DeMaMech Exchange Program Report

Aug. 2005 – Jan. 2006

Technical University Delft & Denmark Technical University

Hokkaido University

Daisuke Ishikawa

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Executive summary

I stayed in Delft from 23rd August to 22nd December and in Lyngby from 2nd to 25th January. It was first time to visit Europe, so everything I had experienced was all fresh and unforgettable.

I engaged in the research whose title is "Noise properties of wavefront sensor in Adaptive Optics." Adaptive Optics (AO) is a method to remove the effect of atmospheric turbulence adaptively in real-time by compensating the aberrated wavefronts and used for various fields such as astronomy, industrial measurement, and so on. AO systems mainly consist of a wavefront sensor, a deformable mirror, and a real-time control system. The aim of my research was to find the noise sources which influence on the output of the wavefront sensor in the measurement of wavefront. Some kinds of noise could be expressed mathematically. It was found that a lot of noise sources (photon noise, truncation noise, etc) cause the quality debasement of the output of the wavefront sensor.

I also took two courses in Delft. One is "Lower intermediate English course", and the other is "Advanced optical imaging". In English course, I learned writing, speaking, and listening English. I could get a relatively high evaluation in this course. In the course "Advanced optical imaging", I studied optical microscopy as well as basic optics. In the end of the course, I made a 40-minute presentation about CCD camera. It was quite difficult for me to present for such a long time in English, but I prepared 30 Power point pages and managed to make it.

The life in Delft was comfortable except for some minor problems; all shops closed on Sunday and the bicycle was easily broken. I could get acquaintance with the people from various countries. I learned the differences between Japan and the other countries. I think it was one of the most important things.

Unfortunately, I could not take any course in Denmark, because the course which I applied for was cancelled due to too few participants. The rest of courses I could take were all far from my specialized field such as bio technology. For this reason, I engaged in the research in my home university. During in Denmark, I lived in the container in which 9 people from various countries lived. I made Su-shi for all the people in my container. It was quite nice experience.

Through this program, I could get a lot of experience and knowledge. In the future, I hope I can work in the other countries with this experience.

Date	Activity

22nd-23rd August 2005	Sapporo-Narita-Paris-Amsterdam
22nd-31st December 2005	Den Haag-Berlin-Copenhagen
25th-27th January 2006	Copenhagen-Munich-Frankfurt-Narita

Travel Schedule

Research

1. Introduction

Adaptive Optics (AO) is a method to remove the effect of the atmospheric turbulence by compensating the aberrated wavefronts and used for various fields such as astronomy and industrial measurement. A typical adaptive optics system has three main components: a wavefront sensor, a deformable mirror, and a real-time control system. A wavefront sensor measures the distortion induced by the atmospheric turbulence on the incoming wavefront. Of the existing wavefront sensors, Hartmann-Shack wavefront sensors are currently the most widely used in astronomy, ophthalmology, and laser beam control. This wavefront sensor comprehends a microlens array placed at a certain distance from an imager. An incoming lightbeam is sampled into as many spots as the number of sub-apertures in the microlens array. The displacement of each spot at the imager is a measure for the local tilt of the wavefront of the incoming beam.

It is desired that the Hartmann-Shack wavefront sensor has infinitely fine sampling of the image and is free of any kind of noise. But, in practice, a large number of factors degrade the performance of the sensor, and they are generally referred to as sensor errors. It is the difference between the actual local wavefront tilt and that seen by the sensor. The sensor error fundamentally limits the accuracy to which a wavefront can be estimated and consequently corrected. For this reason, there have been many attempts to reduce this error. In my research, the properties of some noise source which cause the sensor error are shown.

2. Hartmann- Shack Wavefront Sensor

The Hartmann method is the most promising to measure the phase of incident light. This method consists of an opaque mask with grid of sub-apertures: the Hartmann mask. Fig.2.1 shows the schematics of Hartmann setup. In this method, the wavefront is sampled into as many spots as the number of sub-apertures. When the plane wavefront, which is parallel to the mask and regarded as reference, enters the setup through the mask, each spot centroid on the imager is exactly under its respective sub-aperture. But, when the wavefront is aberrated (i.e. not flat), the spot centroids depart from their reference positions; the distance of which is proportional to the respective local tilt of the wavefront. Using the spot centroid displacement and the distance between the mask and imager, the local tilt can be calculated.

