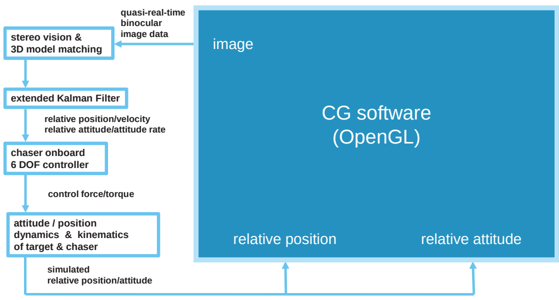
デブリ回収機による故障衛星に対する画像情報に基づく運動推定と近傍飛行マヌーバ

○照井 冬人（JAXA）

比較的大型のデブリである故障あるいは寿命の尽きた衛星（機能不全衛星）を回収する際，衛星近傍（約 50m 以内）における宇宙機（デブリ回収宇宙ロボット）の運動制御にはフィードバック情報として両者の相対位置・姿勢に関する情報を何らかの方法で計測する必要がある．衛星近傍では画像計測が必須であるため、衛星を覆っているしわのある光沢素材（MLI）が太陽光や唯一の乱反射光源である地球からの反射光（アルベド）で照らされるという宇宙特有の条件下で、十分に機能する画像計測アルゴリズムの開発を行うと共に、画像計測結果をフィードバックした宇宙機のデブリ近傍の飛行マヌーバを、CG を活用したシミュレータを用いて評価した結果を示す。



CG を活用したシミュレータの構成

JAXA

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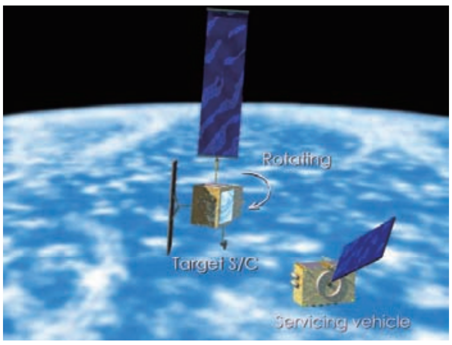
JAXA (Japan Aerospace Exploration Agency)

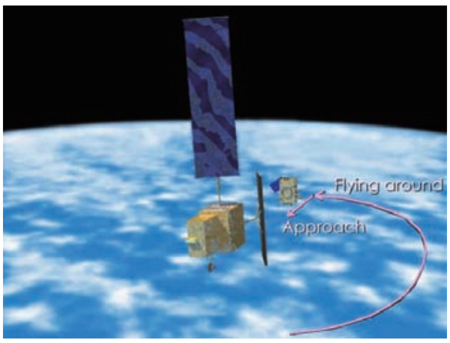
Outline

1. **Motion (relative position/attitude) estimation** algorithm for **ADR (Active Debris Removal) space robot** using image data
   Stereo Vision
   + ICP (Iterative Closest Point) algorithm
   + extended Kalman Filter
4. **Motion estimation experiment** using terrestrial simulator (“on-orbit visual environment simulator”)
5. **Six Degrees of Freedom maneuver control** simulation with motion estimation utilizing **Computer Graphics**
6. Future work

Operation for ADR (Active Debris Removal) space robot requiring “motion estimation” using image

- “target” (failed satellite) & “chaser” (space robot))
- Rendezvous to a distance of approx. 50m





- Station keeping
  - remote visual inspection
  - measure target motion by image processing (“un-cooperative”)
- Fly-around
  - track the capture point maintaining constant relative position and attitude
- Final Approach
  - maneuver towards the target

画像による軌道上非協力物体の運動推定ストラテジの整理 (1/5)

運動推定：搭載センサからの情報に基づいた、計測対象の形状が認識できるような距離での、相対位置・姿勢（及び、それらのレート）の計測

- 計測対象表面に画像処理の拠り所となるリフレクタやマーカは無い
- 計測対象の3次元形状モデルと、精度は低くても動力学モデルは既知と仮定
- 搭載系による完全自律の運動推定アルゴリズムは追求しない（部分的な地上オペレータによる判断は不可欠という前提）

⇩

計測対象の形状（「姿勢が認識しやすい凸凹さ」）、
表面素材（金属光沢 、表面の起伏の程度 、表面のtexture）、
姿勢運動の程度（静止 or シングルスピン or ニューテーション）
に応じて適するアルゴリズムは決まる

