Design and testing of a vision based navigation system for a spacecraft formation flying simulator

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UNIVERSITÀ DEGLI STUDI DI PADOVA

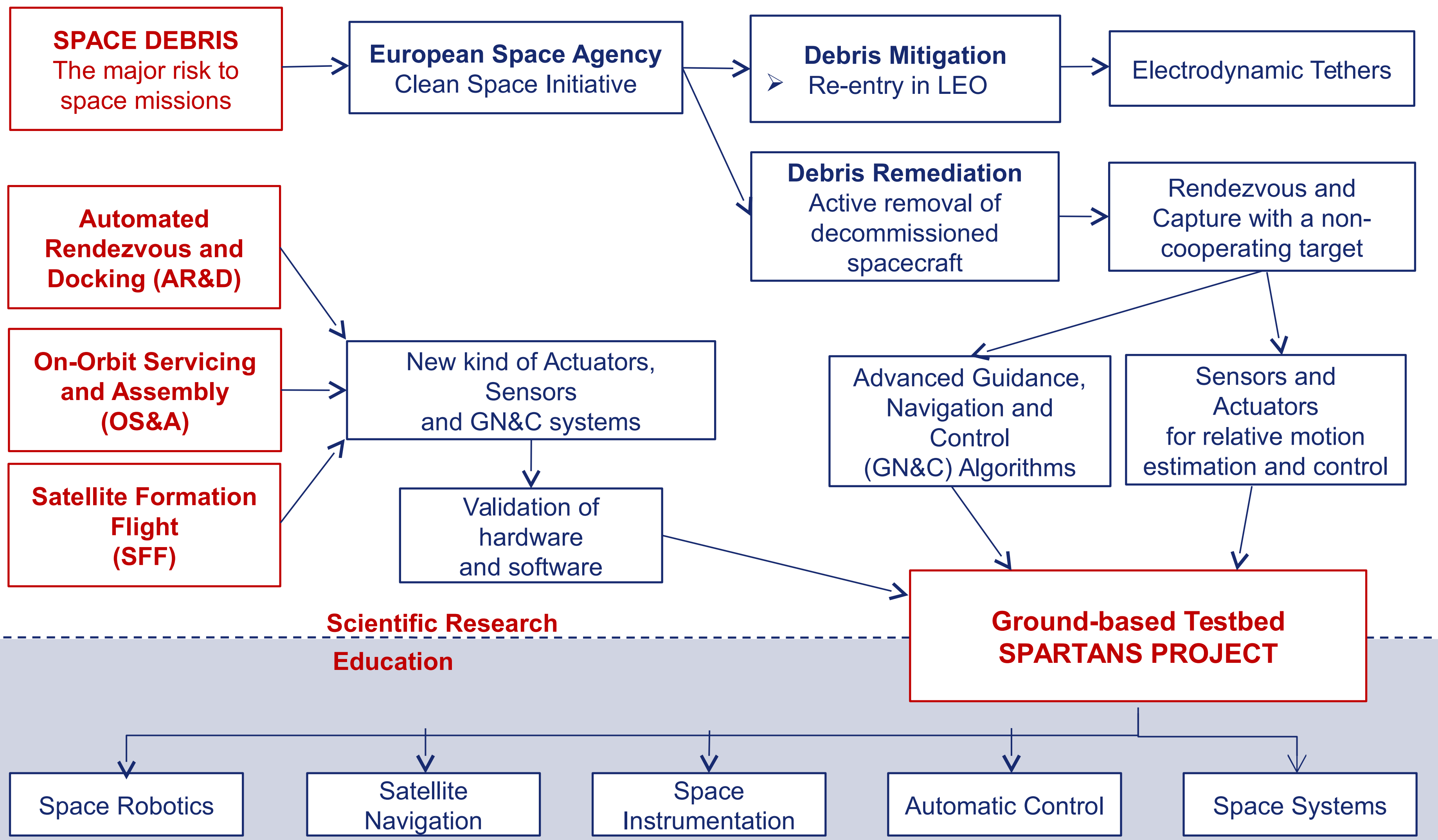
CISAS G. COLOMBO

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

Outline

- Motivation
- Metrological characterization of a monocular vision system for pose estimations
- Developement of a global navigation system for the SPARTANS testbed
- Stereoscopic vision-based navigation
- The PACMAN project

SPARTANS Project Motivation

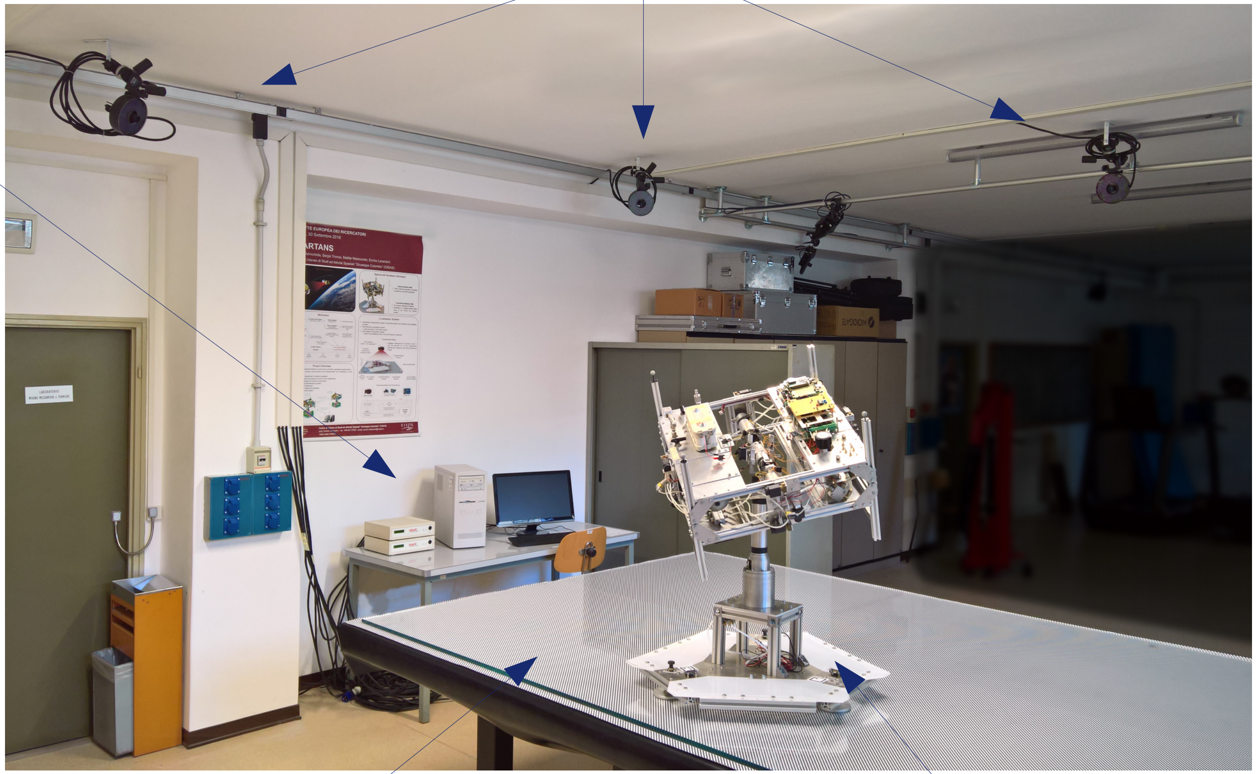


SPARTANS Project Overview

SPARTANS:
cooperating **SPA**cec**R**aft **T**estbed for **A**utonomous proximity operatio**N**s experiment**S**