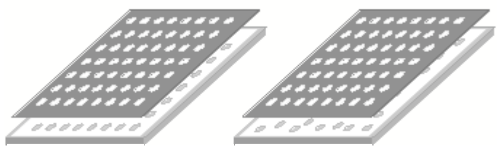
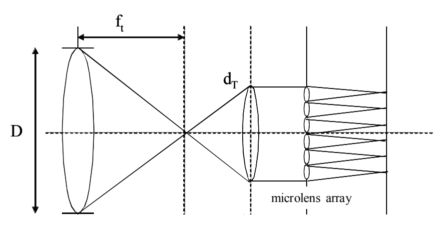


Fig. 2.1 the schematics of Hartmann setup

A variation to Hartmann method is the Hartmann-Shack setup, in which the Hartmann mask is substituted with an array of microlenses. This method has the advantage of gathering more light power per spot and covering the whole sensing area. A simplified schematic of the Hartmann-Shack technique is presented in Fig.2.2. A locally plane wavefront will be focused on the optical axis of the microlens, while a locally tilted one will be focused outside, i.e. the wavefront tilts are obtained with the Hartmann-Shack wavefront sensor by calculating spot centroid displacement on the detector. One of the simple estimations is done by calculating spot’s center of gravity (COG).



3. Noise in measurement with Hartmann-Shack wavefront sensor

Wavefront measurements are corrupted by noise from various sources, which are distinguished in terms of the source of the noise. One is detector noise and the other is truncation noise. Detector noise includes photon (shot) noise, readout noise, dark current noise, fixed pattern noise, and sampling noise.

3.1 Detector noise

Photon noise results from the inherent uncertainty of the arrival rate of photons incident on the detector. The interval between photon arrivals is governed by Poisson statistics and described as follows.

$$N_p \propto \sqrt{S} \tag{3.1}$$

where N_p is the photon noise, and S is the signal, both of which are stated as the number of photons. Photon noise imposes severe limitations on the performance of the sensor particularly under low light levels. This noise is a form of image-dependent noise, which means its strength depends on the number and the distribution of the detected photons.

The general form of the variance due to photon noise is given as follows;

$$\sigma_s^2 \propto \frac{1}{n}\left(\frac{\theta_b d}{\lambda}\right)^2 \quad (\mathrm{rad}^2) \tag{3.2}$$

where n is the number of photons detected per sub-apertures and exposure time, θ_b is the angular size of the source image, and d is the sub-aperture diameter.

Thermal noise is attributable to kinetic vibrations of silicon atoms in the CCD substrate that liberate electrons or holes even when the device is in total darkness. The electrons which are independent of the light falling on the detector are captured by the potential wells of CCD pixels and counted as signals. For this reason, the noise is referred to as dark current noise, which is caused by the rate of generation of dark charges, termed dark current. It is unrelated to photon-induced signal but is highly temperature dependent as the following equation indicates:

$$D = CT^{1.5}e^{-E_g/2kT} \tag{3.3}$$

where D is the average dark current generated, T is the operating temperature (K), E_g is the silicon band-gap energy (eV), and k is the Boltzmann constant (8.62×10^{-5}). The band gap energy varies with operating temperature according to the equation

$$E_g = 1.1557 - \frac{7.021\times10^{-4}T^2}{1108+T}. \tag{3.4}$$

The constant C can be solved at room temperature (300K) yielding

$$C = \frac{N_{dc}P_s}{qT_{rm}^{1.5}e^{-E_R/2kT_{rm}}} \tag{3.5}$$

Where P_s is the pixel size (cm^2), N_{dc} is the dark current at 300K ($\mathrm{nA/cm}^2$), and q is the electronic charge (1.6×10^{-19}). Assuming the quantity N_{dc} follows Poisson distribution, substituting Eq. (3.5) into Eq. (3.3) produces the formula for dark current.

$$D = 2.5\times10^{15}P_sN_{dc}T^{1.5}e^{-E_g/2kT} \tag{3.6}$$

By using the term of dark current, dark current noise only is defined as follows;

$$\sigma_{Dark}^{2} = D \cdot n_{pix} \cdot \Delta t \qquad (3.7)$$

where n_{pix} is the number of pixels of detector, and Δt is the integration time relative to a single frame.

Fig. 3.1 shows the dark current for the temperature. It is readily apparent that cooling CCD reduces the noise to a negligible value. Besides, according to the Eq. (3.7), the level of the noise is proportional to the length of the exposure. Given a long exposure time, the detector becomes fully saturated with electrons in a large part due to the noise.

