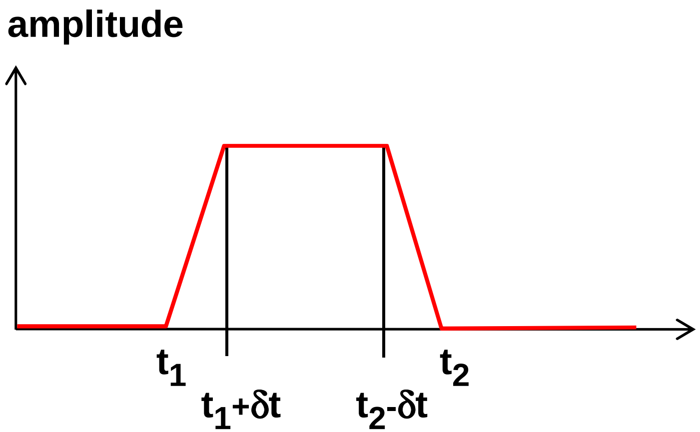
| | spin-stabilized projectile | fin-stabilized projectile |
|---|---|---|
| aerodynamic conception | + | – |
| launcher conception | – | + |
| weighted point trajectory | = | = |
| angular behaviour | – | + |
| sensitivity to perturbations | = | = |
| constraint at deployment point (spin) | – | + |
| **total** | **- -** | **+ +** |

# Transient Flight Phase



- **Theoretical approach**
  - transient phase modelling
    - initial conditions
      - fin-stabilized projectile
      - velocity 100 m/s
      - launching angle 37°
      - lateral deviation 0 °
      - spin 0 Hz
    - force for slowing down the projectile
      - axial constant force
      - starting at $t_1$
      - stop at $t_2$ → quasi-zero velocity
      - transient effects during $\delta t$
    - aerodynamics of the rotors
      - not considered yet





# Transient Flight Phase



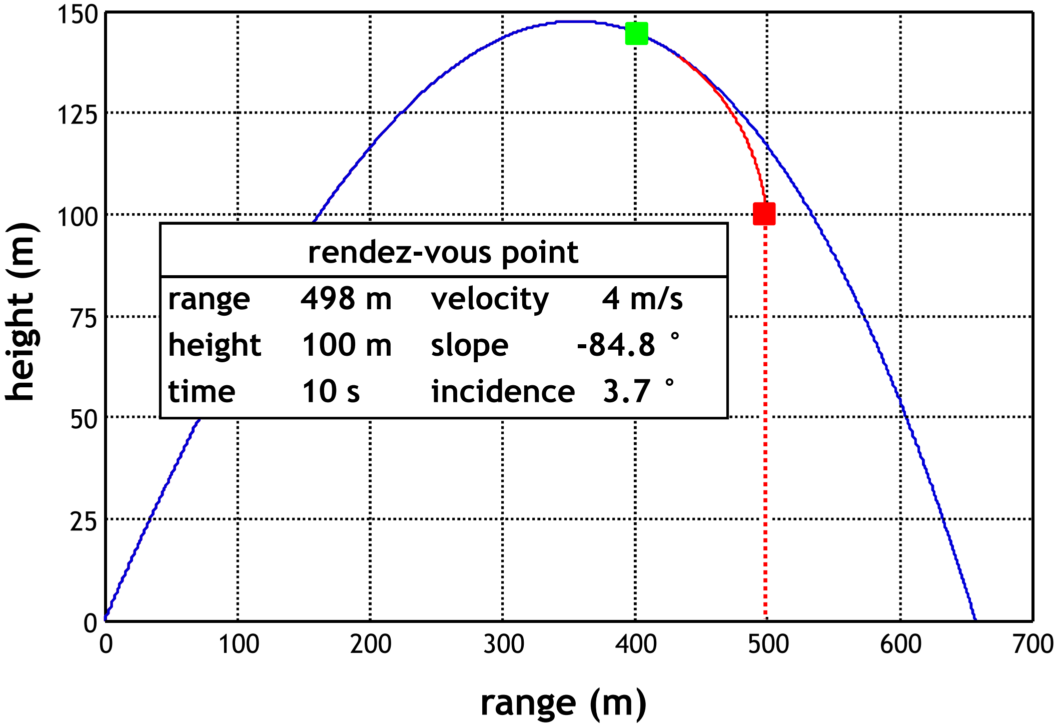


- trajectory with deployment

  - trajectory without deployment (blue)
  - trajectory with deployment (red)