IR cameras

Control station



Glass-covered flat surface

Spacecraft simulator

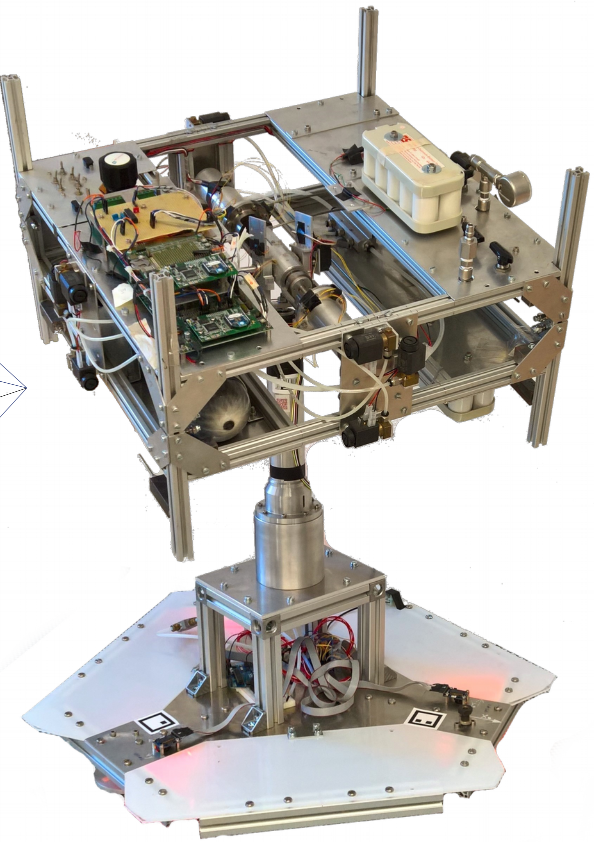
SPARTANS Project Overview

Structural subsystem

Avionics subsystem

Propulsion subsystem

Electric and Power subsystem



Attitude Module

Three rotational degrees of freedom provided by mechanical gimbals

Translational Module

Low-friction planar translations provided by an air cushion system

Structural subsystem

Pneumatic subsystem

On-board electronics

Characterization of a monocular vision system for proximity operations

Main objective

Estimation of the metrological performances of a monocular system for pose estimation in the context of cooperative spacecraft.

Procedure in 4 steps

Custom design of a set of fiducial markers

Development of a simplified satellite mock-up

Development of algorithms for image analysis and processing for measurement purposes

Uncertainty analysis of the metrological system following an experimental approach

Experimental approach

Known displacements can be imposed to the satellite mock-up employng a linear slide and a rotary motorized stage.

The pose of the target is sampled in 990 different configurations:

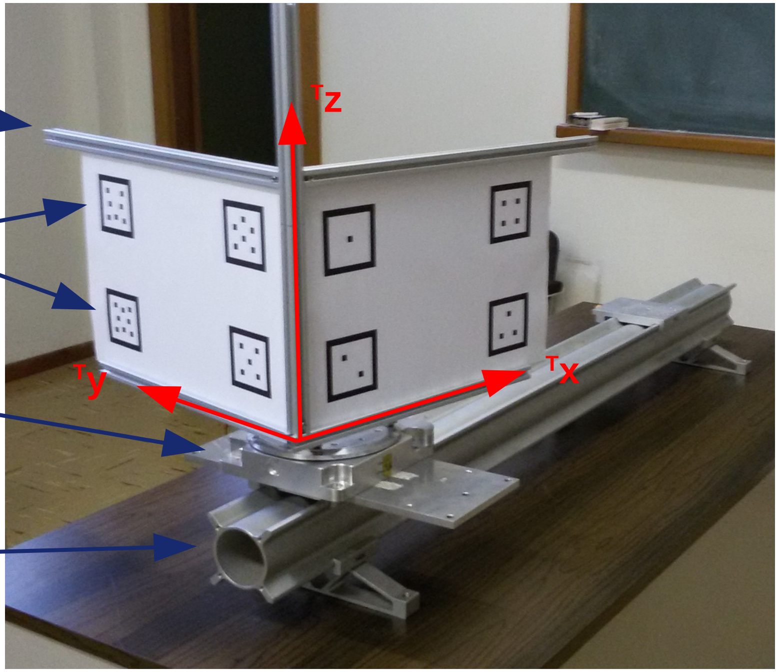
- 22 different positions along the linear with an axial step of 50 mm
- 45 different orientations for each position are imposed with a step of 2 deg

Satellite mock-up

Fiducial markers

Rotary stage

Linear slide



The vision based algorithm is employed to acquire measurement of the target pose.

Each estimation is then compared to the corresponding imposed configuration.

Pose estimation approach

Input:
acquired frames

Image processing and Pattern recognition

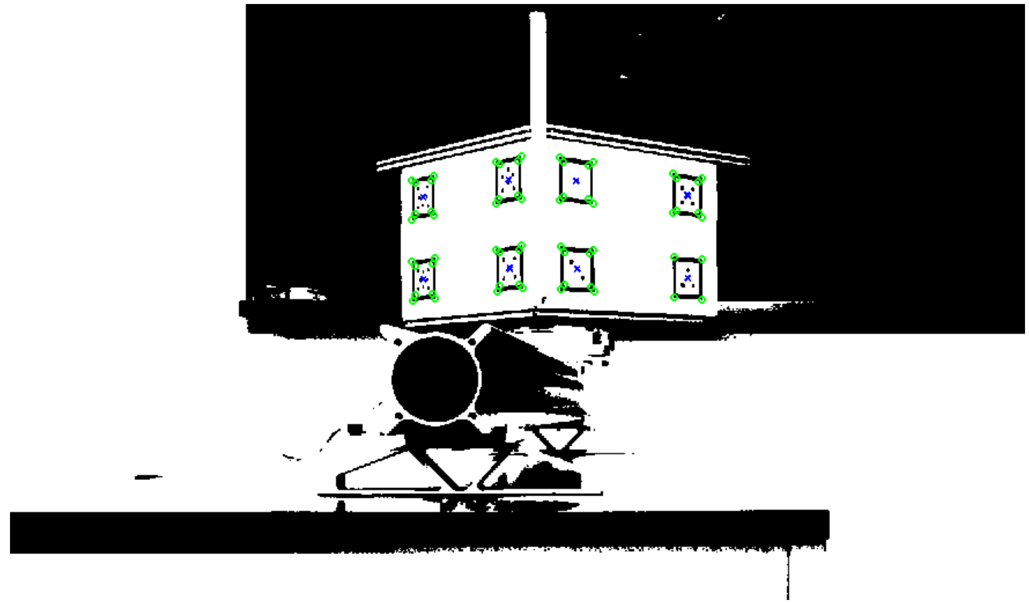
Up to 40 landmarks can be identified

Solution of the Perspective-from-3-Points Problem (P3P)