Characteristics for motion measurement of the failed satellite using image

- Characteristics of the **on-orbit visual environment**
  - intense, highly-directional sunlight
    → **high image contrast**
  - the earth's albedo is the diffuse light source
    → **reduce image contrast**

SFU captured by Shuttle RMS (NASA)

- Surface of the malfunctioned satellite (uncooperative target)
  - **no artificial marker or retro-reflectors**
  - wrapped in **Multi Layer Insulation (MLI)** material for thermal protection
    - aluminized Kapton (gold-colored, specular)
    - beta cloth (white, matte)
    - carbon-polyester coated Kapton (black, matte)
- Optical characteristics of the target
  - **reflective, specular surfaces**,
  - with slight **wrinkles or undulations**

⇩

- measure the shape by Laser Range Finder
- **partially measurable** from image data

On-orbit Visual Environment Simulator

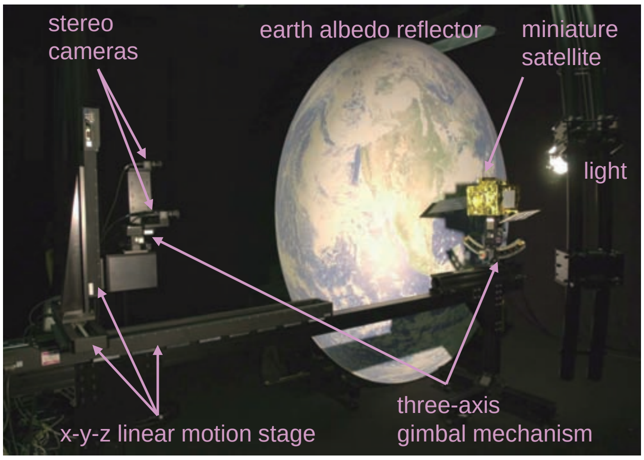
on orbit

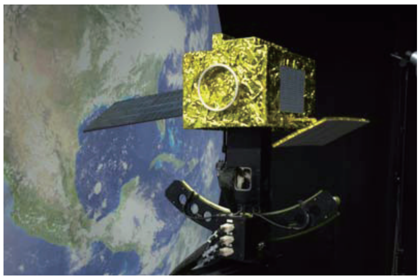
	base line [mm]	400
	distance [mm] (optical center − satellite center)	18700
satellite	body [mm]	3000 × 2500 × 2000
satellite	solar paddle [mm]	4000 × 2000
satellite	rader antenna [mm]	3200 × 1500
camera / lens	resolution [pixel]	640 × 480
camera / lens	focal length [mm]	6.02

1/10 scale ⇒

terrestrial simulator

	base line [mm]	40
	distance [mm] (optical center − mockup center)	1870
satellite mockup	body [mm]	300 × 250 × 200
satellite mockup	solar paddle [mm]	400 × 200
satellite mockup	rader antenna [mm]	320 × 150
camera / lens	resolution [pixel]	640 × 480
camera / lens	focal length [mm]	6.02





