C16

光学観測による宇宙物体の動態推定に関する研究

Study on Estimation of Space Object Behavior Using Optical Measurements

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宇宙物体の形状，表面特性，および姿勢運動の推定（動態推定）を行うための手段として，測光観測や撮像観測などの光学観測を用いた手法が盛んに研究されている．測光観測は，地上から見た軌道上物体の明るさの時間変化（ライトカーブ）を用い，撮像観測は光学望遠鏡による撮像画像に対して補償光学による処理を行い，動態推定に用いる．九州大学ではこれまで，測光観測による動態推定の手法を提案し，シミュレーションにより観測精度の検証を行ってきた．また，測光観測における初期値の推定に撮像観測を用いる手法を提案し，実現可能性を検討してきた．本講演では，測光観測による動態推定の手法とその精度，および測光観測と撮像観測を組み合わせた動態推定のシミュレーション結果について述べる．特に，撮像観測において機械学習の一種である畳み込みニューラルネットワークによる画像識別を適用する取り組みについて取り上げる．

Optical measurements such as photometric observations and imaging observations have been widely applied for estimating the shape, surface characteristics, and attitude motion of space objects. Photometric observation-based methods use light curves, the time history of the brightness of a space object, whereas imaging observation-based methods use images captured by the optical telescope and processed with adaptive optics. In Kyushu University, studies on the state estimation of space object with photometric observations have been conducted. In addition, an imaging observation-based method to determine an initial value for photometric observations and its feasibility have been studied. The current study describes a photometric observation-based method and verifies its accuracy by numerical simulations. Furthermore, a state estimation method that exploits both photometric observations and imaging observations is presented. The proposed method also shows the efficiency to apply image identification by convolutional neural network, a kind of machine learning, in imaging observations.

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Optical measurements

For ADR(Active Debris Removal),
behavior of space object must be estimated

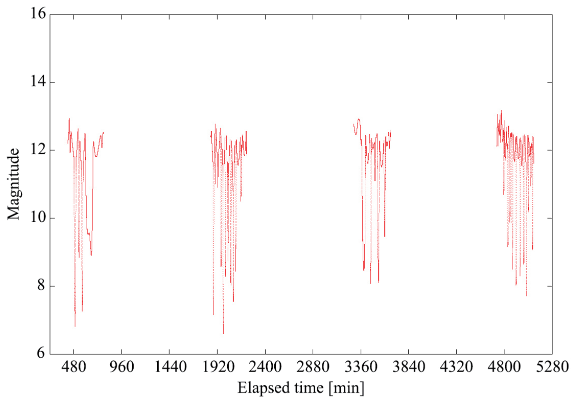
→ Optical measurements

Methods
- Spectroscopic observation
- Polarization observation
- Photometric observation
- Imaging observation

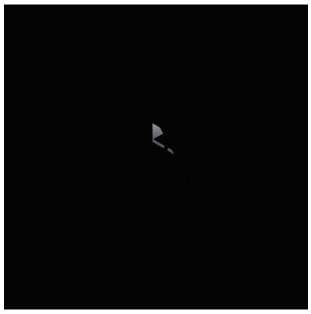
Subjects
- Composition
- Shape
- Surface characteristics
- Attitude