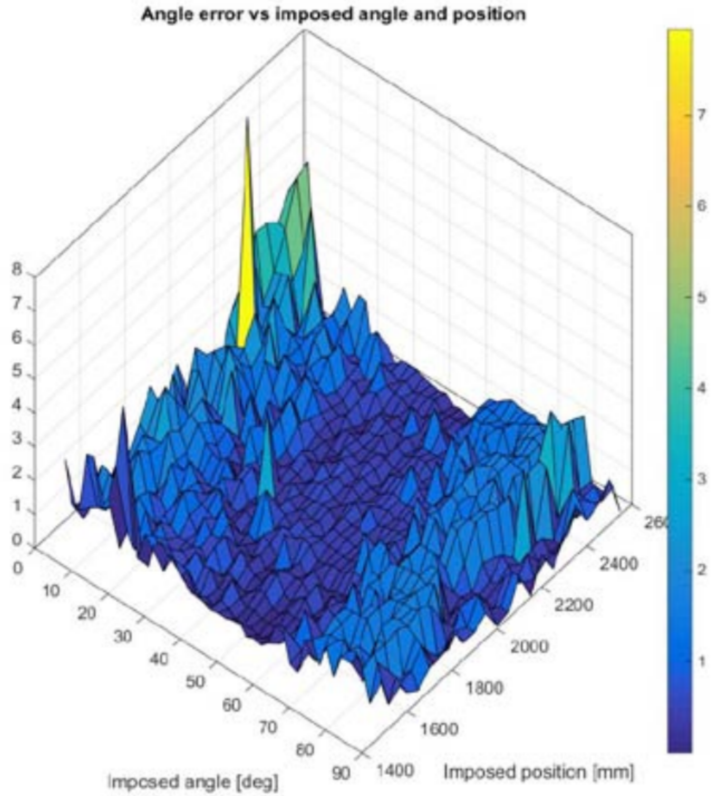
RANSAC
Iterative
Procedure

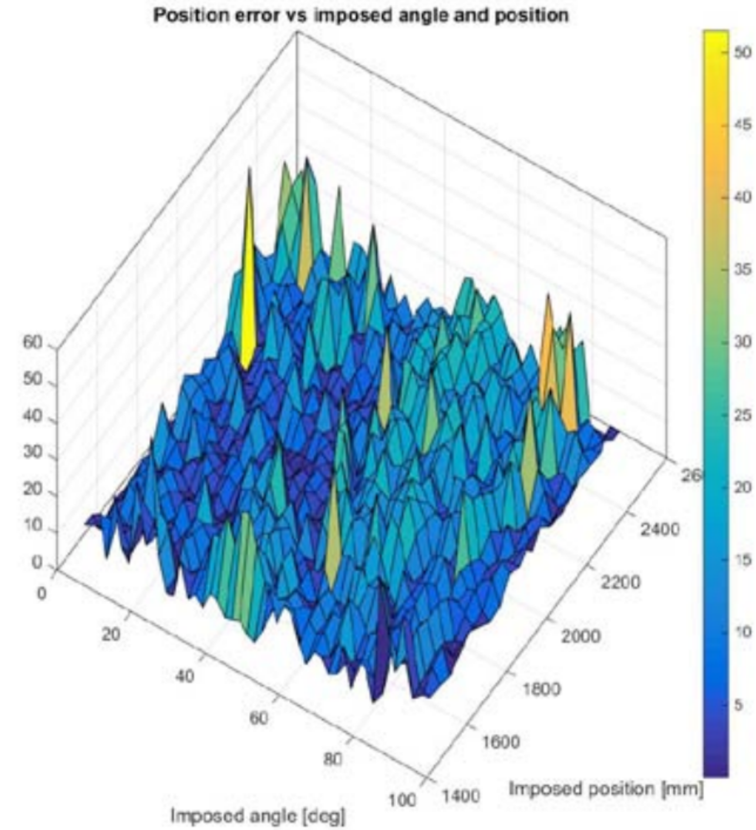
Non-linear optimization for pose refinement

Output:
Pose estimation



Results





- The position and orientation uncertainty of the satellite is evaluated as in an indirect measurement by a Monte Carlo propagation approach.
- The measurement error is compatible with the obtained extended uncertainty.
- The numer of markers in sight and the orientation of the satellite mock-up strongly influence the estimation error.

Development of a Global Navigation system for the SPARTANS testbed

Main objective

determine the position and orientation of the SPARTANS modules with respect to a global reference frame.

Requirements:

- Contactless measurement system
- High-frequency acquisition
  - Good accuracy in the short term period
- Low-frequency acquisition system
  - Reset the uncertainty level of the high frequency segment

Development in 2 steps:

- First prototype of the global navigation system;
- Definition, implementation and calibration of the global navigation system.

Global Navigation System Prototype

Overview

Main objectives

- development of a first prototype of the localization system for the SPARTANS testbed.
- determine the planar position and orientation of the TM with respect to a global inertial reference frame.

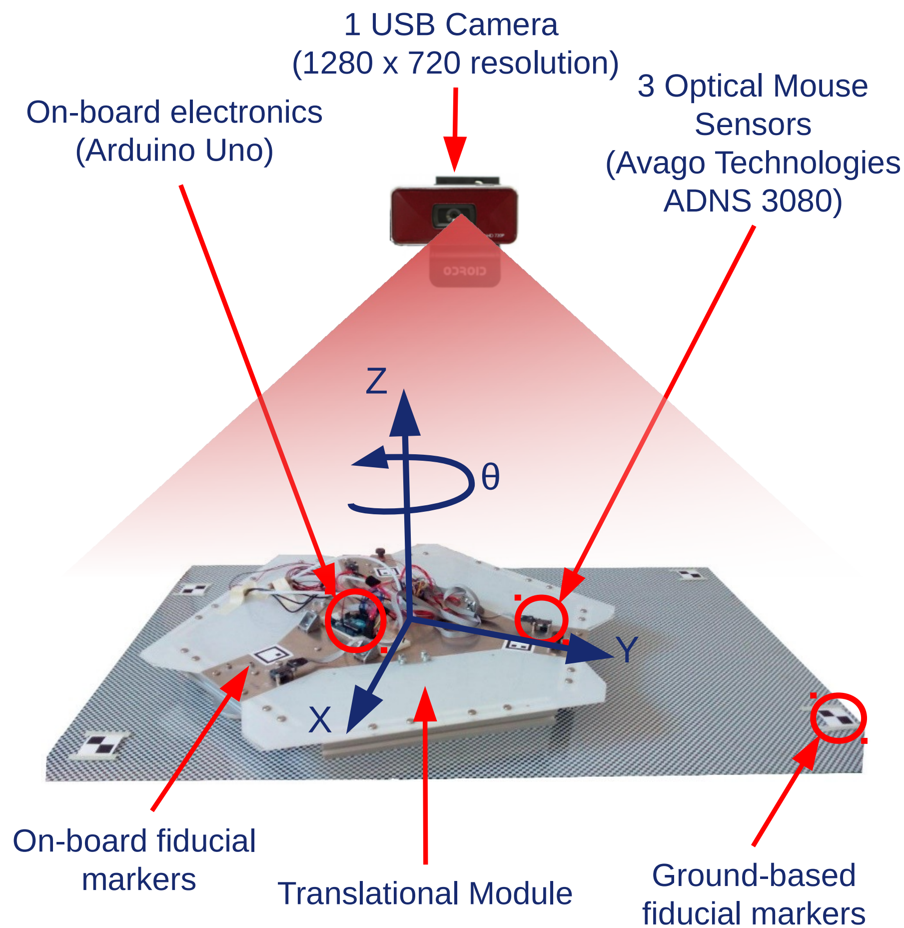
Cost-effective measurement approach by using off-the-shelf components.