miniature satellite

A Motion Estimation Strategy using On-orbit Visual Environment Simulator

quasi-real-time binocular image data →

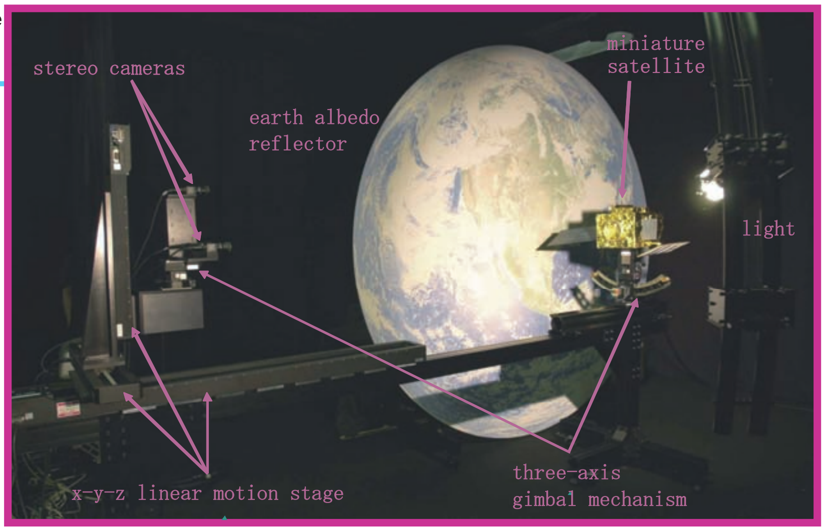
stereo vision & 3D model matching

↓

extended Kalman Filter

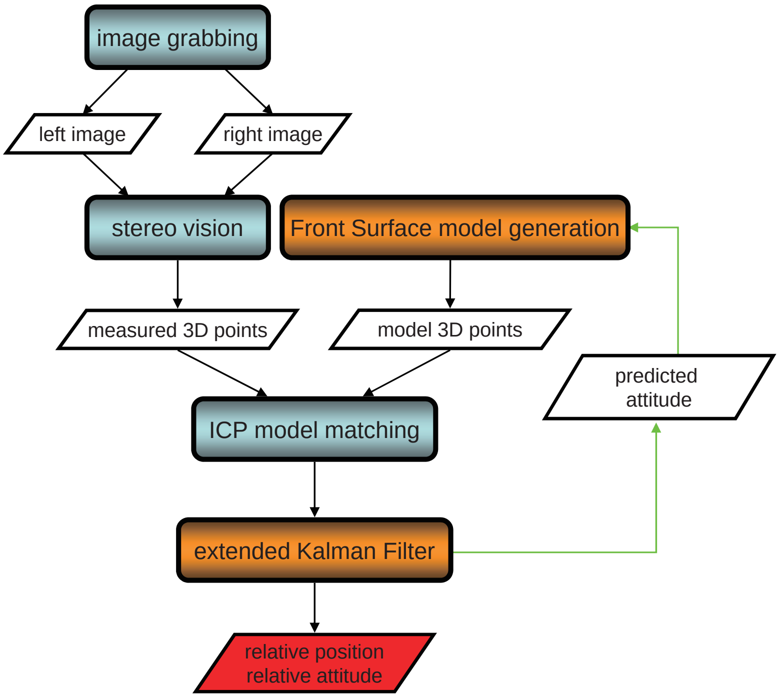
↓

relative position/velocity
relative attitude/attitude rate



software　hardware

A Motion Estimation Strategy using Image (1/3)

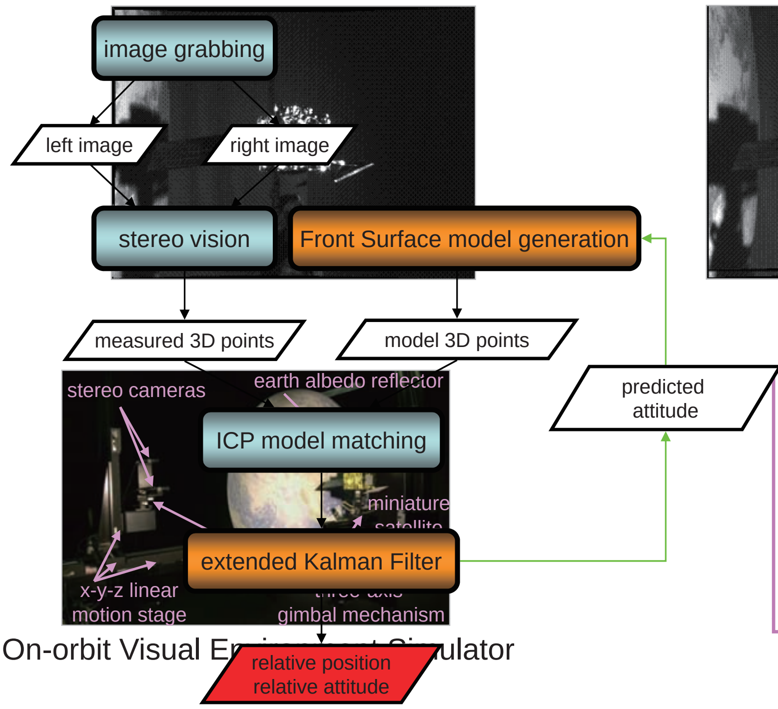


strategy for motion estimation

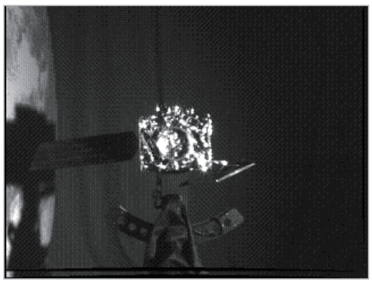
- not affected by **data loss** from
  - **shadows**
  - **occlusion**
  - **specular reflection**
- able to use **3D shape information of visible part of the target** obtained from **ordinary image data**
- **combination of**
  - stereo vision
  - ICP model matching
  - extended KF