Photometric observation

Light curve



History of magnitude
of the space object



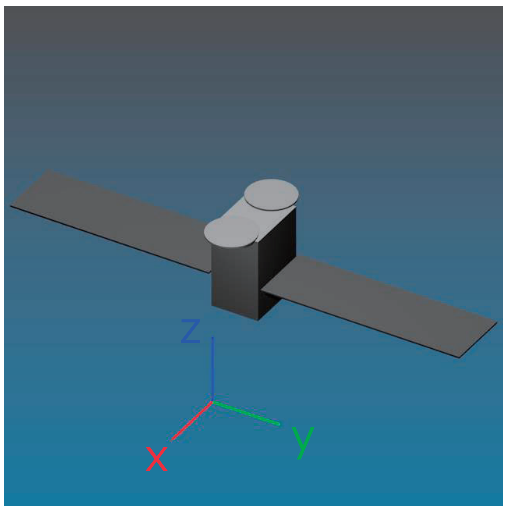
Attitude

Imaging observation is needed
to estimate initial attitude

Satellite model

JCSAT3

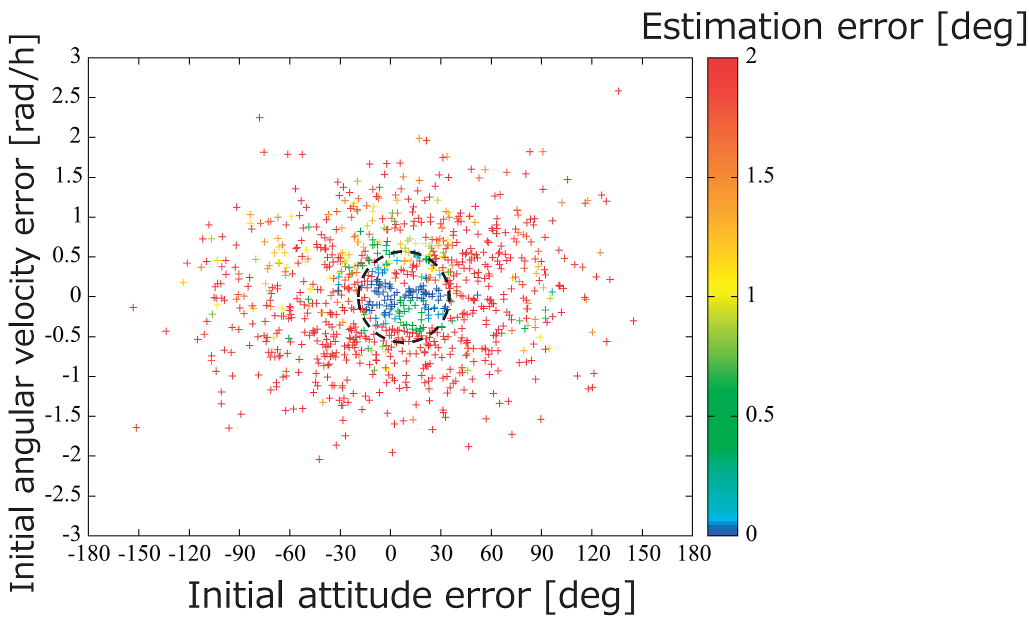
Height stowed	4.9m
Width stowed	2.8m × 3.8m
Solar Arrays deployed	26.2m
Antennas deployed	7.5m



Surface characteristics

	absorption	diffusion	specular
Bus	0.1	0.6	0.3
Paddles	0.76	0.16	0.08
Antennas	0.16	0.56	0.28

Requirement of initial attitude



Initial error should be less than 30 deg

Simulation of imaging

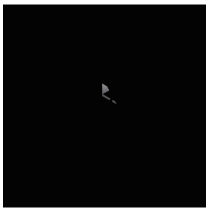
Generating images from 3D model and PSF

PSF(Point Spread Function): Transfer function of the effect of atmospheric fluctuation, telescope, and adaptive optics