| deployment point | | | |
|---|---|---|---|
| range | 407 m | velocity | 57 m/s |
| height | 144 m | slope | -8.2 ° |
| time | 6.1 s | incidence | 0.06 ° |

| thrust force | |
|---|---|
| amplitude | 18.3 N |
| $t_1$ | 6.1 s |
| $t_2$ | 10.0 s |
| $\delta t$ | 0.1 s |




| rendez-vous point | | | |
|---|---|---|---|
| range | 498 m | velocity | 4 m/s |
| height | 100 m | slope | -84.8 ° |
| time | 10 s | incidence | 3.7 ° |

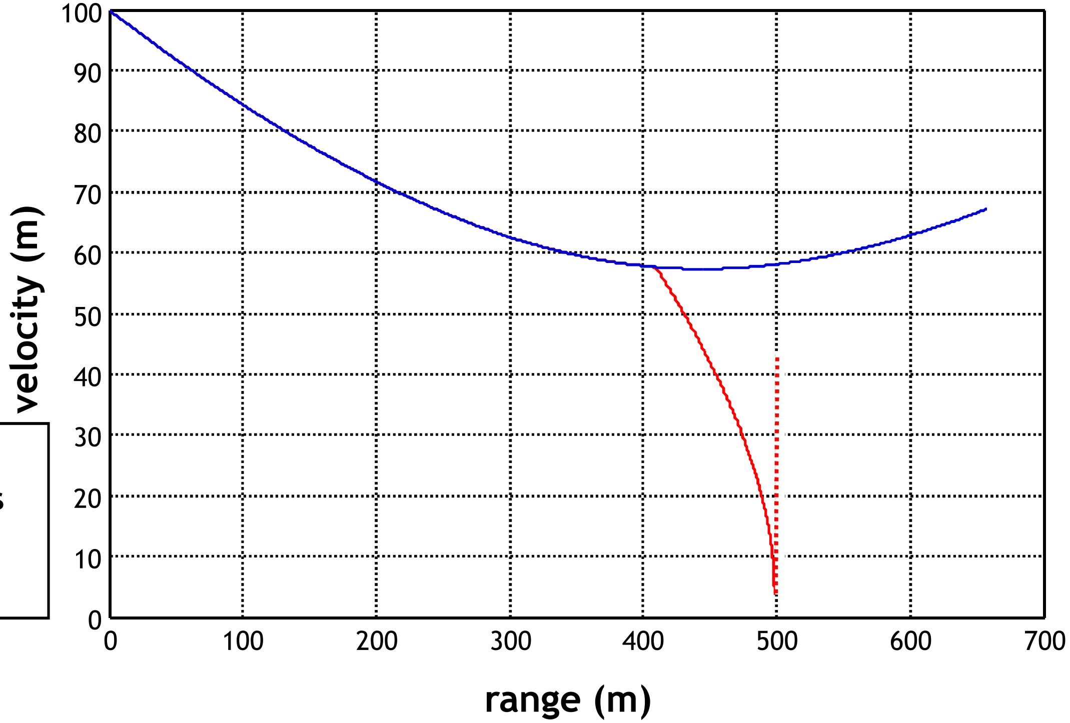
trajectory in the vertical plane

# Transient Flight Phase (WP 5, 3/5)



- trajectory with deployment

  - trajectory without deployment
  - trajectory with deployment




| rendez-vous point | | | |
|---|---|---|---|
| range | 498 m | velocity | 4 m/s |
| height | 100 m | slope | -84.8 ° |
| time | 10 s | incidence | 3.7 ° |

velocity versus range

# Transient Flight Phase (WP 5, 4/5)



- **Experimental approach**
  - simulation of that phase in the ISL subsonic wind tunnel
    - data acquisition for the modelling of the rotor deployment
  - optimization of the rotor deployment