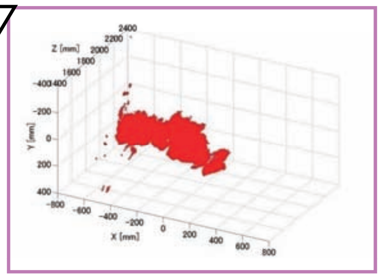
A Motion Estimation Strategy using Image (2/3)

- Stereo Vision



On-orbit Visual Environment Simulator

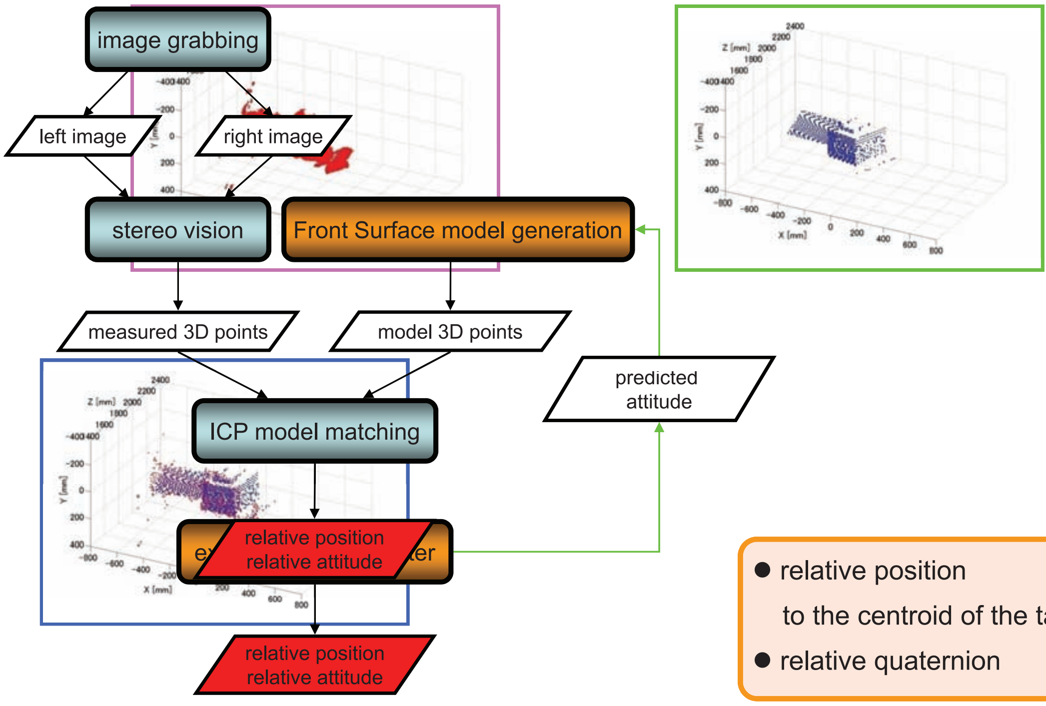




measured 3D points

A Motion Estimation Strategy using Image (3/3)

ICP (Iterative Closest Point) 3D model matching



- relative position to the centroid of the target
- relative quaternion

extended Kalman Filter for attitude estimation

attitude dynamics/kinematics of the satellite

- dynamics (nonlinear)

$$\dot{\boldsymbol{\omega}}_{IT}^{T} = -\left(I_T^T\right)^{-1}\left(\boldsymbol{\omega}_{IT}^{T} \times I_T^T \boldsymbol{\omega}_{IT}^{T}\right)$$

- kinematics

$$\dot{\mathbf{q}}_I^T = \frac{1}{2}\mathbf{q}_I^T \bullet \begin{bmatrix} \boldsymbol{\omega}_{IT}^{T} \\ 0 \end{bmatrix}$$

I : inertial reference frame
C : **chaser**-fixed reference frame
T : **target**-fixed reference frame
$\mathbf{q}_a^b$: quaternion from **a**-frame to **b**-frame
$\boldsymbol{\omega}_{IT}^{T}$: angular velocity vector of T-frame, with respect to **I**-frame, expressed in T-frame