Convolution

Raw image PSF Simulated image

Attitude estimation



Raw images

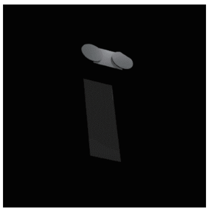
$I_n\ (i,j)$

Dataset

$I'_n\ (i,j)$

$\boldsymbol{f}_{I'_n}$

Comparison



Raw target images

$T(i,j)$

Target images

$T'(i,j)$

Poisson distribution

$SNR = \sqrt{N}$

$\boldsymbol{f}_{T'}$

Image comparison algorithm

Feature extraction : using methods of template matching

R^n_{SAD} Brightness error against target image

R^n_{ZNCC} Cosine similarity against target image

$$\boldsymbol{f}_{I'_n} = (R^n_{SAD},\ R^n_{ZNCC})$$

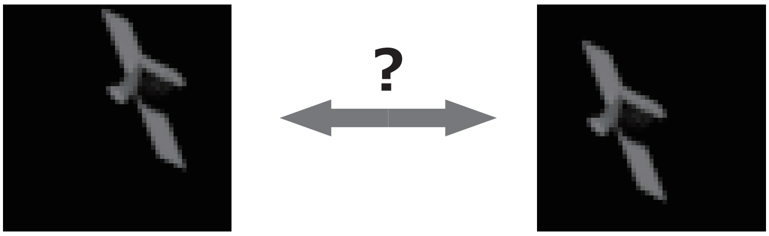
$$\boldsymbol{f}_{T'} = (0.0\,,1.0)$$

$$\mathrm{norm}_n = \left\|\boldsymbol{f}_{T'} - \boldsymbol{f}_{I'_n}\right\|$$

→ Find a image that minimize norm_n from dataset

Problems

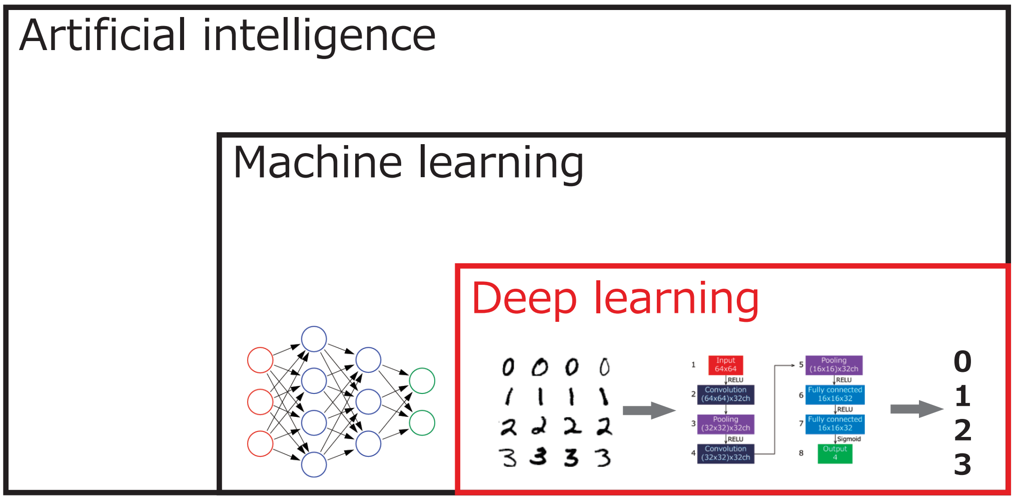
- Satellite images that are not centered cannot be compared with dataset



- In some cases attitude error increased due to the symmetry of the satellite

Deep learning

Deep learning is a field of artificial intelligence and widely used in image processing



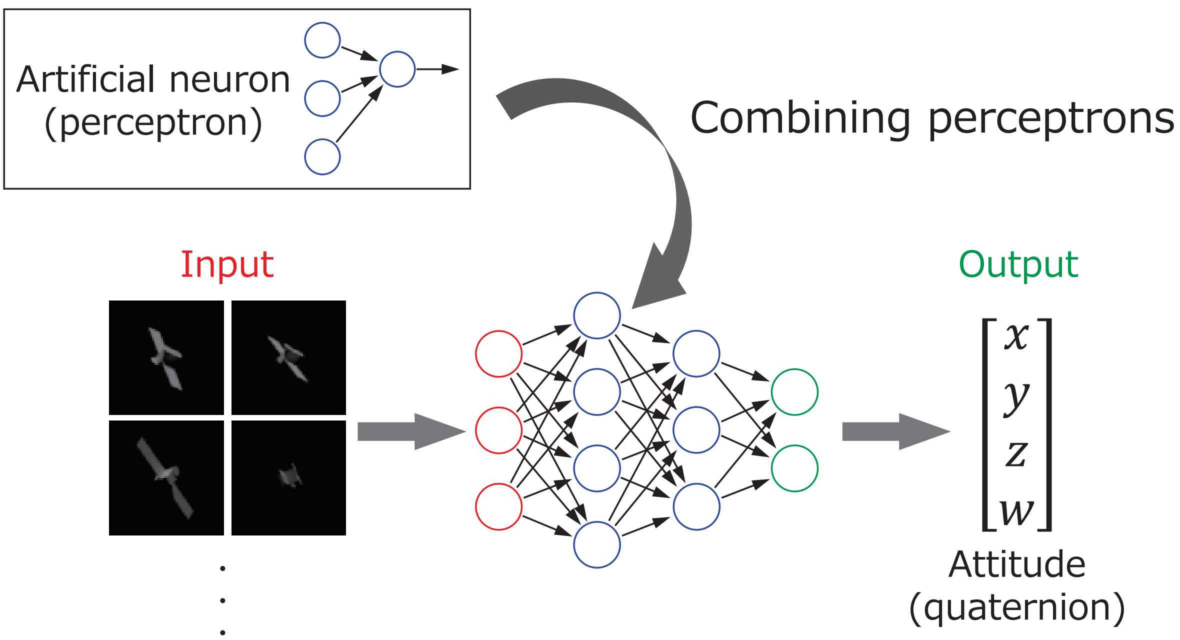
Objective

Improving robustness of imaging observation
without increasing processing time by deep learning

