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Guidance, Navigation and Control issues for Hayabusa follow-on missions

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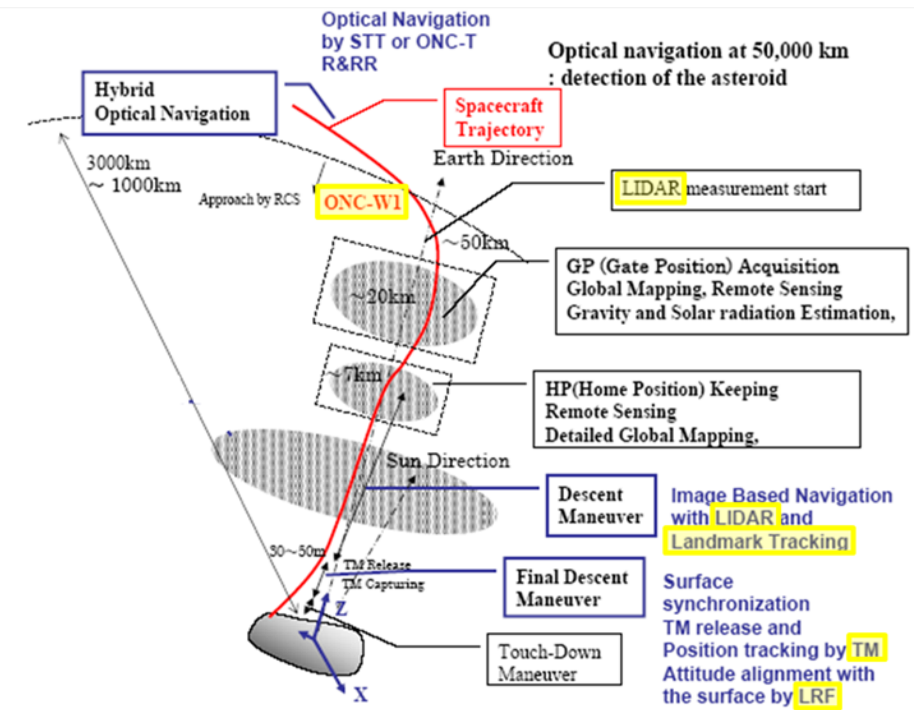
Lessons and Learned & heritage from Proximity Operation（＜50km ）of Hayabusa

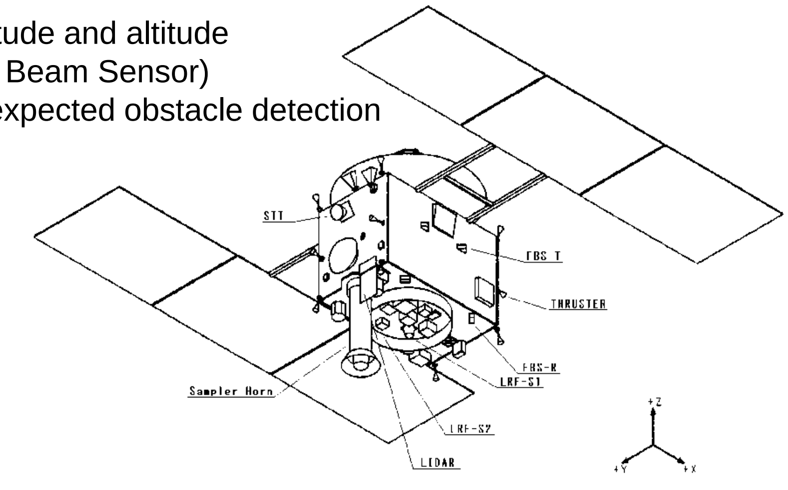
- **measuring** relative position and attitude
- **controlling** relative position and attitude to the asteroid

are **not easy tasks** for the asteroid that have **not seen beforehand**



Rendezvous and landing scenario of HAYABUSA

LIDAR
for altitude measurement
ONC-W1 (FOV 60degx60deg)
for Itokawa or Target Marker tracking
LRF
for attitude and altitude
FBS(Fan Beam Sensor)
for unexpected obstacle detection