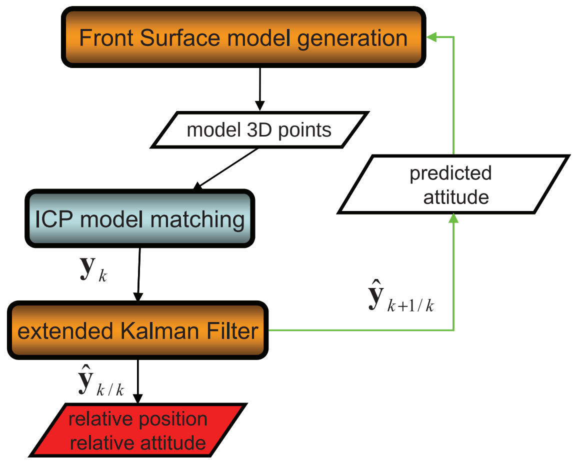
extended Kalman Filter

- states and measurements

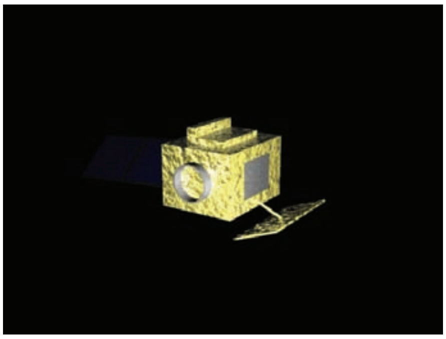
$$\mathbf{x} = \begin{bmatrix} \mathbf{q}_I^T \\ \boldsymbol{\omega}_{IT}^{T} \end{bmatrix} \qquad \mathbf{y} = \begin{bmatrix} \mathbf{q}_C^T \\ \Delta\mathbf{q}_C^T \end{bmatrix}$$

※ $\mathbf{q}_B^T = \left(\mathbf{q}_I^B\right)^{-1} \bullet \mathbf{q}_I^T$, $\Delta\mathbf{q}_C^T = \frac{\Delta t}{2}\mathbf{q}_C^T \bullet \begin{bmatrix} \boldsymbol{\omega}_{TC}^{C} \\ 0 \end{bmatrix}$

Δt : sampling time



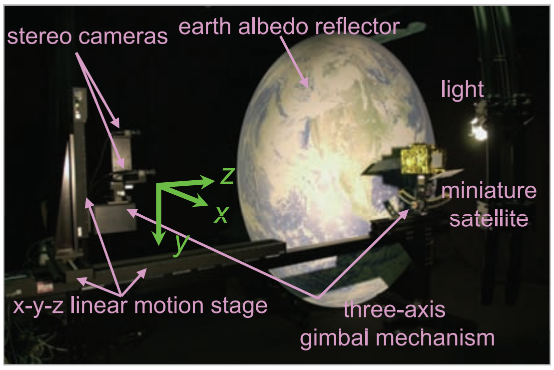
Motion Estimation Experiment



3 kinds of attitude motion（0～100sec）

- Sample A (attitude motion around y-axis)
- Sample B (3-axis relatively small attitude motion)
- Sample C (3-axis relatively big attitude motion)

On-orbit Visual Environment Simulator		scale	1/10
		base line [mm]	40
		distance [mm] (optical center − mockup center)	1870
	satellite mockup	body [mm]	300×250×200
		solar paddle [mm]	400×200
		rader antenna [mm]	320×150
	camera / lens	resolution [pixel]	640×480
		focal length [mm]	6.02

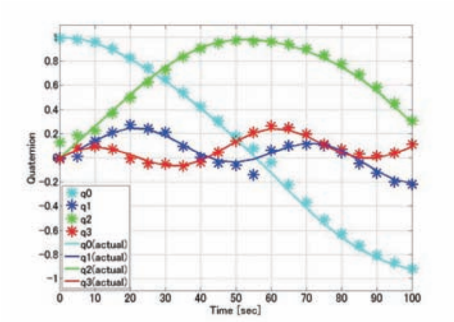


On-orbit Visual Environment Simulator

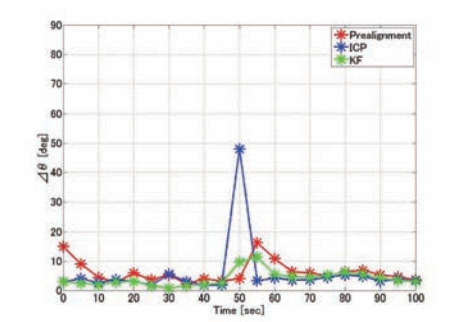
3-axis attitude motion of the miniature satellite model