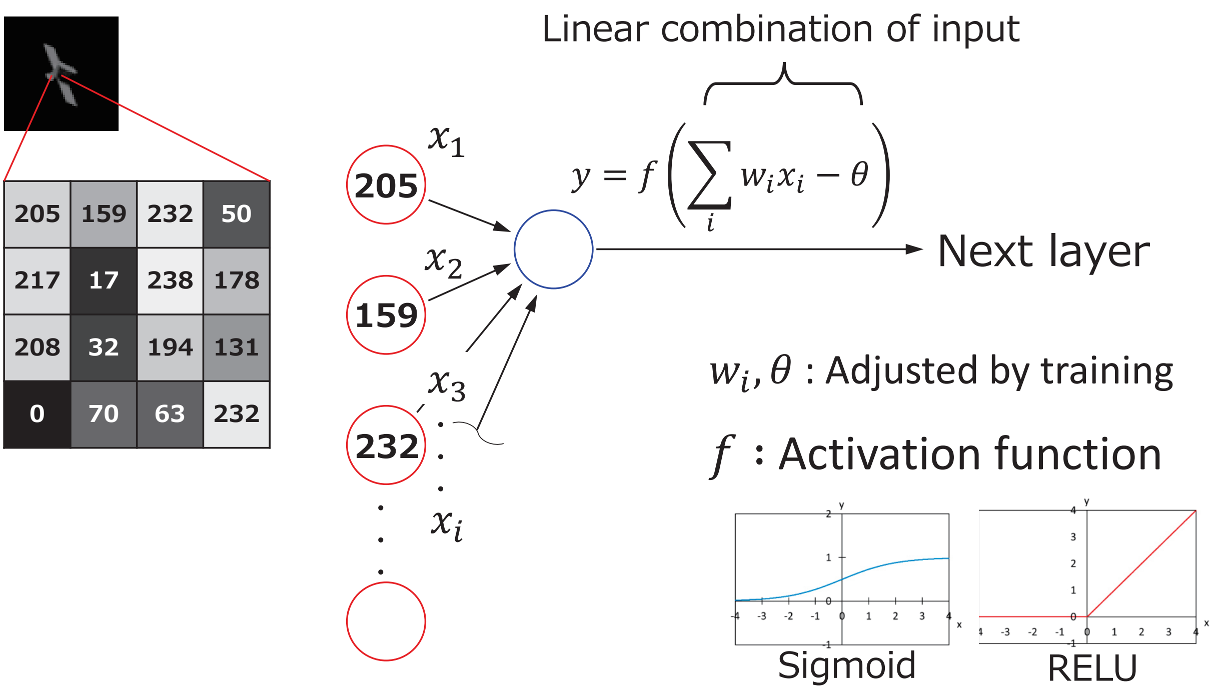
↓

Using images without noise to estimate attitude
as the first step

Artificial neural network



Function of artificial neuron



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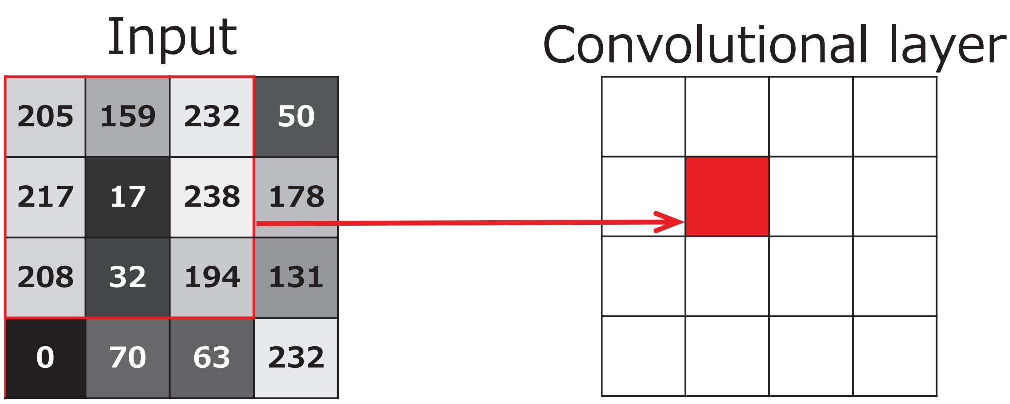
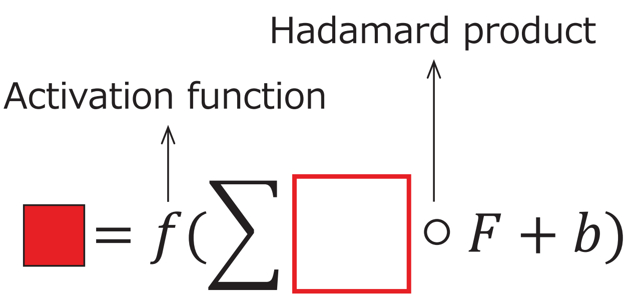
Convolutional layer