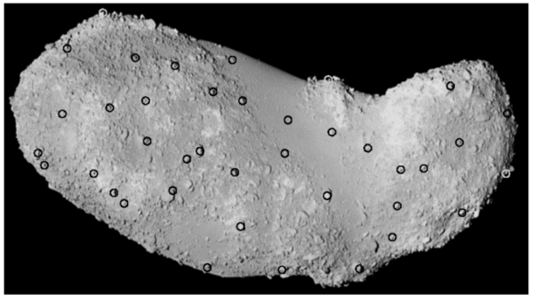


Navigation sensors of HAYABUSA

Heritage from HAYABUSA and Lessons Learned

1. Successfully performed the approach to Itokawa (approx. 50km → 100m) using ONC-W1(wide view camera) and LIDAR

    Feature points (“landmark”) in the image of Itokawa were extracted **manually** on the ground and matched with “3D feature points model” **manually** on the ground for image based navigation (position)



Feature points

autonomous on-board visual navigation algorithm is desirable

Developing autonomous (not on the ground) **image based navigation** system exploiting actual images of Itokawa

Technical issues and ongoing research for MP GNC (1/2)

"need to prepare various GNC algorithms for asteroids with various shape, surface, spin rate, etc."

1. Guidance Phase（altitude : approx. 8km → approx. 500m) : LIDAR, ONC

whole area of the asteroid e.g. "Itokawa" is in FOV of the Onboard Navigation Camera

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autonomous measurement algorithms are now under development

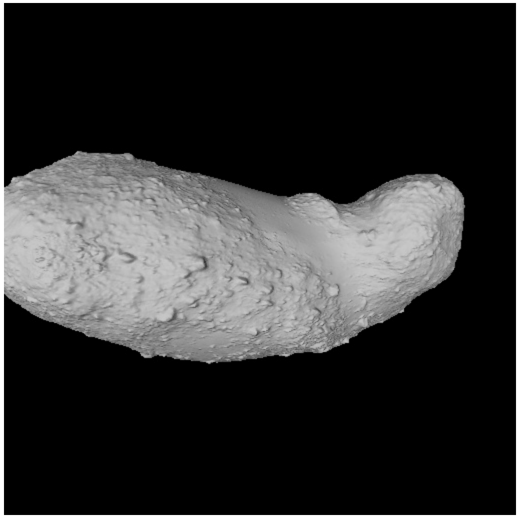
1. **centroid** extraction algorithm → already developed
2. **silhouette** based 3D model matching algorithm for relative position measurement
3. **autonomous GCP(Ground Control Point)-NAV algorithms onboard**
   - **feature points extraction** algorithm
   - autonomous **navigation and guidance** algorithm using **GCP data base**

Autonomous Matching Using Asteroid's Silhouette (1/2)

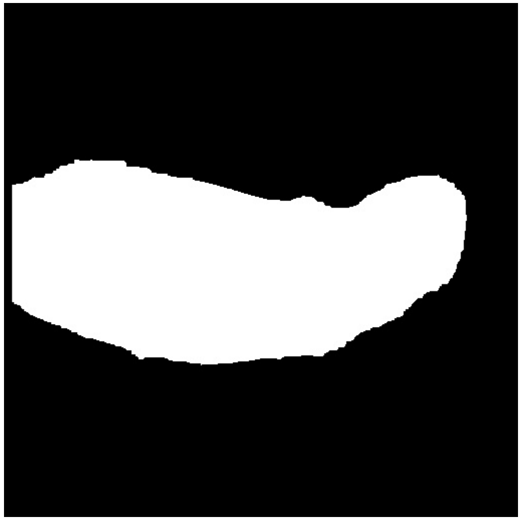
Guidance Phase (8km-500m approx.):