Raw data are provided by:

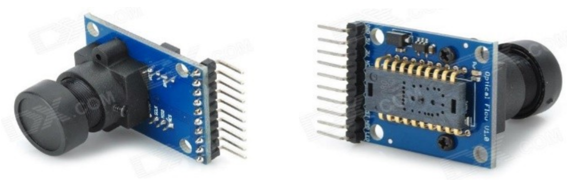
- Optical Flow Sensors (OFS) – high acquisition rate;
- USB camera – low acquisition rate.

Measurement Testbed

Experimental Setup



Global Navigation System Prototype
Optical Flow Sensors



- Planar displacement *(Δx, Δy)* is measured with respect to the OFS-fixed reference frame;
- Redundant measurements (3 OFS);
- Rotations can be measured by combining at least 2 OFS;
- High acquisition rate (20 Hz);
- **Incremental measurements** are provided.

Estimation of the TM 3D state at time *k*:

$$ {}^{G}\mathbf{S}_k = {}^{G}\begin{Bmatrix} X_k \\ Y_k \\ \theta_k \end{Bmatrix} = {}^{G}\begin{Bmatrix} X_{k-1} \\ Y_{k-1} \\ \theta_{k-1} \end{Bmatrix} + \begin{Bmatrix} \Delta X_k \cos(\Delta\theta_k) - \Delta Y_k \sin(\Delta\theta_k) \\ \Delta X_k \sin(\Delta\theta_k) + \Delta Y_k \cos(\Delta\theta_k) \\ \delta\theta_k \end{Bmatrix} $$

Pose estimations from optical flow sensors Show a drifting behavior

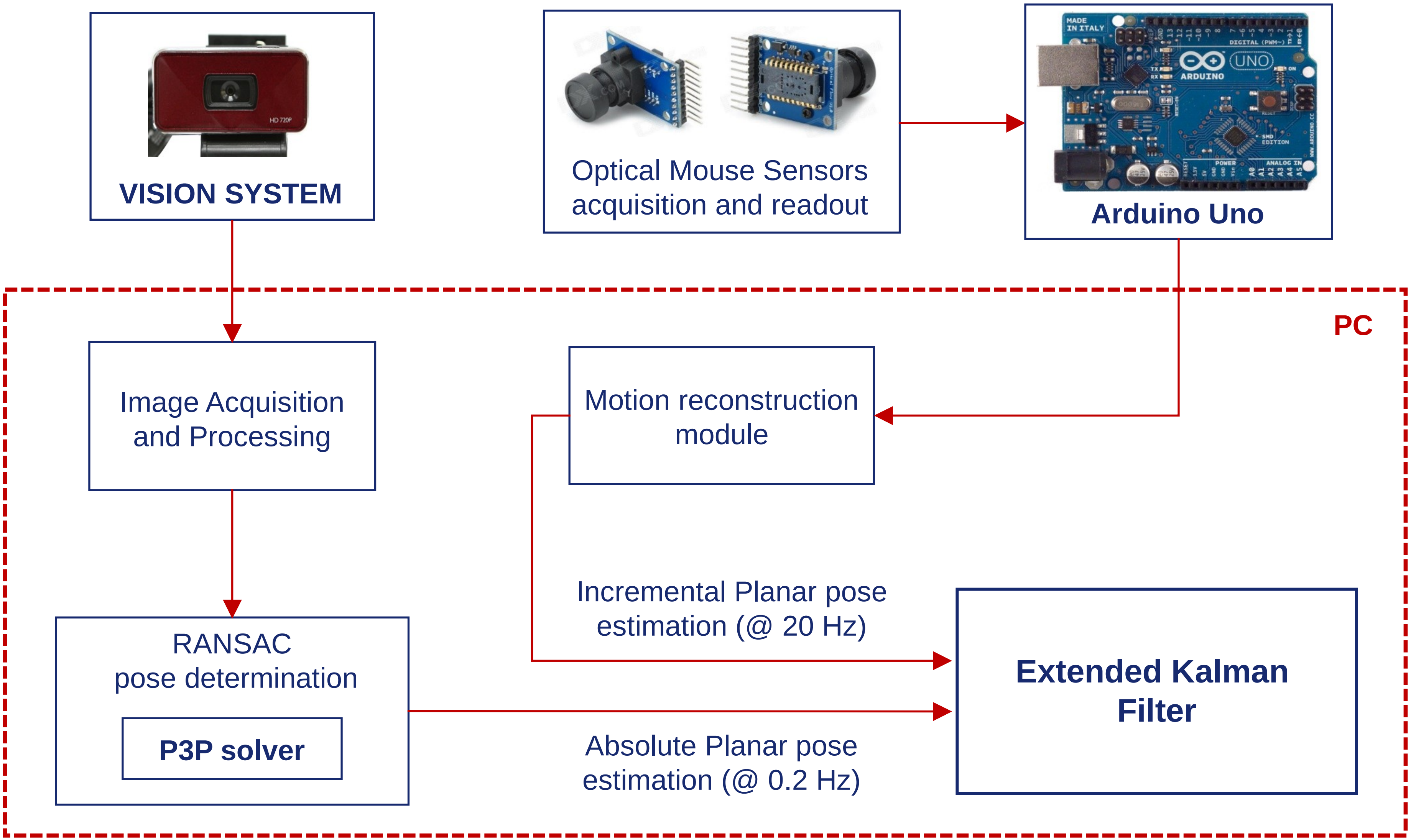
- Image acquisition
- Image processing and analysis
  - Pattern recognition
  - Feature extraction
- P3P + RANSAC

- Low acquisition rate (0.2 Hz)