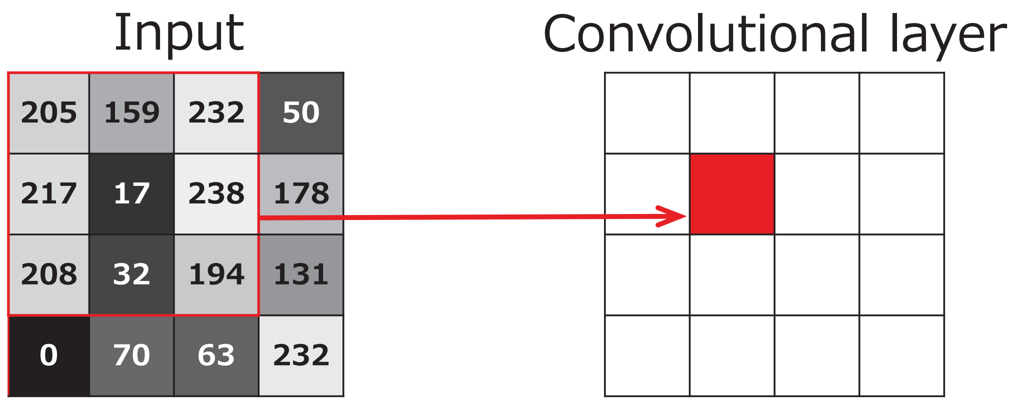


F : Filter

$$F = \begin{bmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{bmatrix}$$



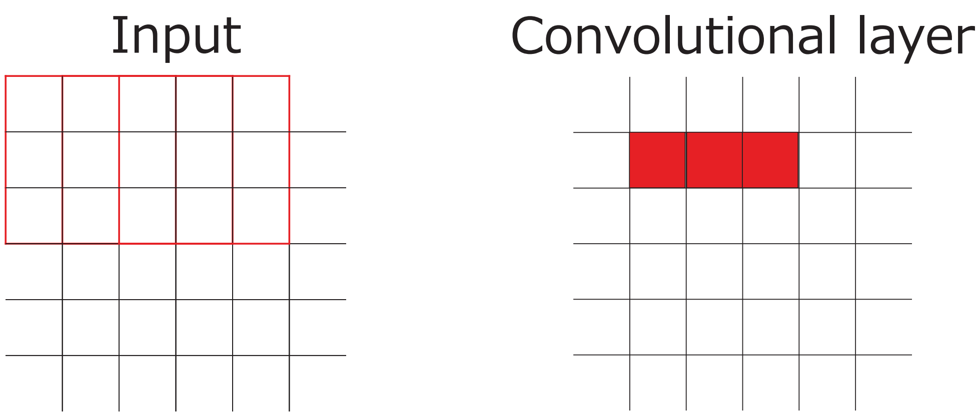
Convolutional layer



= f(Linear combination of)

Partly, it is the same process
as a fully connected layer

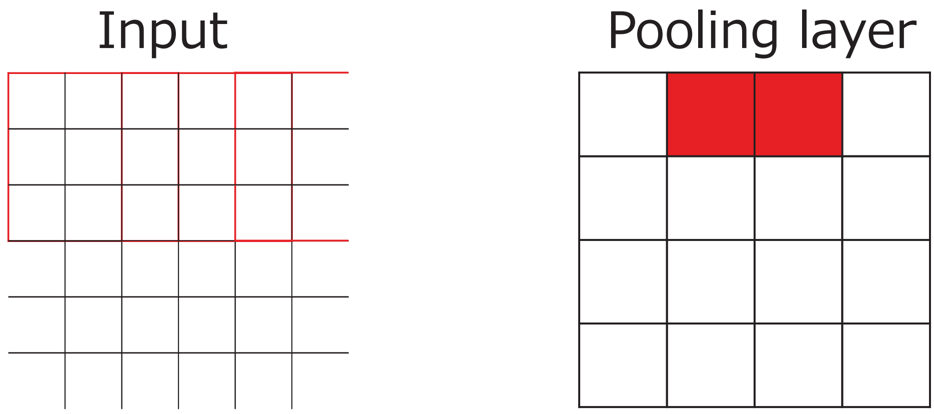
Convolutional layer

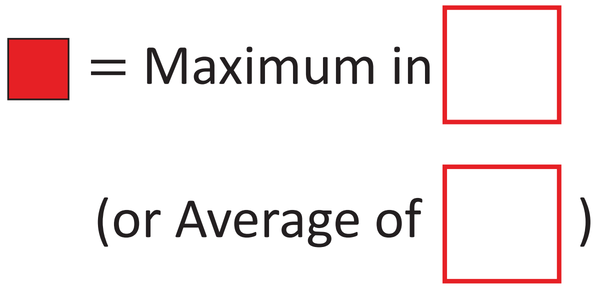


= f(Linear combination of)