Too far for GCP-NAV

The whole asteroid is inside the FOV ➔ Use Silhouette of the Asteroid



Real Images



Silhouette

On-Board Autonomous Matching with 3D Model

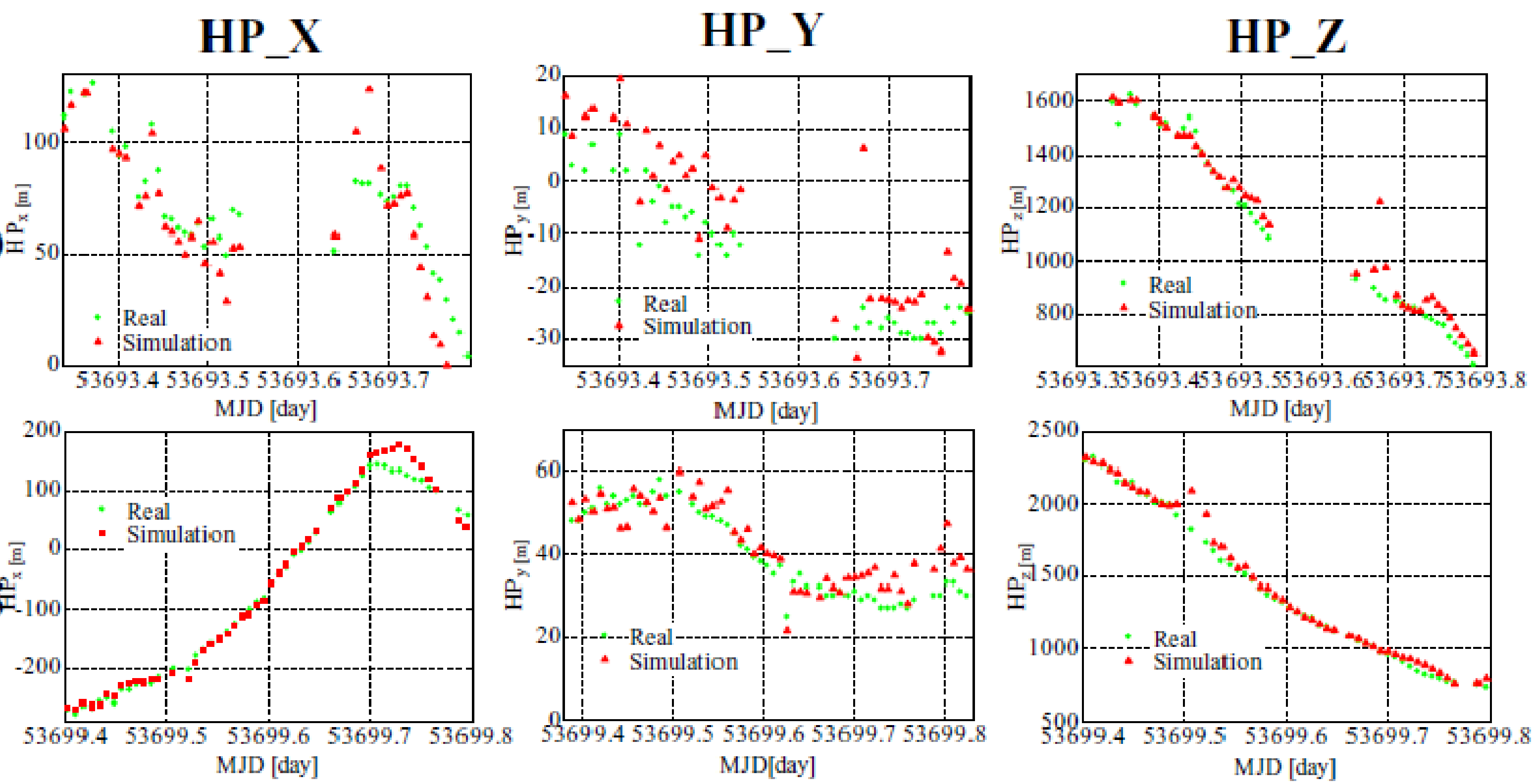
→ Relative Position

Autonomous Matching Using Asteroid's Silhouette (2/2)

Simulation

TD#1
05/11/19

TD#2
05/11/25

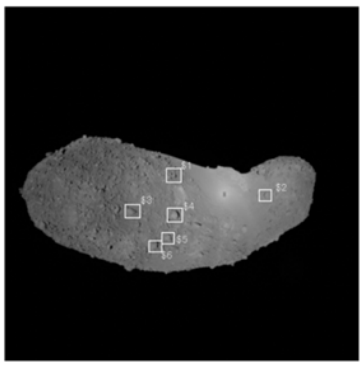


Simulation results using Itokawa images indicated **the performance comparable to the actual ground operation** (matching by human) → The validity was confirmed

Autonomous GCP-NAV algorithms onboard (1/5)