# Transient Flight Phase



- **3-axis system for a kneecap connection**
  - will be tested soon


# Operational Flight Phase (WP 6, 1/5)

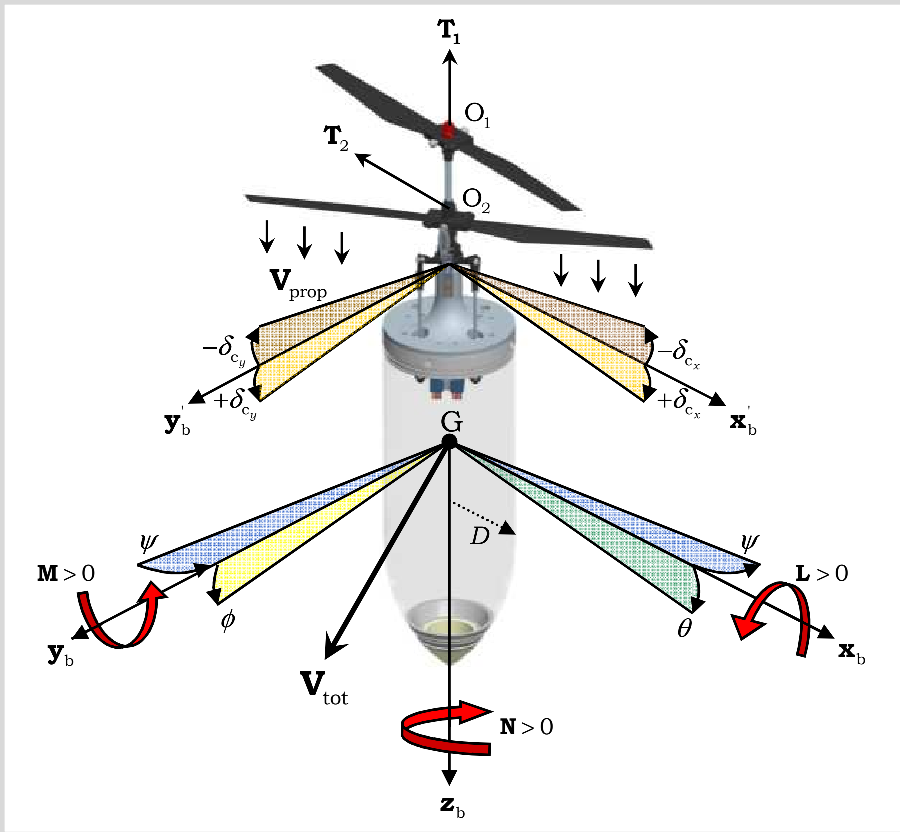


- **Hover and quasi-hover flights**
  - platform stabilization against wind gusts (< 10 m/s)
- **3 main steps**
  - modelling, identification and validation
    - modelling
    - identification of aerodynamic parameters
    - identification of linear velocity components
    - experimental validation
  - synthesis of command laws (in progress)
  - implementation on the prototype (not started)