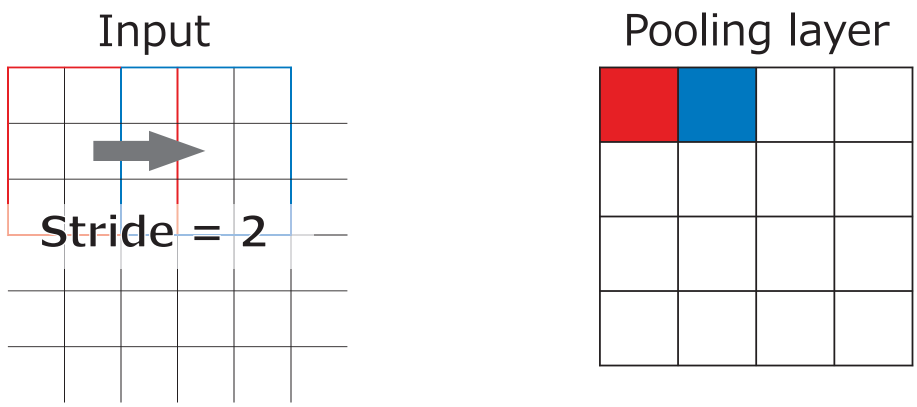
Partly, it is the same process
as a fully connected layer