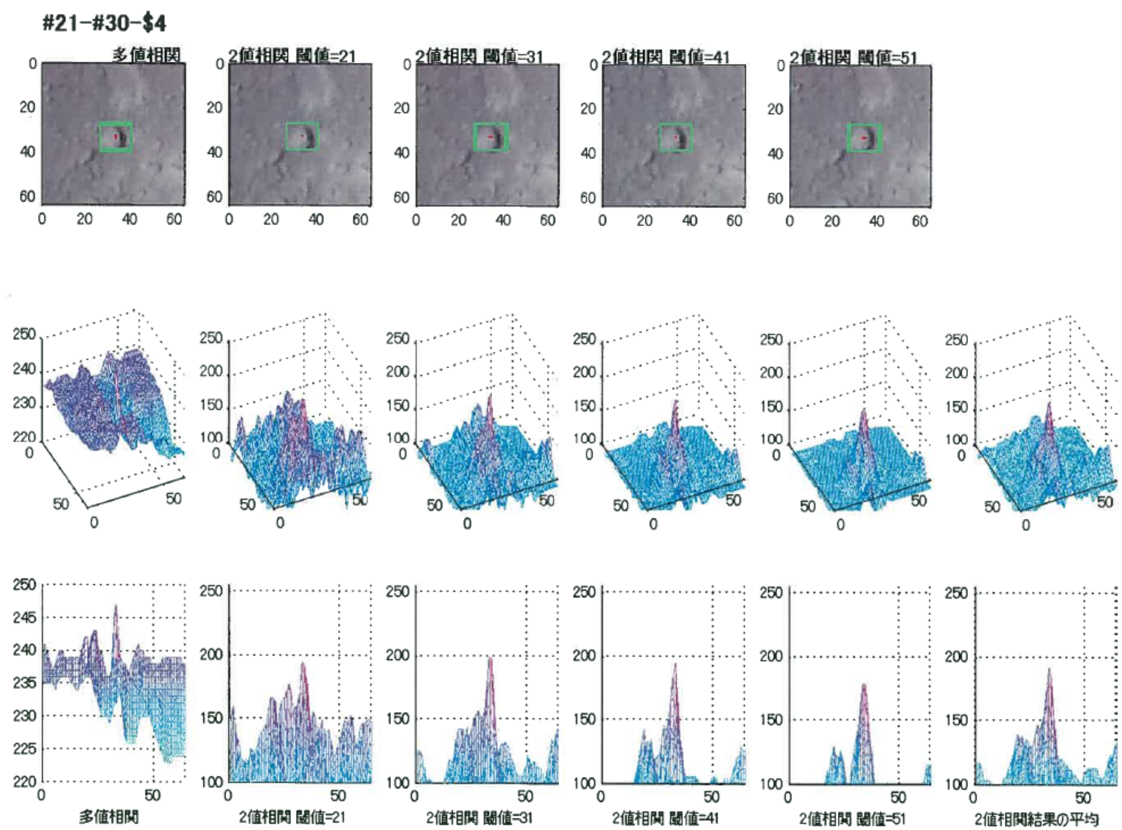
GCP such as feature points **extraction** algorithm
developed using images of “Itokawa”

1. construct **template of feature points** using images taken at the **1st TD** (2005/11/19)
   (e.g feature point “$4” in the 1st TD image is used as the sample feature point)
2. autonomous **matching** of templates **with** images taken at **2nd TD** (2005/11/25)
   (e.g corresponding place in the 2nd TD image is extracted applying correlation based matching)



#21：1st TD image
(feature point extracted)

#30：2nd TD image



Autonomous GCP-NAV algorithms onboard (2/5)

Guidance and Control strategy
exploiting GCP(feature points) on JU3

assumption

- attitude motion of JU3 is **one-axis spin** and its attitude is given as **a function of time**
- attitude of the probe is measured correctly