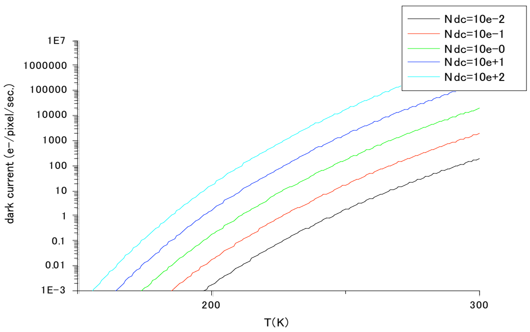


Fig. 3.1 dark current for the temperature

Readout noise is a combination of system noise components inherent to the process of converting CCD charge carriers into a voltage signal for quantification, and the subsequent processing and analog-to-digital (A/D) conversion. The major contribution to read noise usually originates from the on-chip preamplifier, and this noise is added uniformly to every pixel. The readout noise is a form of image-independent noise, and its variance increase with the number of pixels as follows:

$$\sigma_{RN}^{2} = n_{pix} \cdot {N_R}^{2} \qquad (3.8)$$

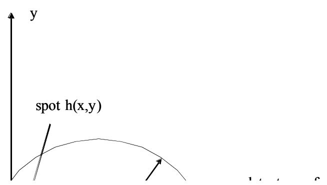
where n_{pix} is the number of pixels and N_R is readout noise.

Fixed-pattern noise is characterized as spatially fixed variations in the gain of the imaging system, i.e. variations in the amount of output signal for a given input quantity. The source of fixed-pattern noise in the systems under investigation is quantum efficiency (QE) variation from pixel to pixel.

As the size of CCD array in pixels is a fixed quantity, it is impossible to divide the detector into the infinite number of pixels. The finite number of pixels causes sampling noise. On the other hand, increasing the sampling rate causes isolated photon events, because the number of photons received by the detector is spread out over a higher number of pixels. As a result, the dynamic range drops proportionally to the sampling rate.

3.2 Truncation noise

Reducing the width of the detector causes truncation noise. This noise occurs because the spot has a certain width on a detector, and a limiting the region of integration involves truncating part of the spot. Fig.3.2 shows the geometry of the error measurement on a detector array due to truncation. In this figure, the hatched area denotes the truncation region. It is assumed that the spot is held at the origin and the detector surface is allowed to move around. As seen in Fig.3.2, truncation noise causes a displacement of the centroid (i.e. the spot centre on the detector surface) from the reference, with the noise becoming more severe as the detector moves further away. The displacement *b(m)* of the centroid is calculated in one direction.



$$b(m)=\frac{\int_{x=-\rho+m}^{\rho+m}\int_{y=0}^{\sqrt{\rho^2-(x-m)^2}} x\,h(x,y)dxdy}{\int_{x=-\rho+m}^{\rho+m}\int_{y=0}^{\sqrt{\rho^2-(x-m)^2}} h(x,y)dxdy} \tag{3.9}$$

where m is a variable to denote the horizontal shift of the detector, and the denominator represents the area of the spot inside the detector. The movement of the centroid obeys the Gaussian distribution with a variance, σ^2, given by following formula.

$$\sigma^2 = 0.36 r_0^{-5/3}\lambda^2 D^{-1/3} = 0.36\left(\frac{\lambda}{D}\right)^2\left(\frac{D}{r_0}\right)^{5/3} \tag{3.10}$$

where D is the width of the sub-aperture, λ is the light wavelength, and r_0 is Fried parameter. Two-dimensional Gaussian PDF is given by

$$f_G(x)=\frac{1}{\sqrt{2\pi\sigma}}\exp\left[\frac{-(x-\varsigma_j)^2}{2\pi\sigma^2}\right]\exp\left[\frac{-(y-\varsigma_j)^2}{2\pi\sigma^2}\right] \tag{3.11}$$

Thus the expected variance due to the truncation in two-dimensional is

$$\sigma_t^2 = 2\left(\frac{2\pi}{d}\right)^2\int_{-\infty}^{\infty}(b(m))^2 \times f_G(x)dx \tag{3.12}$$

As can be seen in this equation, the variance depends on the detector radius and the centroid displacement of the detector. This noise decreases as the detection radius increases because the larger the detector, the smaller the truncated area, and the smaller the effects of truncation.

An AO system uses closed loop control aimed at flatterning the wavefront. In this way, only slight movement of the spots occurs, resulting in less influence from truncation error.