Estimation of the TM pose with respect to a Global reference frame

Global Navigation System Prototype

Data filtering

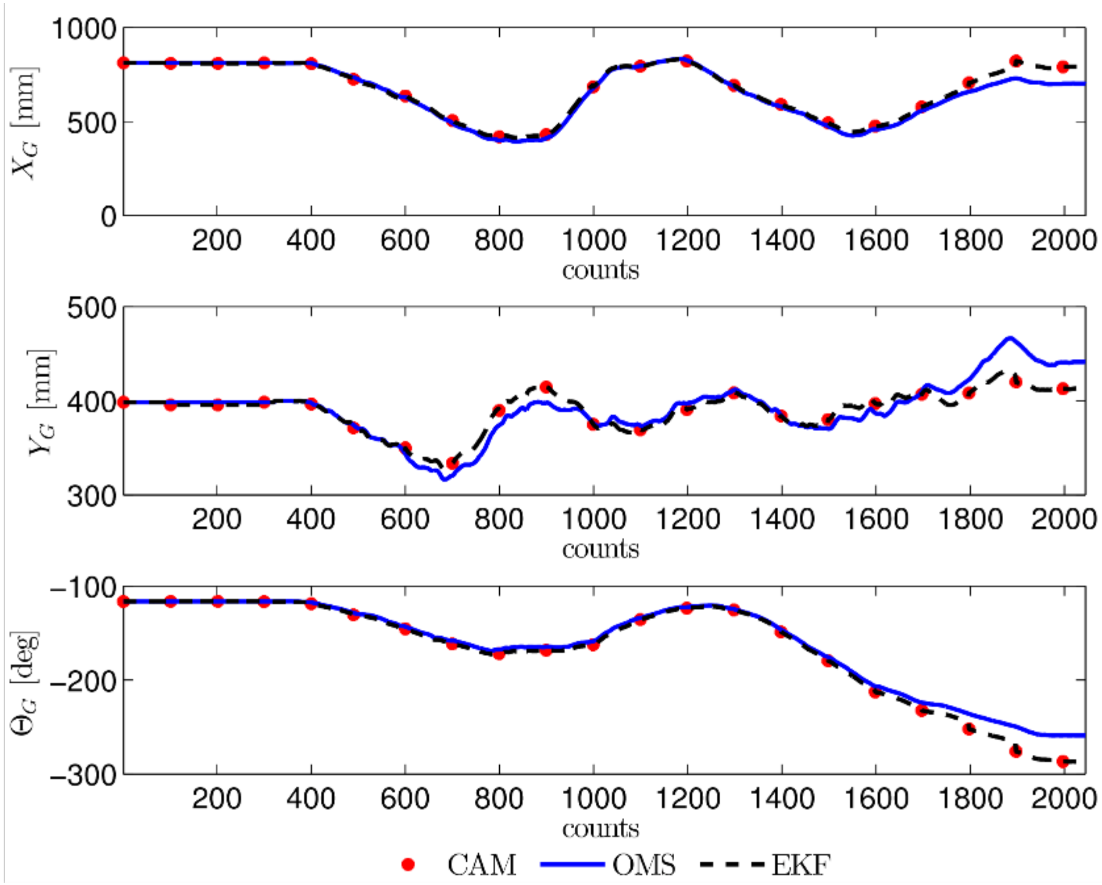


Global Navigation System Prototype
Results

- OFS system provides high-frequency incremental pose estimations
- External vision system provides low-frequency absolute pose estimations
- Experimental results show the effectiveness of the filtering technique used in the global estimation problem

Highest values of the uncertainty on the state estimation (immediately before the measurement update step)

Variable	σ max
X	7.38 mm
Y	7.38 mm
θ	1.76 deg



Global Navigation System

Overview

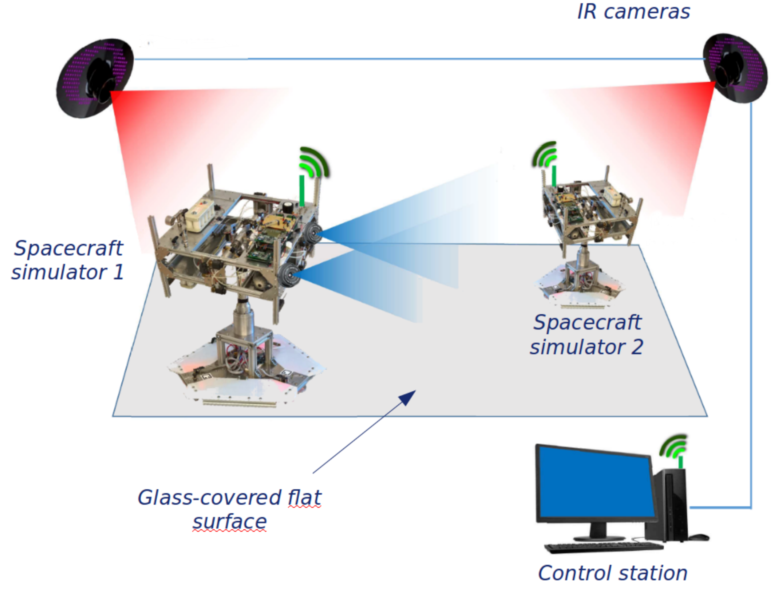
The conceptual design of the first prototype must be extended to cope with the final configuration of the SPARTANS laboratory.

A **Motion Capture** system is identified as the proper solution in order to:

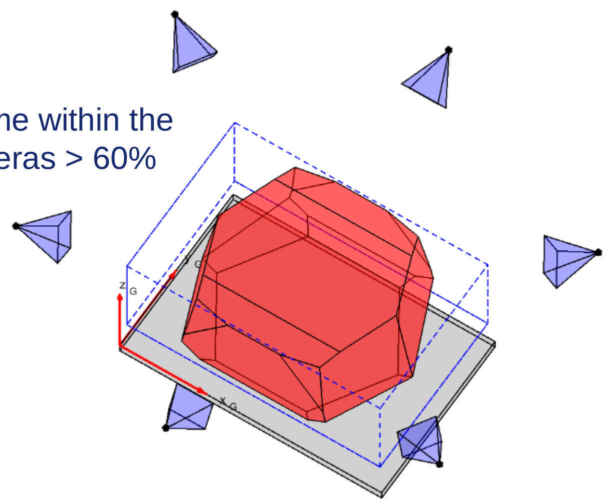
- Track each mini-satellite without interfering with their motions
- Define a Global reference frame common to all the modules in the laboratory

The system consists of:

- 6 IR cameras with a FOV of 35x45 deg
- A set of retro-reflective markers (spheres)
- A control station devoted to collecting and processing the images.

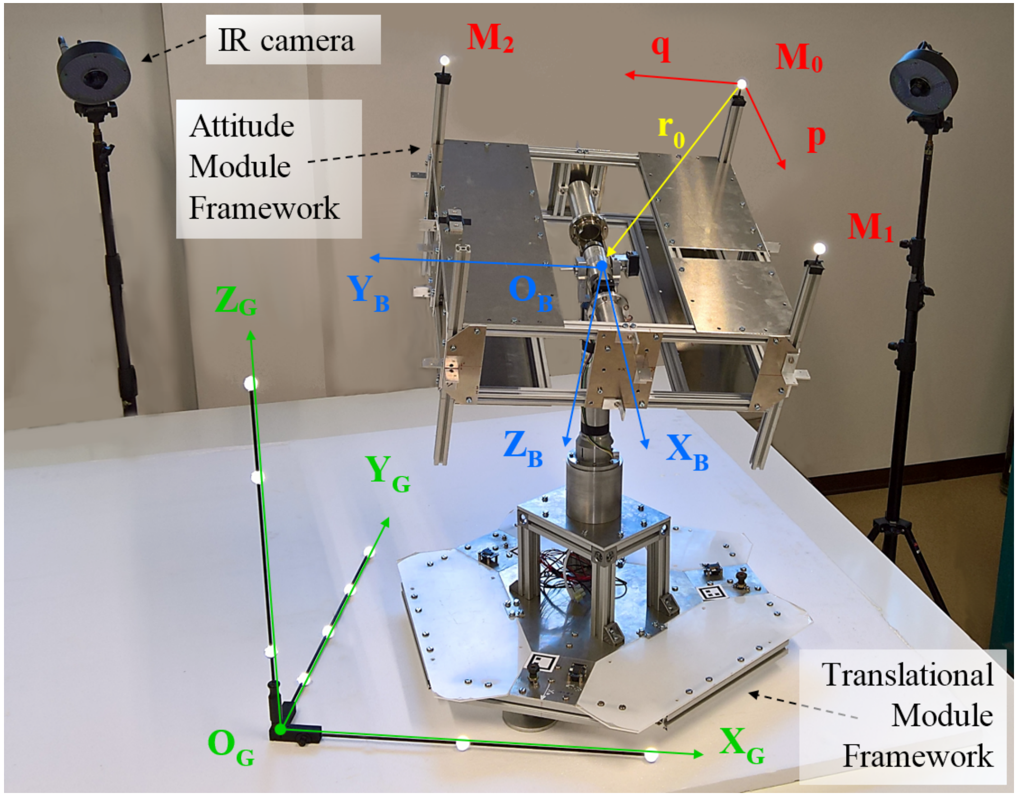


Operative volume within the FOV of 6 cameras > 60%



Global Navigation System

Pose estimation strategy



Three markers (M_0, M_1, M_2) define the Motion Capture (MC) fixed reference frame .