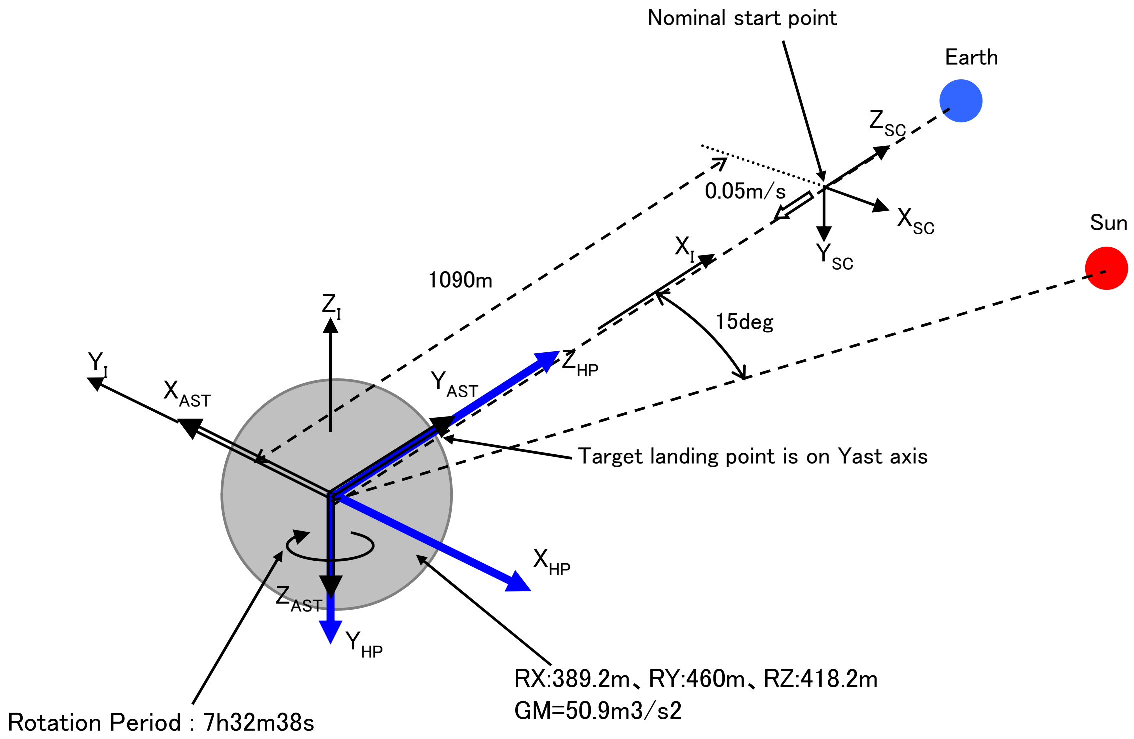
algorithm

1. **construct "GCP 3D data base"** using images taken during **the rehearsal approach** (altitude : 600[m] → 100[m])
2. **extract GCP** in the image taken during **the actual approach phase**
3. calculate **position difference** between
   - virtually-imaged estimated position of GCP from **"GCP 3D data base"**
   - extracted GCP position in **the actual image**
4. the above difference is used as a input to **Kalman Filter** and **relative position/velocity** are estimated and used for **position guidance**

Autonomous GCP-NAV algorithms onboard (3/5)

Numerical Simulation of GNC for the approach to JU3

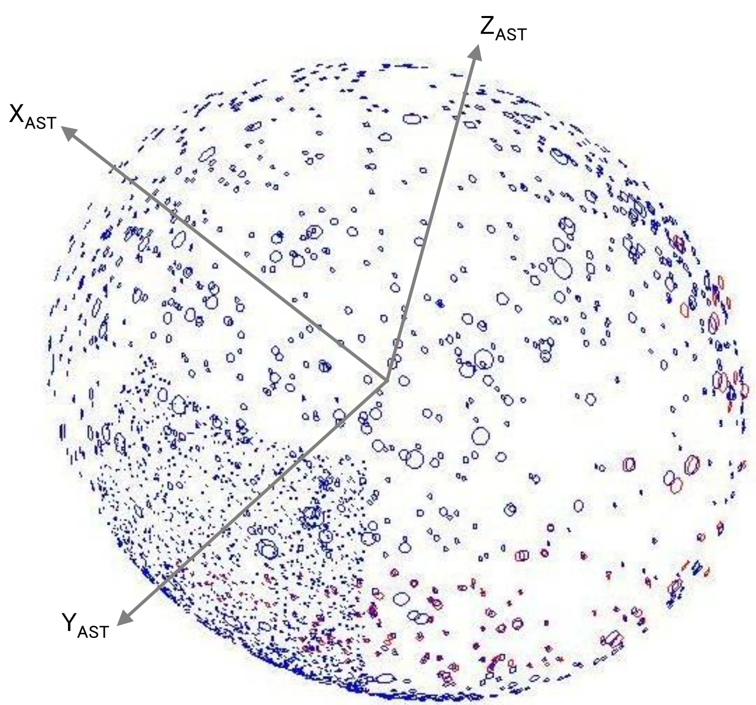
- Navigation using image from **one onboard camera** with FOV 60 [deg] x 60 [deg]
- Navigation using **GCP 3D data base** and **recognized GCP position in the image**
- **Approach phase** : going down toward the center of the asteroid
- JU3 is assumed to be one-axis (Z) spinning with its period of 7h32m38s