# Operational Flight Phase (WP 6, 2/5)



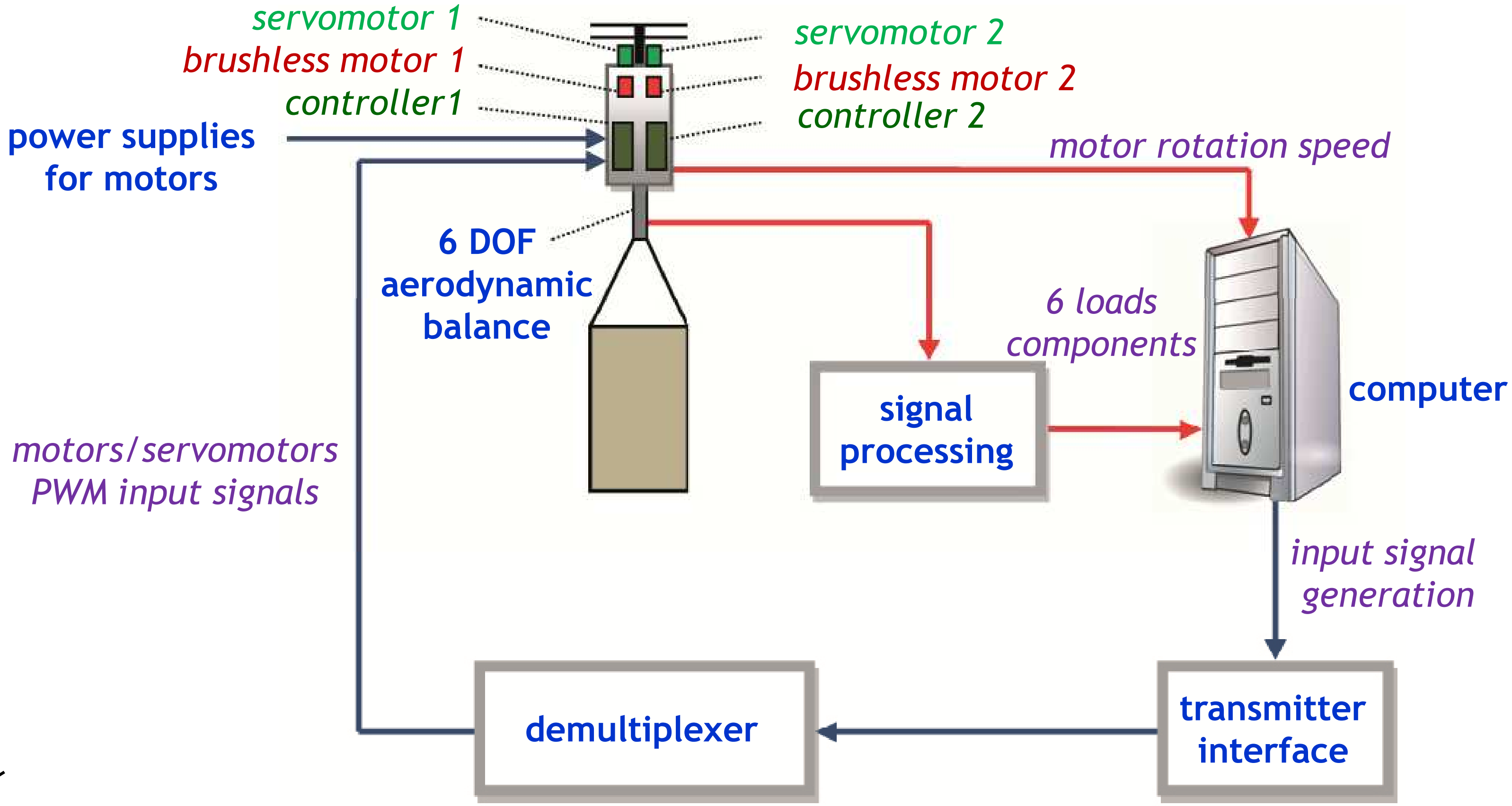
- determination of a mathematical model of the platform behaviour from measured input-output data




GLMAV modelling

# Operational Flight Phase (WP 6, 3/5)

- measurements of force and moment components as functions of rotor rotation speeds and swashplate angles



# Operational Flight Phase (WP 6, 4/5)



- measurements of force and moment components as functions of rotor rotation speeds and swashplate angles