Sample C

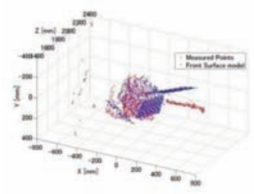
Motion Estimation Experiment
(Sample C)



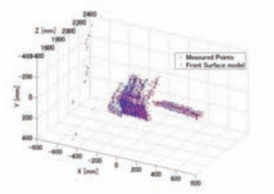
quaternion (actual/estimated)



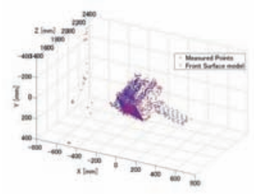
"error attitude angle"
from the error quaternion



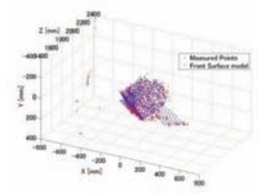
50 sec



55 sec



60 sec



65 sec

A Motion Estimation Strategy using On-orbit Visual Environment Simulator

quasi-real-time binocular image data

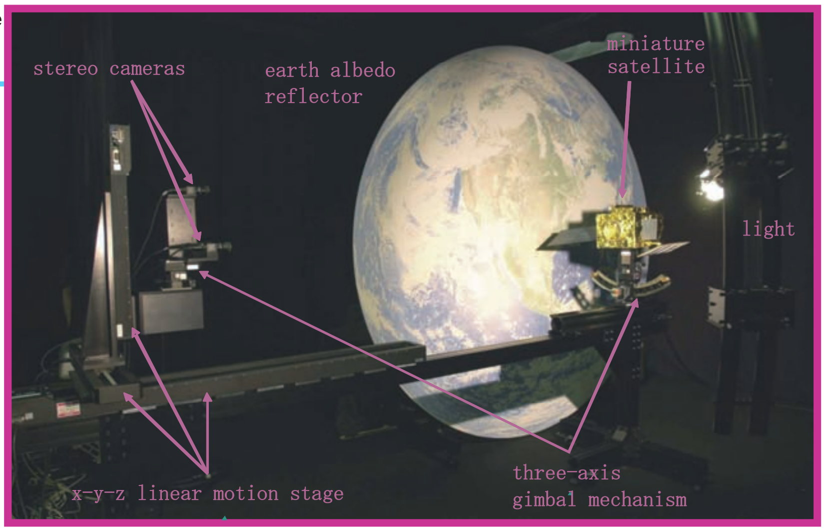
stereo vision & 3D model matching

↓

extended Kalman Filter

↓

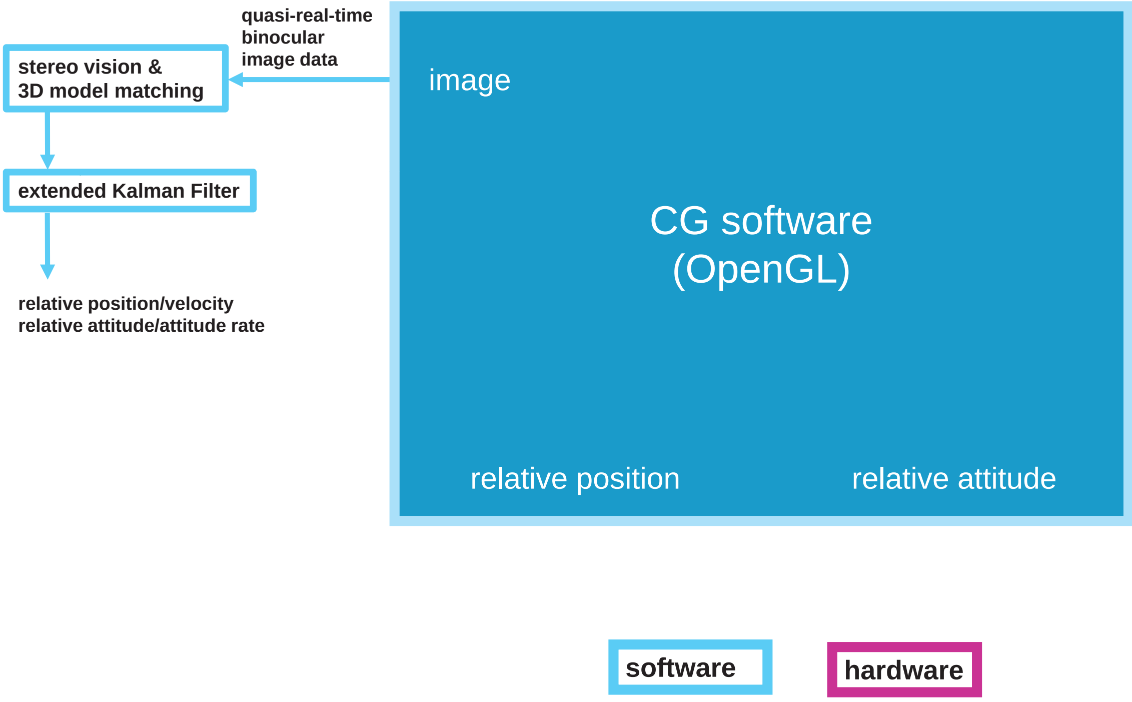
relative position/velocity
relative attitude/attitude rate