4. Conclusion

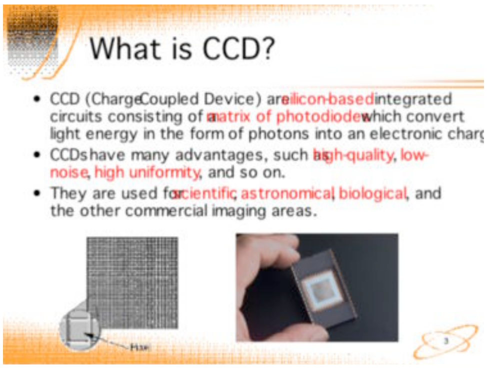
Some noise sources in the Hartmann-Shack wavefront sensor are described. These noises are influenced on many factors, such as the number of photons and pixels, temperature, and so on. A lot of effort is made to reduce the noise in the wavefront sensor. If the effect of noise can be minimized in the future, for instance in astronomy, we will obtain clearer images of the stars far from the Earth, which is a contribution to the space industry.

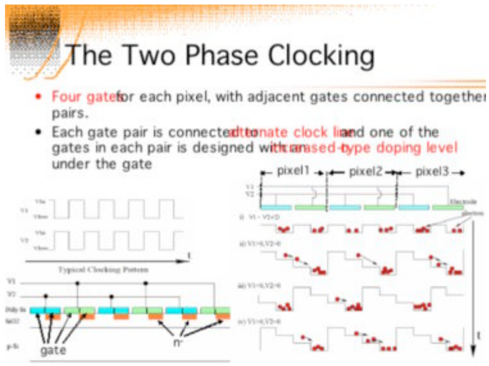
Course

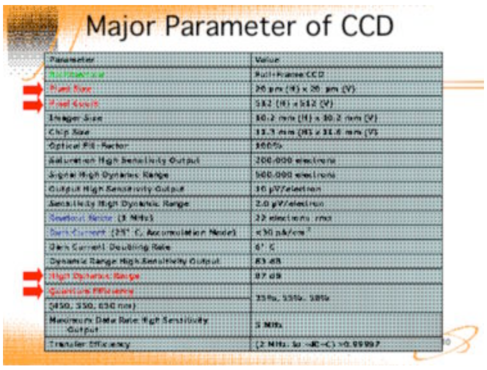
The course "Advanced Optical Microscopy" in Delft is described because I could not take 3-week course in DTU due to the cancellation of the course I applied for.

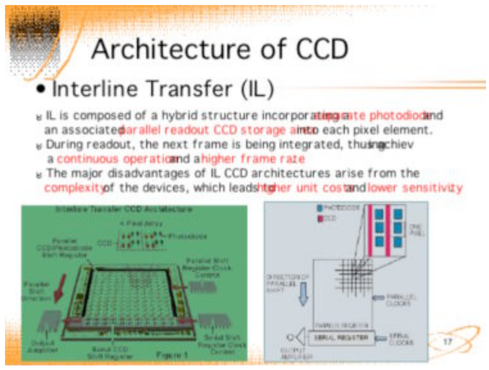
The aim of this course was to learn basic optics, some kinds of microscopy, and basic biology. In the first half of the course, the teacher explained the concept of basic optics, microscopy, and biology. In the second half of the course, each student made an over 30-minute presentation. My presentation was about CCD camera. At first, I worried about the presentation because I must present over 30 minutes. I made 27 power point slides, and practiced so that every participant could understand well.

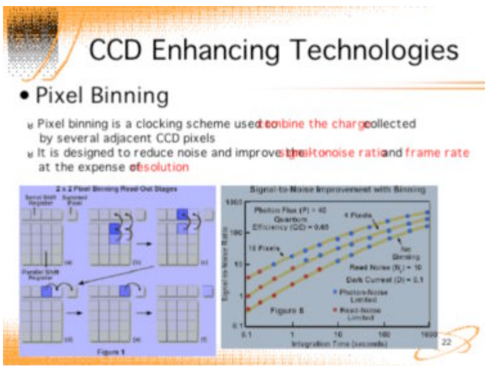
On the presentation day, I had some trouble with explanation, so I sometimes use the script. The teacher, looking at my script, said that I should explain without it. I managed to finish the presentation without it. After presentation, the teacher evaluated that I should have improved my English but the slides was quite nice and easy to understand. In the following, some slides I made are shown.