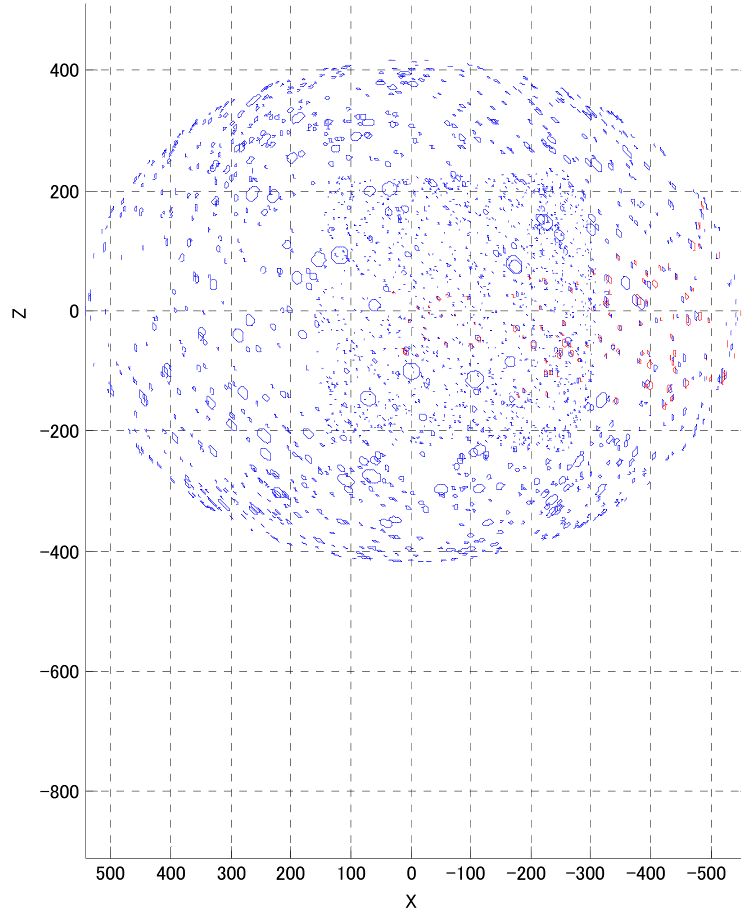


Autonomous GCP-NAV algorithms onboard (4/5)

GCP 3D data base for JU3

- Appropriate distribution of **GCP with various size**
- Particular area for closer view at the rehearsal approach has much more **GCP with smaller size**
- The rehearsal approach and the actual approach have **similar trajectories** in order to get similar views