$$\hat{p} = M_0 M_1$$
$$\hat{q} = M_0 M_2$$

$$X_{MC} = \hat{p}/\|\hat{p}\|$$
$$Y_{MC} = X_{MC} \times Z_{MC}$$
$$Z_{MC} = \hat{p} \times \hat{q}/\|\hat{p} \times \hat{q}\|$$

Both the position and the orientation of the mini-satellite is measured as a function of the 3D locations of the markers in global frame.

$$^{G}_{MC}R = [X_{MC}, Y_{MC}, Z_{MC}] = f(M_0, M_1, M_2)$$

$$\phi = \arctan\left(\frac{^{G}_{MC}r_{3,2}}{^{G}_{MC}r_{3,3}}\right)$$
$$\theta = \arcsin\left(-^{G}_{MC}r_{3,1}\right)$$
$$\psi = \arctan\left(\frac{^{G}_{MC}r_{2,1}}{^{G}_{MC}r_{1,1}}\right)$$

Global Navigation System

Results

An **uncertainty analysis** is performed to assess the performances of the Global Navigation system.

The uncertainty on the measured 3D position of the markers is propagated employng the Kline-McClintock propagation formula.

Uncertainty on the measured **position** of the Origin of the Body frame ⇒ **lower than 1 mm** along the x,y,z coordinates

Uncertainty on the measured **attitude** of the mini-satellite ⇒ **lower than 0.1 deg**

The Global Navigation System can thus be employed for two main purposes:

- Updating the pose of the mini-satellite modules in a GPS-like manner;
- Providing reliable pose estimations to be used to assess the effectiveness of Guidance Navigation and Control strategies.

Stereoscopic vision-based navigation

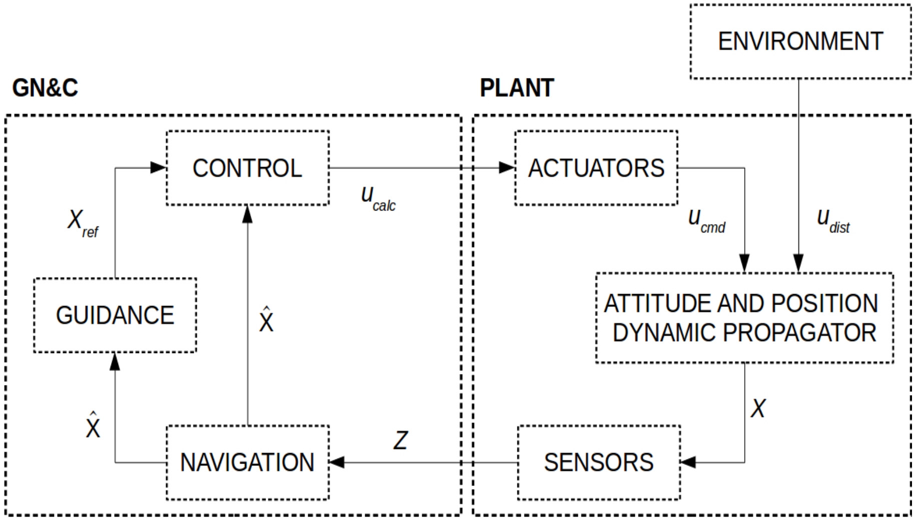
Main objective

Estimation of the of the dynamic state of an orbiting object exploiting only visual data

The Navigation strategy it aimed at enabling on-orbit autonomous operations.

The estimation approach for the orbital scenario relies on numerical simulations:

- Orbital dynamics is reproduced by means of numerical simulations;
- A set of measurements is generated taking into account the sensor models (i.e. stereo camera)
- The Navigation module exploit the available measurements to estimate the state of a target object.



Assumption:

The geometry of the target is known.

The Navigation algorithm is based on an **Extended Kalman Filter (EKF)** to cope with the inherent non-linearities of the estimation problem

Stereoscopic vision-based navigation

Filter implementation – Process model

The correct modeling of the dynamical system is crucial for autonomous operations.

State vector: $X=[\rho,\dot{\rho},q,\omega]^T$

Relative translational dynamics.

- The dynamic state of the target is written with respect to the Chaser reference frame.
- The adopted formulation overcomes the limitations of the Chloessy-Wiltshire equations which are valid for circular target orbits and small relative distances.

$$^{I}\rho=r_T-r_C$$

$$^{I}\ddot{\rho}=\mu\frac{(r_C+\rho)}{\|r_C+\rho\|^3}-\mu\frac{r_C}{\|r_C\|^3}=\frac{d^2\rho}{dt^2}+2\omega_C\times\frac{d\rho}{dt}+\dot{\omega}_C\times\rho+\omega_C\times(\omega_C\times\omega_C)$$

Relative rotational dynamics.

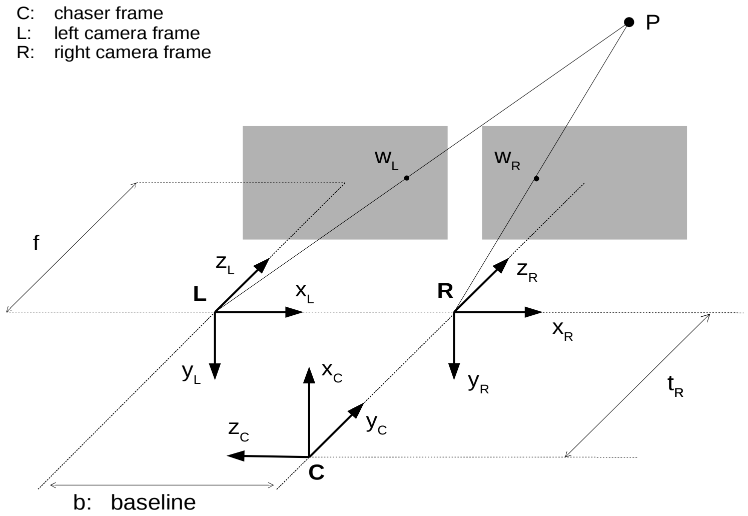
- The rotational model has its foundation in the Euler's equations

$$\omega=\omega_T-\omega_C$$

$$\dot{\omega}={}^{C}_{T}R[I_T^{-1}(-\omega_t\times I_T\omega_T)]-I_C^{-1}(T_C-\omega_C\times I_C\omega_C)$$