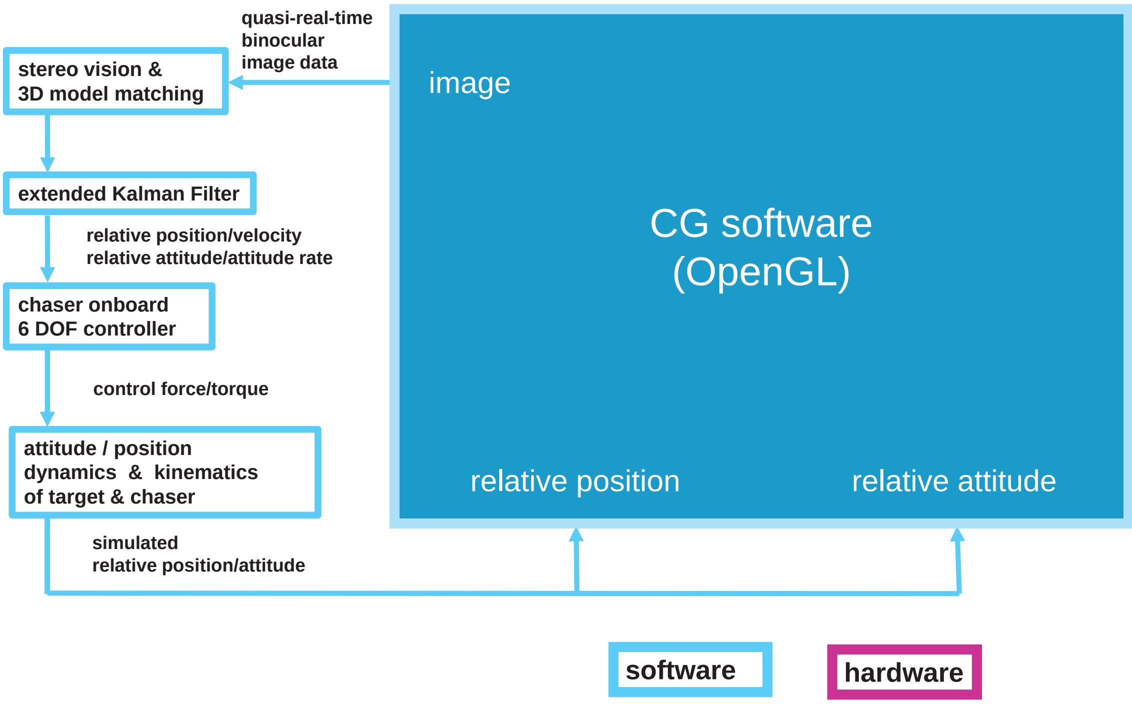
software

hardware

Motion Estimation utilizing CG



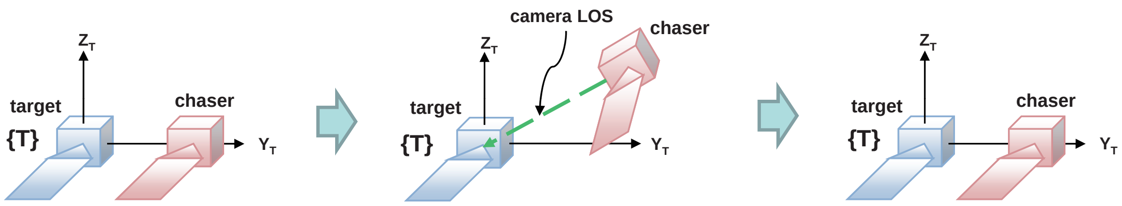
6-DOF maneuver simulation with motion estimation utilizing CG