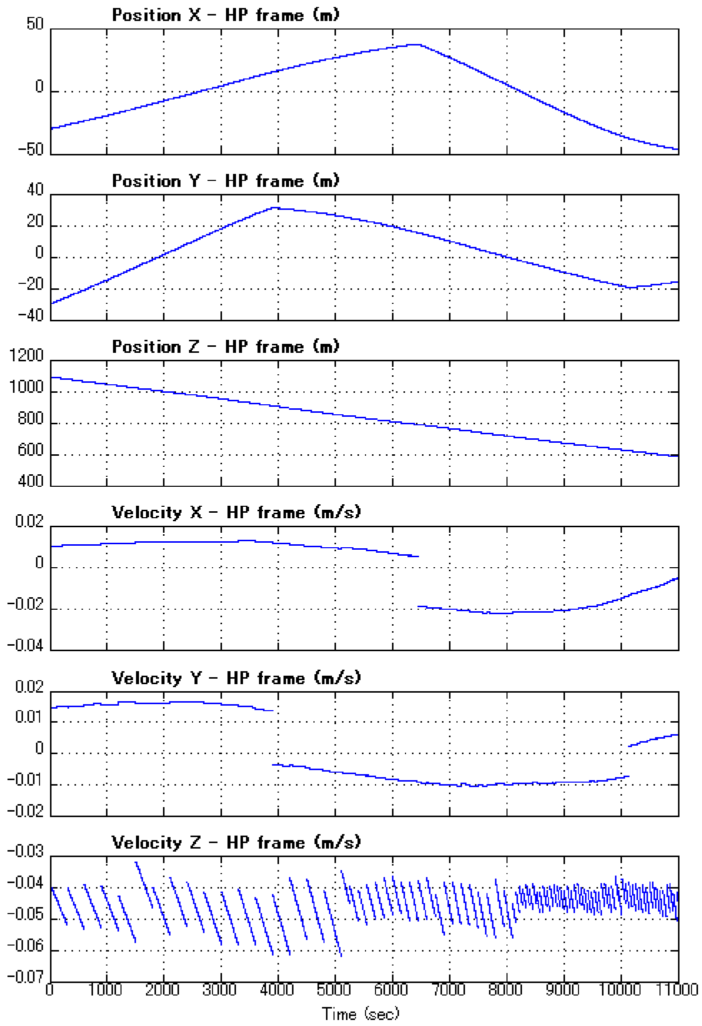




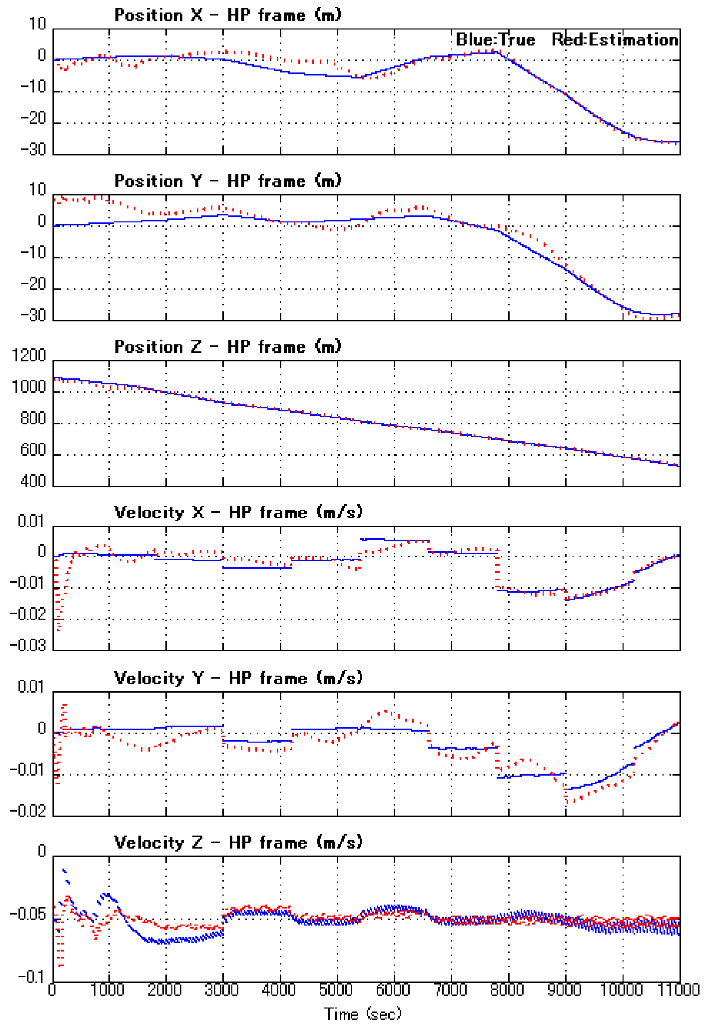
Autonomous GCP-NAV algorithms onboard (5/5-a)

Result of the numerical simulation of GNC for the approach to JU3
→ successfully approached to the JU3

Rehearsal approach



Actual approach

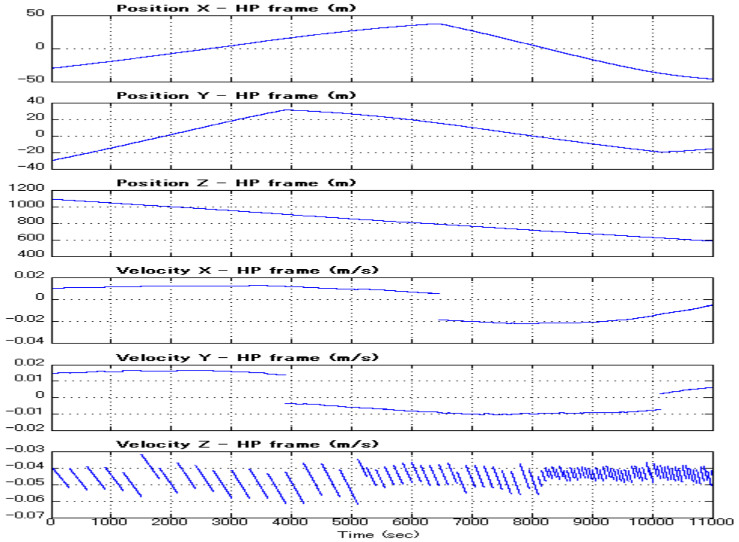


Autonomous GCP-NAV algorithms onboard (5/5-b)