Stereoscopic vision-based navigation

Filter implementation – Observation model



The observation model exploits only the perspective projection model

Given a feature point P, its projections on the left and right image planes can be estimated by means of the following:

$$u_R = f\frac{x_P}{z_P} \qquad u_L = f\frac{x_P - b}{z_P}$$

$$v_R = f\frac{y_P}{z_P} \qquad v_L = f\frac{y_P}{z_P}$$

The 2D velocity of the feature points can be related to the relative velocity of the target with respect to the chaser as:

$$\begin{bmatrix}\dot{u}\\ \dot{v}\end{bmatrix} = \frac{1}{\rho_z}[A(u,v)]\dot{\rho} + [B(u,v)]\omega$$

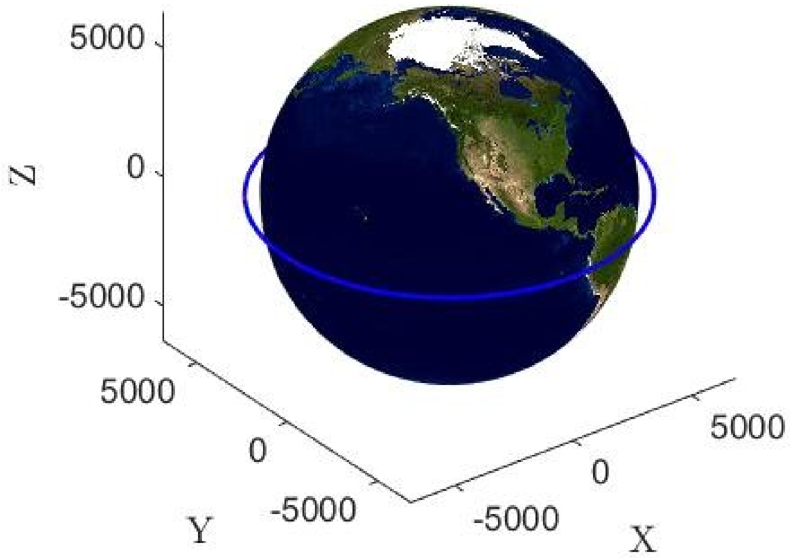
The disparity is defined as:

$$d = u_L - u_R$$

The measurements vector can therefore be related to the relative dynamic state:

$$Z = h(X) = [u_r, v_r, u_L, v_L, \dot{u}_r, \dot{v}_r, \dot{u}_L, \dot{v}_L, d]$$

Stereoscopic vision-based navigation
Space scenario



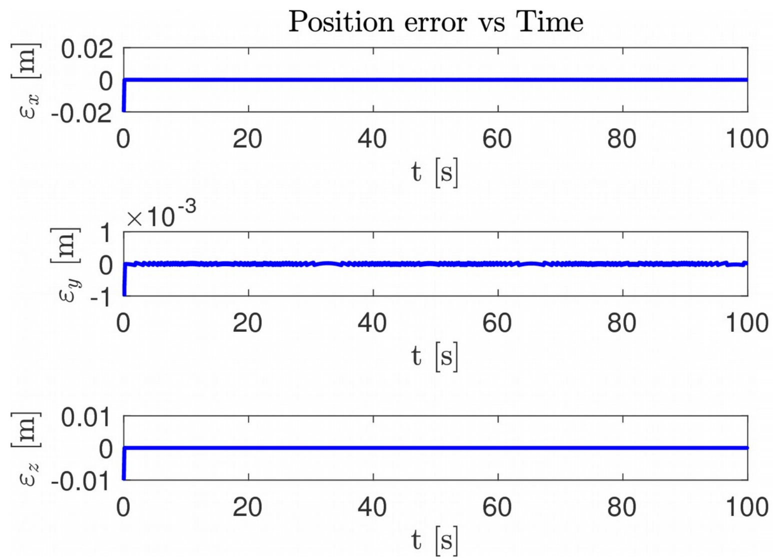
Formation in-line

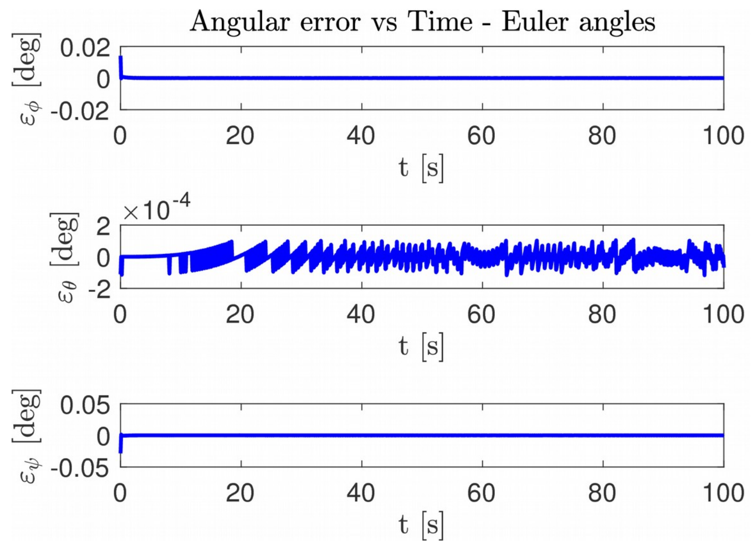
- h = 500 km
- ρ = [0, 40, 0] m
- dρ/dt = [0, 0, 0] m/s
- q = [0, 0, 0, 1]
- ω = [0.1, 0, 0.1] deg/s

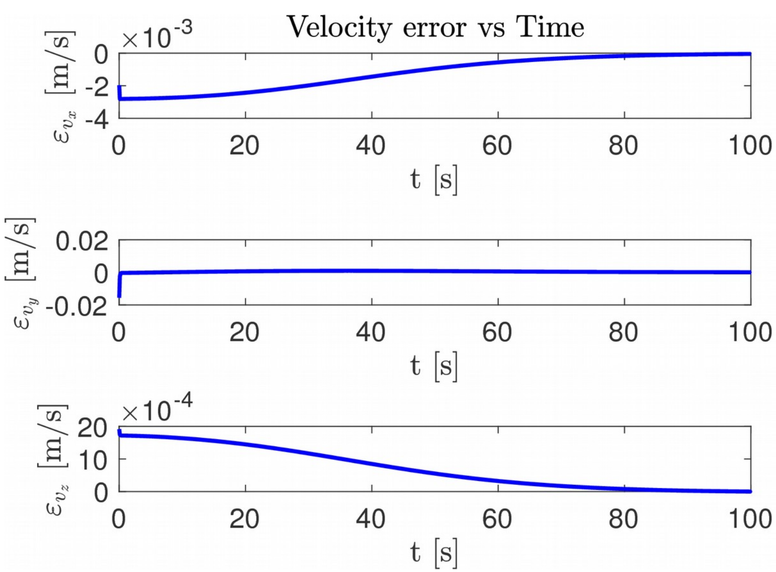
Initial conditions for the EKF

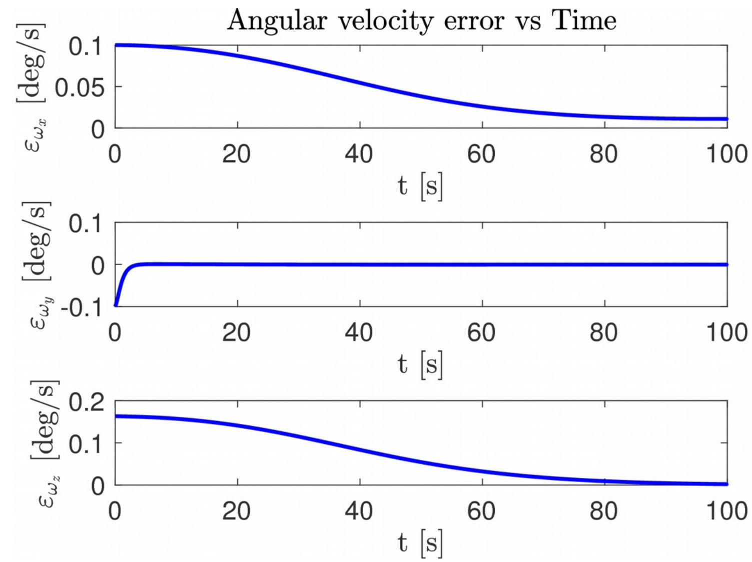
- ρ = [0.4, 42, 0.2] m
- dρ/dt = [0, 0, 0] m/s
- q = [0, 0, 0, 1]
- ω = [0, 0, 0] deg/s

