Report

on the

DeMaMech EU-Japan Exchange Program

2005-2006

Philip Donath

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1. Personal Data and University Information

1.1 Personal Data

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1.2 Home Institute

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- Engineering Design and Methodology -
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Supervisor: Prof. Dr. Lucienne BLESSING

1.3 Host Institute

Department of System Design Engineering
Faculty of Science and Technology
Keio University
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Murakami Toshiyuki Laboratory

Supervisor: Prof. Toshiyuki MURAKAMI

2. Executive Summary

Friends of mine, who had already been accepted for it, told me about the DeMaMech exchange program in June 2006. Due to a deadline extension, I also received the chance to apply. Just a few days later I was also accepted to join the program by march 2006. The accepted project actually was my first choice: "Intelligent Control in Human Assist System" at Professor Murakami's Laboratory at Keio University. Although it was still a long time to go, I contacted Prof. Murakami immediately. He referred me to Ladies of the International Office at Yagami Campus. During the following months they answered all my questions and did a great job arranging everything from the dormitory to the Certificate of Eligibility.

A two-week workshop in the beginning of August 2005 also helped to answer the upcoming questions. This year's 26 participants met in Berlin to attend lectures held by the European supervising Professors and listened to the reports and tips of last year's participants. Daily language classes were hold to introduce some basic Japanese. Further activities and a group work helped to get to know each other.

During the following winter-semester, I attended a second Japanese language class at the "Sprach- und Kulturbörse" of the TU Berlin.

In March 2006, I could finally apply for the visa and received it three days before my departure. On my arrival, I was picked up in Yokohama by Ms. Sakiko Tashiro and two other lab-members. On the following days, they were a great help to start my life in Japan. Whether I had to open a bank account, register as an alien or wanted to buy a mobile phone, they always showed me where to go and translated all the upcoming questions. Luckily, their and everybody's helpfulness lasted the whole stay.

After the registration was done, I met with Prof. Murakami to specify my task. He told me about the projects of his laboratory and than gave me one week to chose a project and another week to think of a specific task for the chosen project. Although it was great to have this freedom of choice, it also was very difficult and new to me. Before, it was always the professor's task to hand out the specific project.

I chose the redundant manipulator as my project and skipped through several papers to get an idea for a topic. In a further talk with Prof. Murakami, we decided for me to implement a simulation of a control algorithm, which allows the position control of the end-effector and a null-space-movement of the manipulator without influence on the effector. The practical idea was to balance an inverted pendulum on a joint in the null-space while the end-effector position is also being controlled.

The implementation was supposed to be realized in C and OpenGL, so that it took a little while to get used to it. While I handled the theory behind the manipulator by myself, Prof. Murakami explained the control algorithm to me. Although I understood the idea behind the algorithm, it still took me a long time and further talks with Prof. Murakami before I found all mistakes in my code and made the simulation run. Sadly, it was no time left for experiments.

In the end of September, I had to leave Japan and my exciting life at Keio University. But I took much new knowledge and great memories with me and hope to stay in contact with Professor Murakami and many Japanese and International Friends.

3. Travel Schedule

3.1 Outward Journey

06.03.2006	Berlin(Tegel) – Frankfurt	Lufthansa
06/07.03.2006	Frankfurt – Tokyo (Narita)	ANA

3.2 Return Journey

24.09.2006	Tokyo (Narita) – Copenhagen	Scandinavian Airlines
24.09.2006	Copenhagen – Berlin (Tegel)	Scandinavian Airlines

4. Technical Report

4.1 Introduction

Manipulators are machines made up of links connected with joints, which together result in a kind of moveable chain. They can perform miscellaneous movements through different kind of joint movements. Combined with a tool at the free end of that chain, the so called end-effector, manipulators are capable to fulfil various tasks.

Each task has its own degree of freedom n, which can be defined by the required position, orientation or both. The manipulator also has a certain degree of freedom m, which is defined by its number of joints. Is the manipulator's degree of freedom bigger than required for a certain task, the manipulator is called "kinematically redundant" and has a certain degree of redundancy m-n. The advantage of a redundant manipulator is its capability to fulfil a task in various positions. The additional degrees of freedom allow it to avoid certain places of the work-space, optimize its position or even perform a secondary movement in the so called "null-space" without an influence on the main task.

Nowadays, manipulators are mostly found in the production industry, where they are used for welding, spray-painting, assembling or just movement of different objects. If the location of the task is difficult to reach, redundant manipulators can be used. A typical example is a concrete pump, which is build to reach over houses or other obstacles.

In the future, manipulators are expected to support men as service-robots in all kind of situations. Especially in aging societies as in Japan or Germany, manipulators could be used as helpful tools for old and handicapped people or to take care of them. But to use such a robot in a person's living space, they need to be perfectly safe. A secured control needs to be installed to avoid unexpected movement and any harm for the user.

The idea of my work was to implement a simulation of a control algorithm for redundant manipulators to test and prove its performance.

4.2 Software

The programming language C was used for the simulation while the graphical illustration was created by OpenGL. While C was easy to learn, it required more time to get used to OpenGL and create the correct movement of the manipulator.

The implementation was done using cygwin. This free software tool simulates a Unix-system on a computer with a Windows XP operating system and contains a C-compiler as well as all necessary libraries for OpenGL.