Pooling layer





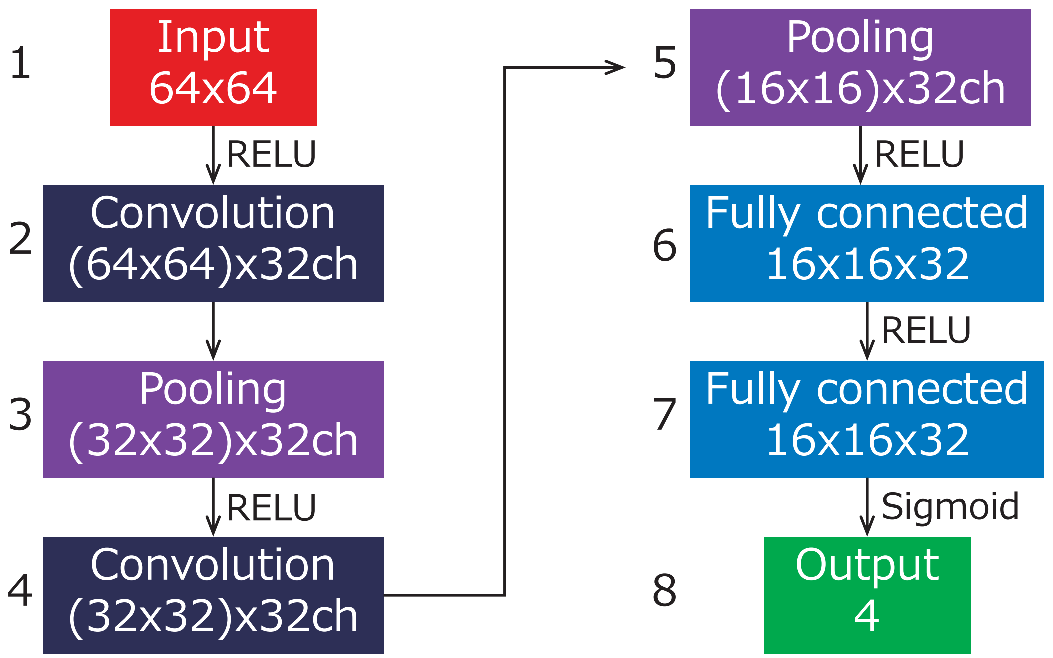
Pooling layer



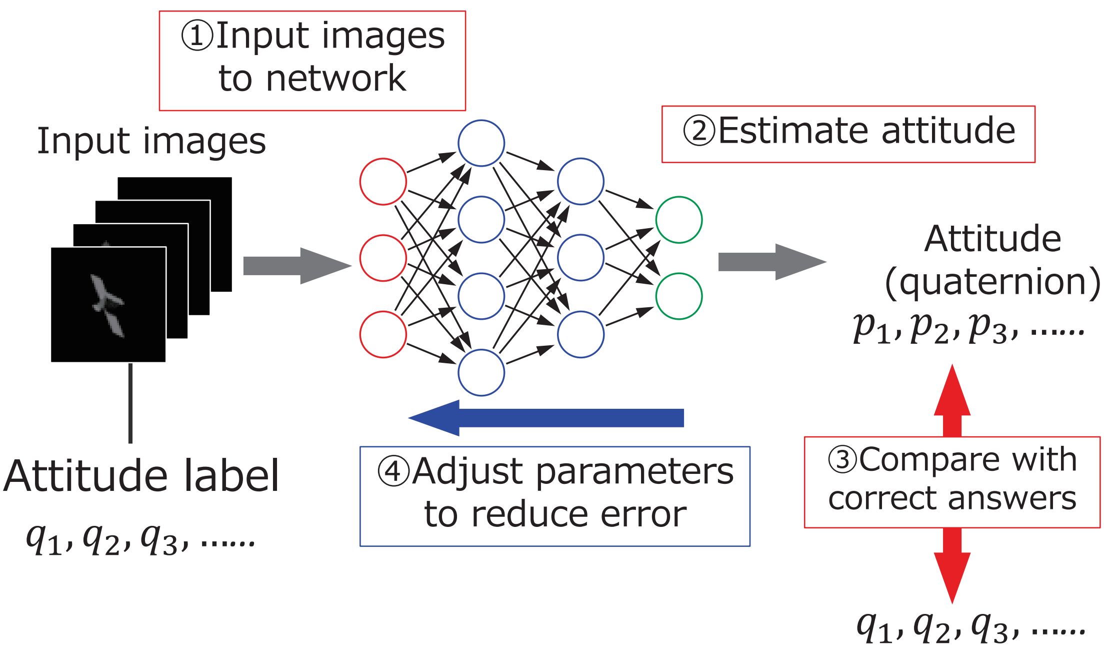
Stride : interval of pooling window sliding

Feature value can be condensed
by setting the **stride** larger than 1

Overall picture of the model



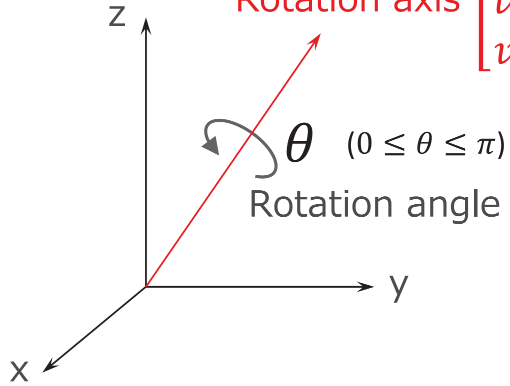
Steps of learning



Quaternion

Attitude representation by quaternion

Rotation axis $\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}$: Unit vector



$$\text{Quaternion } \tilde{q} = \begin{bmatrix} v_x \sin\frac{\theta}{2} \\ v_y \sin\frac{\theta}{2} \\ v_z \sin\frac{\theta}{2} \\ \cos\frac{\theta}{2} \end{bmatrix}$$

Definition of error angle

Error valuation based on quaternion

$\tilde{q}$: True quaternion $\tilde{q} = \begin{bmatrix} q_x \\ q_y \\ q_z \\ q_w \end{bmatrix}$

$\tilde{p}$: Estimated quaternion

$\tilde{e}$: Error quaternion

$$\tilde{q} = \tilde{e} \otimes \tilde{p}$$

$$\tilde{e} = \tilde{q} \otimes \tilde{p}^{-1} = \begin{bmatrix} q_w & q_z & -q_y & q_x \\ -q_z & q_w & q_x & q_y \\ q_y & -q_x & q_w & q_z \\ -q_x & -q_y & -q_z & q_w \end{bmatrix} \begin{bmatrix} -p_x \\ -p_y \\ -p_z \\ p_w \end{bmatrix}$$