Numerical Simulation (1)

6-DOF proximity flight around the target

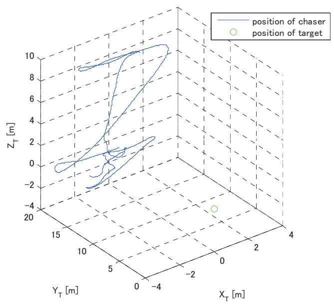
- station keeping -



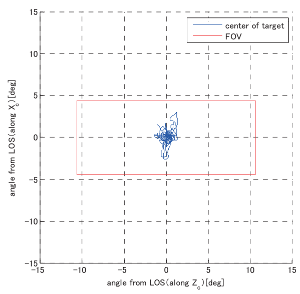
- The **attitude** of the **target** is fixed to the inertia frame.
- The chaser controls its **position** so that its own center of mass to be coincident with the desired position in the target fixed frame {T}
- The chaser controls its **attitude** so that the LOS of the onboard camera points to the mass center of the target
- Images of the target was generated by **CG** and these are processed by motion estimation algorithm (stereo vision + ICP + Kalman Filter) onboard
- The direction of **Sun light** : -Y_T axis → suitable for image capturing

time [sec]	desired position $\mathbf{r}^T_{req}$ [m]
0～400	[0, 18.0, 0]
400～700	[0, 18.0, 10]
700～1000	[0, 18.0, 0]

Numerical Simulation Results (1)



3D position of the chaser in {T}



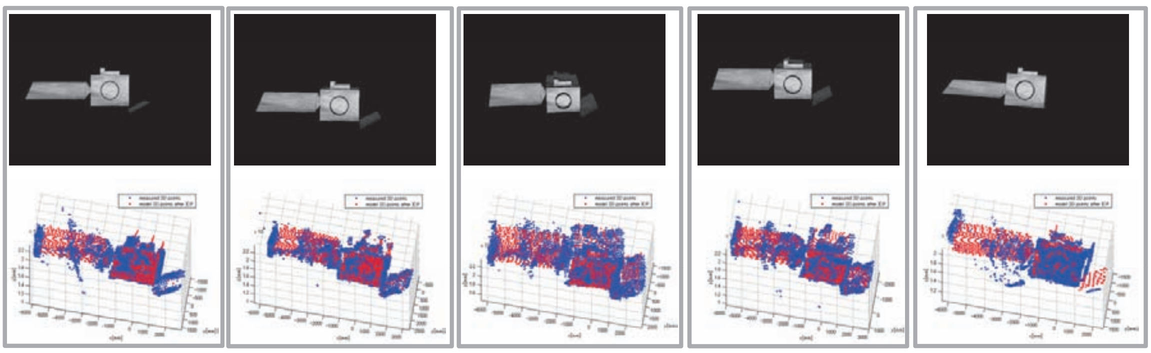
position of the target in FOV

time [sec]	desired position $\mathbf{r}^T_{req}$ [m]
0～400	[0, 18.0, 0]
400～700	[0, 18.0, 10]
700～1000	[0, 18.0, 0]

case1logic3.avi

CG images (left camera)

5 sec 450 sec 700 sec 750 sec 1000 sec



blue : measured 3D points red : model 3D points after ICP

Summary and Future Work

Summary

- **Motion (relative position and attitude) estimation** of a large space debris (e.g. failed satellites) object using **image**
  - **Stereo Vision**
  - **ICP (Iterative Closest Point) algorithm**
  - **extended Kalman Filter**

- 3-axis attitude motion and (static) position are estimated using **a terrestrial simulator**

- **Six Degrees Of Freedom maneuver simulation** with motion estimation utilizing **Computer Graphics**
  - **station keeping**
  - **following nutating target**

Future Work

- **Hardware-In the Loop** simulation for 6-DOF maneuver