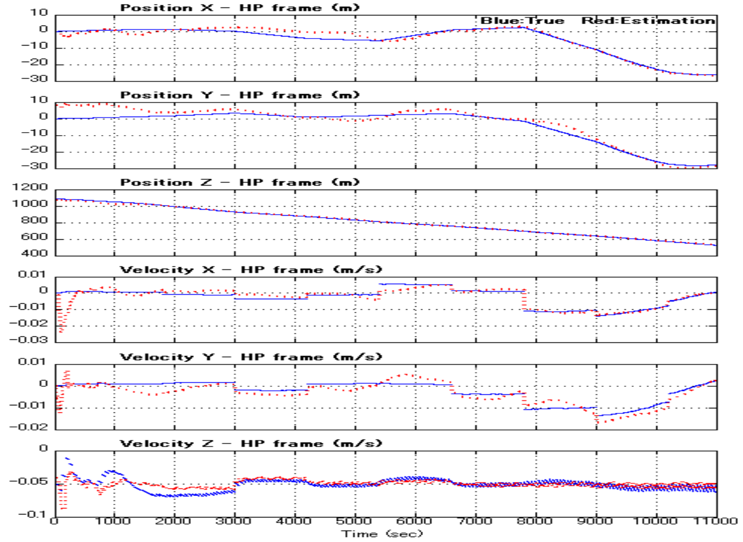
Result of the numerical simulation of GNC for the approach to JU3
→ successfully approached to the JU3

- **lateral direction position control** with interval of 1200[sec] was started after 1800[sec] waiting for **the convergence of the image based navigation error**
- **vertical direction position control** with interval of 1200[sec] was started after 1800 [sec] waiting for **the convergence of the image based navigation error**
- **vertical direction velocity control** with interval of 60[sec] was started from the start of the manoeuvre

Rehearsal approach



Actual approach



Technical issues and ongoing research for MP GNC (2/2)

2. Vertical Descent Phase（altitude : approx. 500m → approx. 40 m)
: LIDAR, ONC(Onboard Navigation Camera)
a part of the asteroid e.g. “Itokawa” is in FOV of the vision sensor

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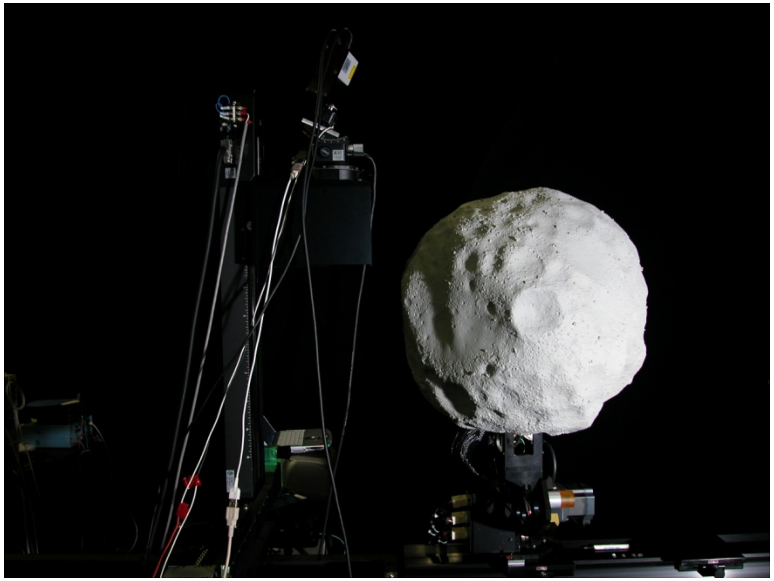
autonomous **measurement algorithms are now under development**

- **GCP-NAV algorithms onboard**
  - robust **feature points extraction** algorithm
  - **autonomous matching** algorithm between **feature points**
- **autonomous 3D model matching** algorithm utilizing **image features**

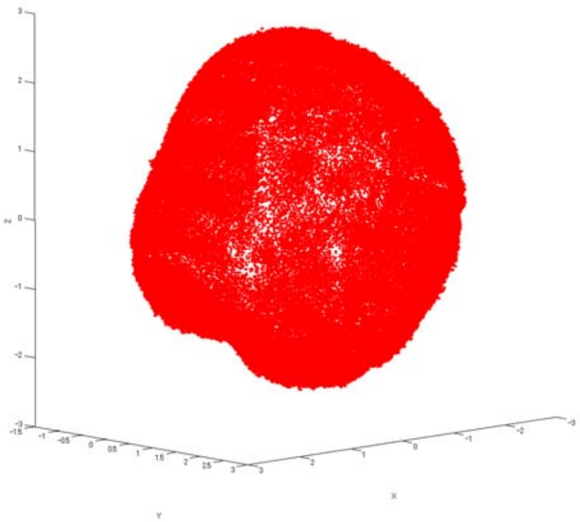
Terrestrial experiment asteroid model for development/evaluation of algorithms

development and evaluation of algorithms using

- **Computer Graphics**
- **images given from terrestrial experiment with parallel light facility**



**asteroid model &
scan-type Laser Range Finder
for measuring 3D shape of the model**



**measured 3D shape
of the asteroid model**