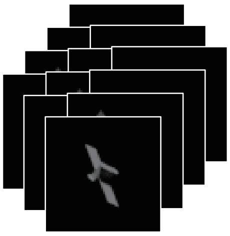
$$e_w = |\tilde{q} \cdot \tilde{p}|$$

$\otimes$: Quaternion product

$$\text{Error angle} = 2\cos^{-1}|\tilde{q} \cdot \tilde{p}|$$

Training and test data

Training data
12416 images



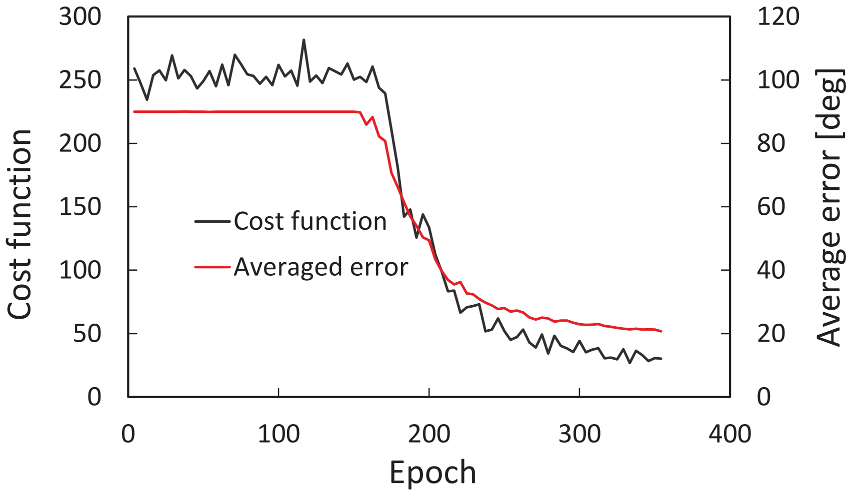
Images with
evenly spaced
attitude

Test data
1000 images

Images with
random attitude

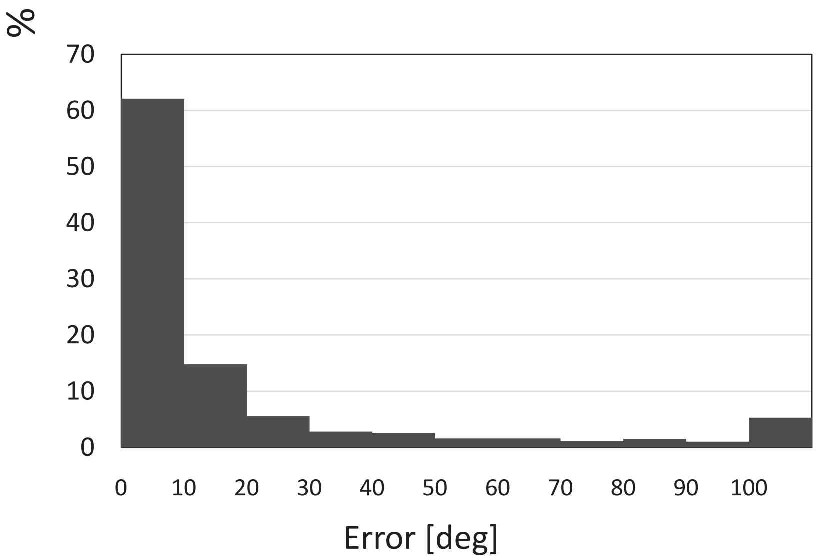
PSF was not considered

History of learning



Average error converged to 21 degrees

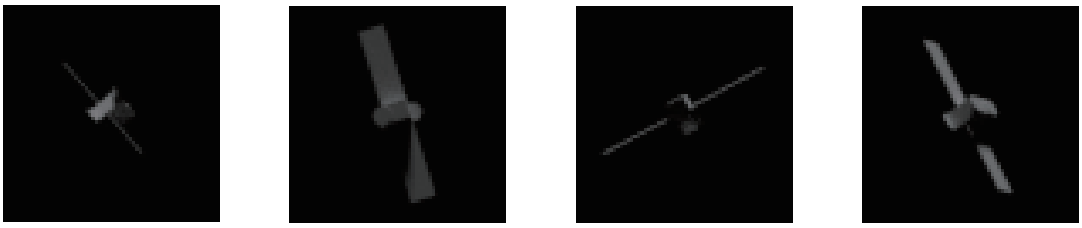
Distribution of errors



More than 80% of test cases are under 30 deg

Cases with biggest errors

Input images



Estimated attitude

Error = 177° 178° 179° 176°

Most of these are difficult to estimate attitude from images

Conclusion

- Over the 80% of estimated initial attitude results satisfy the requirements for accurate photometric observation
- In some cases attitude error increased due to the symmetry of the satellite