simplified model

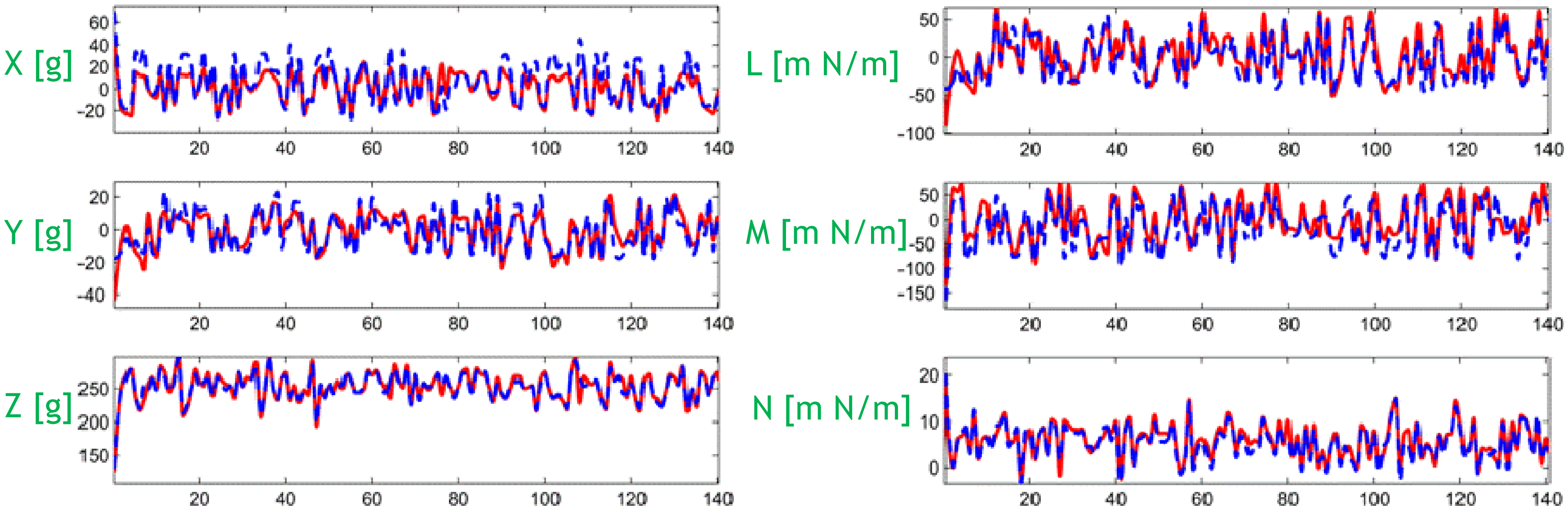

6 DOF aerodynamic balance

influence of a lateral airflow

# Operational Flight Phase (WP 6, 5/5)

- **Model validation**
  - force components
  - moment components

blue line: model output
red line: measurement



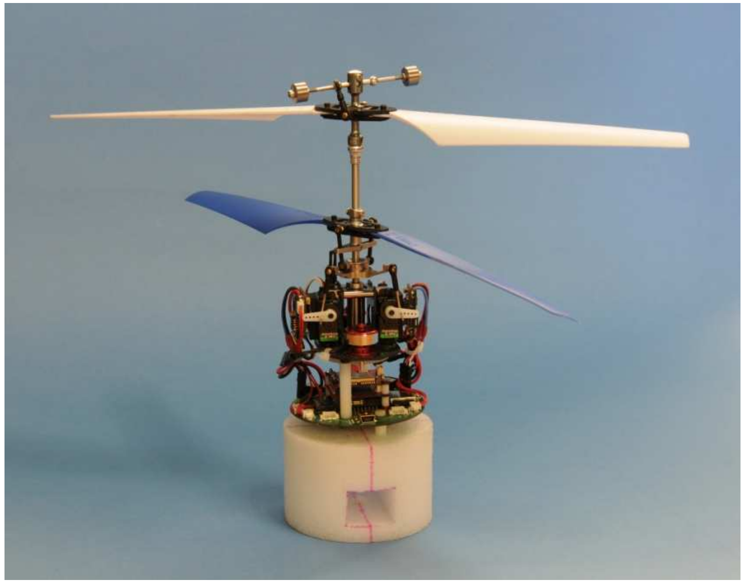
# Conclusions



- **Laboratory launcher and acceleration tests**
  - initial velocity 130 m/s, acceleration peak 2500 g
  - main components successfully tested
- **Embedded electronic system**
  - successful tests of each functionality
  - successful hardened against acceleration
- **Ballistic investigations**
  - technical difficulties for a spin-stabilized version, 80-100 Hz
  - choice of a fin-stabilized version for simplicity reasons