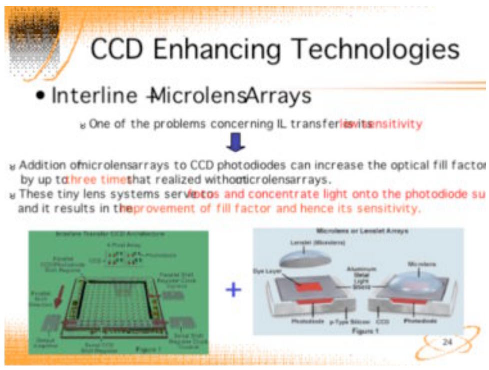












Exchange Student Life

1. Technical University Delft

I stayed in Delft from 23rd August to 22nd December. While I was in Delft, I had a lot of precious experiences which I could not get in Japan. In the following, the environment which I lived in and my consideration for it are described.

University

I belonged in Delft Centre of Systems and Control (DCSC) in TU Delft. I mainly use two facilities; 3mE building and the Centre Library in the university. Three faculties are included in 3mE building; mechanical, maritime, and material engineering. DCSC is one of the departments of mechanical engineering. In my laboratory, there are no rooms for students, so I studied my research in the shared space. We can use internet through our own computer because the wireless LAN is available in the whole area in the university.

I could also use the Centre library. The building is characterized by its artistic shape. Contrary to the laboratory in my home university, we can not use all facilities in the university on weekends, except for the library. For this reason, I usually went there on weekends when I had to progress my research. I sometimes spent whole day in this building.

The biggest problem during my stay in Delft was that I could not contact my supervisor well because of his business. From the beginning of November, PhD student supervised my research. I could hold meetings with him per a week and he kindly gave me some useful advices. Thanks to him, I could manage to finish my report.

I took two courses as well as I made research. To my surprise, the students participating in these courses are very active. They asked many questions to the teacher, and nobody fell asleep during courses. I think that Japanese students should learn these points. Besides, teachers were eager to teach to the students and their courses were attractive, which would results in high motivation of the students.

English

The English skill of Dutch people and the people from the other countries is quite high. Even Asian people can speak it fluently in Delft. In order to talk with those people well, I took a English conversation course which is run by the International Neighbor Group as well as the English course in the university. The students were from Spain, Brazil, and Japan, and the teacher is from Scotland. This course is really good and I could learn some English skill through it.

Life in my accommodation

My accommodation in Delft was tall building and there are many people who have various nationalities. The location is very good because the supermarket is next to the building, and it took 10 minutes from there to the university by bicycle (Bicycles are the most important transportation in Delft). There is also big shopping center near the building, and I could get everything I needed. In my room, my friend’s room, or some bars, a lot of parties were took place, such as birthday parties and farewell parties. Also, the international student parties were held on every Wednesday in the bar located in the center of Delft. I could get acquaintance with many people from various countries. Although my English skill is not so high, they kindly talked to me.

2. Denmark Technical University

From 2^{nd} January to 25^{th} January, I stayed Lyngby, which DTU is located in. Though the life there was so short, I could have nice experiences.

University

The campus of DTU is as large as TUD, but the atmosphere was different from it. I mainly studied in my room, a university library, or a data bar, where I can use wireless LAN.

Life in my accommodation

In Lyngby, I lived in Campus Village, where more than 100 foreign students lived. Campus Village consists of many containers named Container A, Container B, and so on. I stayed in Container A, in which people from China, Canada, Chile, Pakistan, Lithuania, and Vietnam. We used shared kitchen, toilet, and shower, so when I cooked, I had a opportunity to talk with all the people in my container. They are very kind and helped me when I had trouble with something. In the last night in Lyngby, I took place a farewell party, in which I made Su-Shi. My Chinese friend also made Chinese food, and we enjoyed both Japanese and Chinese food. It was a nice experience.

3. Sightseeing

Delft, where I stayed for 4 months, is very nice city; there is a tall old church in the center of the city, and the atmosphere is really nice around there. Rotterdam is next to Delft, and I went there 5 times for shopping or dinner. I also went to Amsterdam, Den Haag, and Gouda on weekends. Besides, I went to Paris, Brussels, Luxembourg. In such a nice travels, the most impressive trip is when we went to the centre of Europe at the end of December. After we, students from Delft, met the DeMaMech students belonging in Berlin Technical University, we traveled together to Prague, Vienna, Bratislava, and Budapest.

Summary

The days both in the Netherlands and Denmark are precious and unforgettable. I got lots of experience and idea there though my English skill did not improve as expected. I think the most important thing I experienced is that I could get acquainted with many people who have totally different backgrounds. I would like to make good use of the experience in my life and hope that I will work in foreign countries in the future.

I am very grateful to have been given such a great opportunity. Besides, I appreciate my friends from Hokkaido, Tokyo, Keio and Osaka University. Thanks to them, I managed to finish my exchange program.