Stereoscopic vision-based navigation
Results









PACMAN

Position and Attitude Control with Magnetic Navigation

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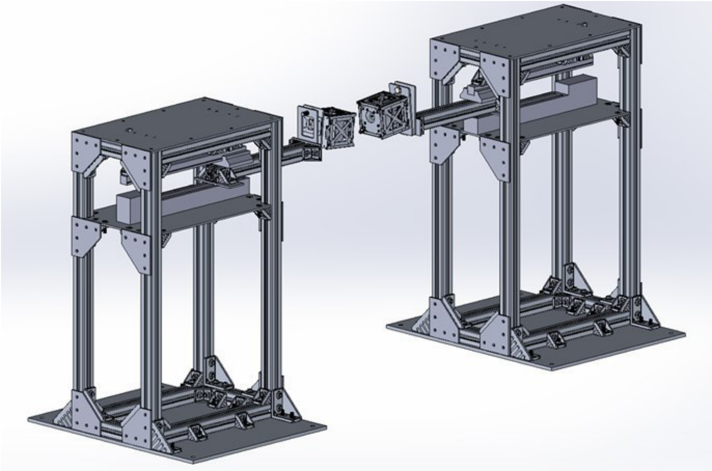
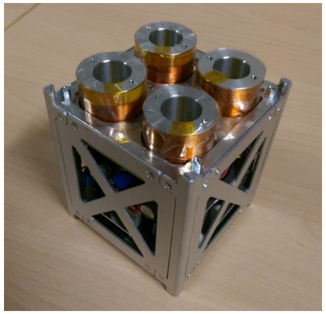
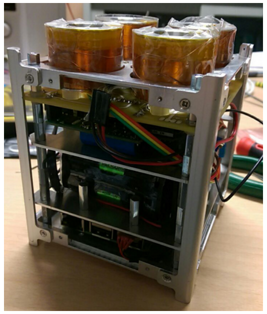
OBJECTIVES

- ➢ Develop a system for proximity navigation and soft docking based on magnetic interactions
- ➢ Develop a dedicated low-range navigation system based on markers/camera system
- ➢ Validate the whole PACMAN system in the relevant low-gravity environment



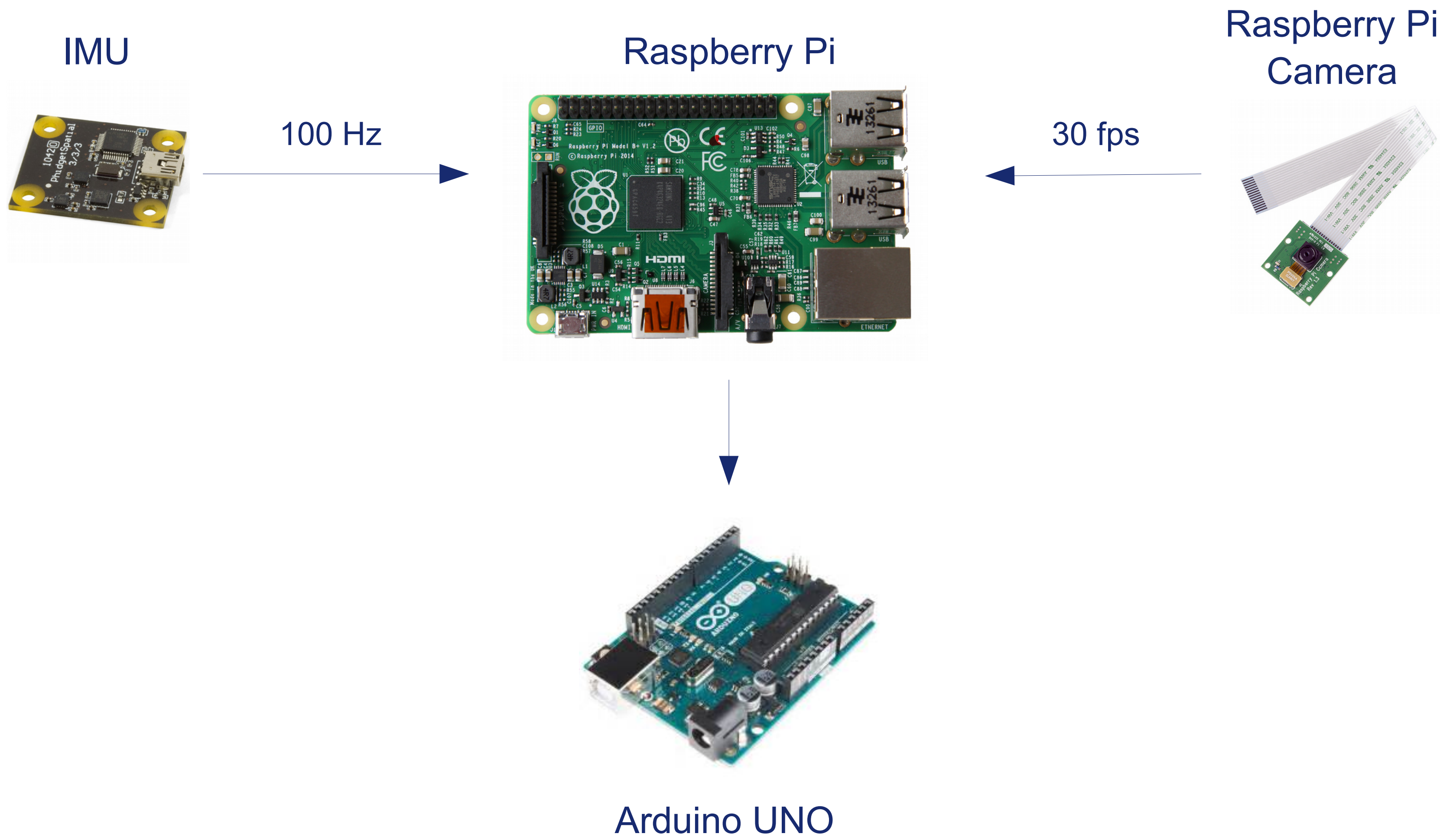
- The design of the experiment is highly dependent on the peculiar conditions of the parabolic flight.
- Main drivers for the design of the navigation subsystem are **simplicity** and **reliability**.





PACMAN

Navigation Subsystem Architecture



Publications

2015

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THANK YOU!
QUESTIONS?