# Conclusions

- **Transient phase**
  - theoretical approach begun
  - special device available for subsonic wind-tunnel experiments
- **Operational phase**
  - first platform available for implementation of command laws



# Short-Term Future Work

- **Outdoor launcher for ballistic flights**
- **New acceleration tests for**
  - SBG Systems IMU, GPS antenna, some supports, deployment system, complete mounted rotors
- **Platform**
  - CFD computations for rotor optimization
  - laboratory tests for aerodynamic performance evaluation
  - reduction of mass
- **Embedded electronic system**
  - antenna tests
  - development of programs for the autopilot
  - fail safe to be studied

# Short-Term Future Work

- **Optical lens for camera**
  - to be defined soon
- **Ballistic investigations**
  - analysis of the fin-stabilized version will continue, if necessary
- **Transient phase**
  - theoretical investigations will continue
  - tests in wind tunnel will start soon
- **Operational phase**
  - tests will continue
  - theoretical investigations will continue in order to withstand wind gusts

# Dissemination

- **Symposia, publications**
  - WISG 2010, Troyes, January 2010, paper & poster
  - IMAV - EMAV 2010, Braunschweig, July 2010
  - AIAA Guidance Navigation & Control Conference, Toronto, Canada, August 2010, paper
  - 49th IEEE Conference on Decision and Control, Atlanta, USA, December 2010, paper
  - WISG 2011, Troyes, January 2011, paper & poster
- **Exhibition**
  - EUROSATORY, Villepinte, June 2010, poster & artificial model → paper in Janes Defence
- **Oral presentations with model presentation**
  - visit of "Brigade Franco-Allemande" (BFA), February 2011
  - visit of a DGA delegation, February 2011
  - visit of 23rd SERA (Session Internationale des Responsables d'Armement en Europe), Mars 2011

# Publications


- Gnemmi P., Haertig J., “Gun Launched Micro Air Vehicle: a New Concept for MAVs”, European Micro Air Vehicle Conference and Flight Competition (EMAV 2008), Braunschweig, Germany, July 8-10, 2008
- Gnemmi P., Haertig J., “Concept of a Gun Launched Micro Air Vehicle”, AIAA paper 2008-6743, 26th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, 18 - 21 August 2008,
- Gnemmi P., Koehl A., Martinez B., Changey S., Theodoulis S., “Modeling and Control of Two GLMAV Hover-Flight Concepts”, 4th Annual International Micro Air Vehicle Workshop and Flight Competition (IMAV 2009), Pensacola/FL, US, June 1-5, 2009
- Gnemmi P., Changey S., Boutayeb M., Lozano R., Siryani R., “Conception and Realisation of a Demonstrator for a Hybrid Projectile/MAV System (in French), Workshop Interdisplinaire sur la Sécurité Globale (WISG'10), Troyes, France, 26-27 January 2010
- Koehl A., Rafaralahy H., Martinez B., Boutayeb M., “Modeling and Identification of a Launched Micro Air Vehicle: Design and Experimental Results”, AIAA Guidance, Navigation and Control Conference, Toronto, Canada, 2-5 August 2010
- Koehl A., Boutayeb M., Rafaralahy H., Martinez B., “Wind-Disturbances and Aerodynamic Parameters Estimation of an Experimental Launched Micro Air Vehicle”, 49th IEEE Conference on Decision and Control, Atlanta, US, 15-17 December 2010
- Gnemmi P., Changey S., Roussel E., Meder K., Wey P., Bernard L., Martinez B., Boutayeb M., Lozano R., Siryani R., “Conception and Realisation of a Demonstrator for a Hybrid Projectile/MAV System (in French) – State of the Work after 8 Months”, Workshop Interdisplinaire sur la Sécurité Globale (WISG'11), Troyes, France, 25-26 January 2011