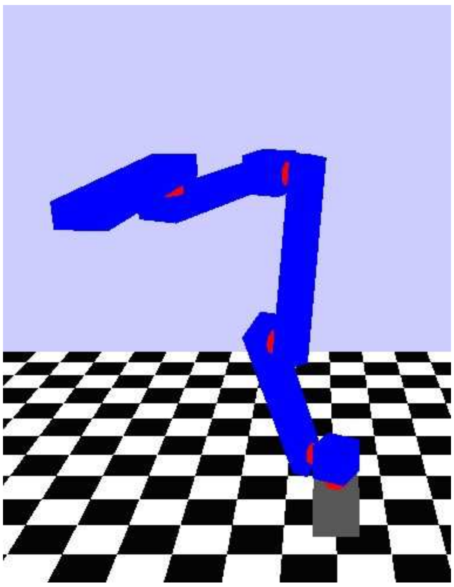

Fig. 1: Manipulator by OpenGL

4.3 Kinematics of the Manipulator

To be able to fulfil a task with a manipulator, the exact position of the end-effector is required. It can be described in two different ways. On the one hand, there are the joint angles, which are easy to measure but not very descriptive. On the other hand, a Cartesian coordination system based in the workspace along with the three Yaw-Pitch-Roll angles to access the orientation is very descriptive. The connection between these two systems is given by the kinematics. Hereby, a distinction is drawn between the direct kinematics, which compute the end-effector's position when given the joint angles, and the inverse kinematics, which compute the joint angles for a given end-effector position.

For this work, a manipulator with five joints (= five degrees of freedom) is used. To obtain a redundant manipulator, it was necessary to create a task which only regards the position and ignores the orientation. The result are a two degrees of redundancy, which can be used for a secondary null-space task.

4.3.1 Direct Kinematics: $\vec{x} = f(\Phi)$

In order to obtain the direct kinematics, a Cartesian coordination-system is placed in each joint. Similar to the Denavit-Hartenberg convention, the z-axis of each system is coincident with the joint axis. Two additional coordination-systems are placed on the end-effector and in the base of the manipulator. The one in the base serves as the world-coordination system and is the origin of the work-space.

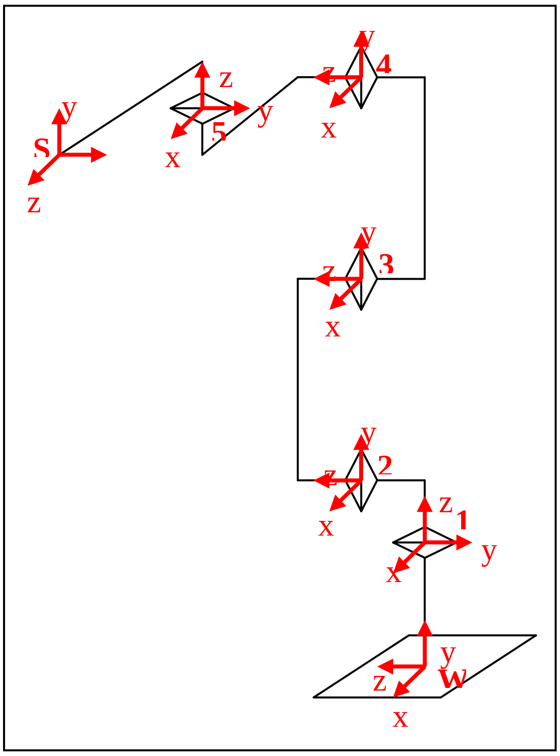

Fig. 2: Coordination Systems

Using the homogenous transform, the relationship between two neighbouring joints can be expressed by a 4 x 4 Matrix.

$$A_{i,i+1} = \begin{pmatrix} n_x & o_x & a_x & x \\ n_y & o_y & a_y & y \\ n_z & o_z & a_z & z \\ 0 & 0 & 0 & 1 \end{pmatrix} \quad (1)$$

(x, y, z) is the translation between joint i and i+1. The values n_x, n_y, n_z, o_x, o_y, o_z, a_x, a_y and a_z describe the rotation. They result from the multiplication of rotation-matrices around the axis of joint i and can be dependent of the joint-angle Θ_i or even constant.

Finally, the direct kinematics A_{WS} can be calculated by multiplying all transformation-matrices $A_{i,i+1}$:

$$A_{WS} = A_{W,1} \bullet \prod_{1}^{4} \left(A_{i,i+1}\right) \bullet A_{5,S} \quad (2)$$

4.3.2 Inverse Kinematics $\Phi = f^{-1}(\vec{x})$

While the direct kinematics are easy to calculate, the inverse kinematics can become very complicated. Especially analytical methods can usually only be applied for simple manipulators. In many cases there may be several solutions, in some cases no solution.

Numerical methods like the calculation based on the Jacobian matrices can easily become very expensive, but usually find a solution. Yet, the method actually requires the inverse Jacobian. Since this manipulator's Jacobian is a (3x5) matrix, it is not invertible. Therefore the Moore-Penrose pseudoinverse needs to be used. For a Jacobian matrix J with more columns than rows, the following formula is used:

$$J_{aco}^{pseudo} = J_{aco}^{t} \cdot (J_{aco} \cdot J_{aco}^{t})^{-1} \quad (3)$$

For the redundant manipulator, the following equation can be used:

$$\dot{q} = J_{aco}^{pseudo} \dot{x} + (I - J_{aco}^{pseudo} J_{aco}) \dot{x}_{null}^{ref} \quad (4)$$

4.4 Control algorithm

The control algorithm is based on the control cycle shown in Fig 4. The basic idea of the algorithm is to control the end-effector position x by a PD-Controller and just add the input for the null-space movement $\ddot{q}_{null}^{ref}$ to the input $\ddot{q}_x^{ref}$ of each joint.

To avoid an influence of the null-space control on the end-effector position x, a disturbance-observer is used to monitor the workspace and it is therefore called workspace-observer.
Furthermore, each joint is equipped with a disturbance-observer to avoid the use of force-sensors. Thanks to these observers, it is also not necessary to regard the dynamics of the system. For the simulation, these

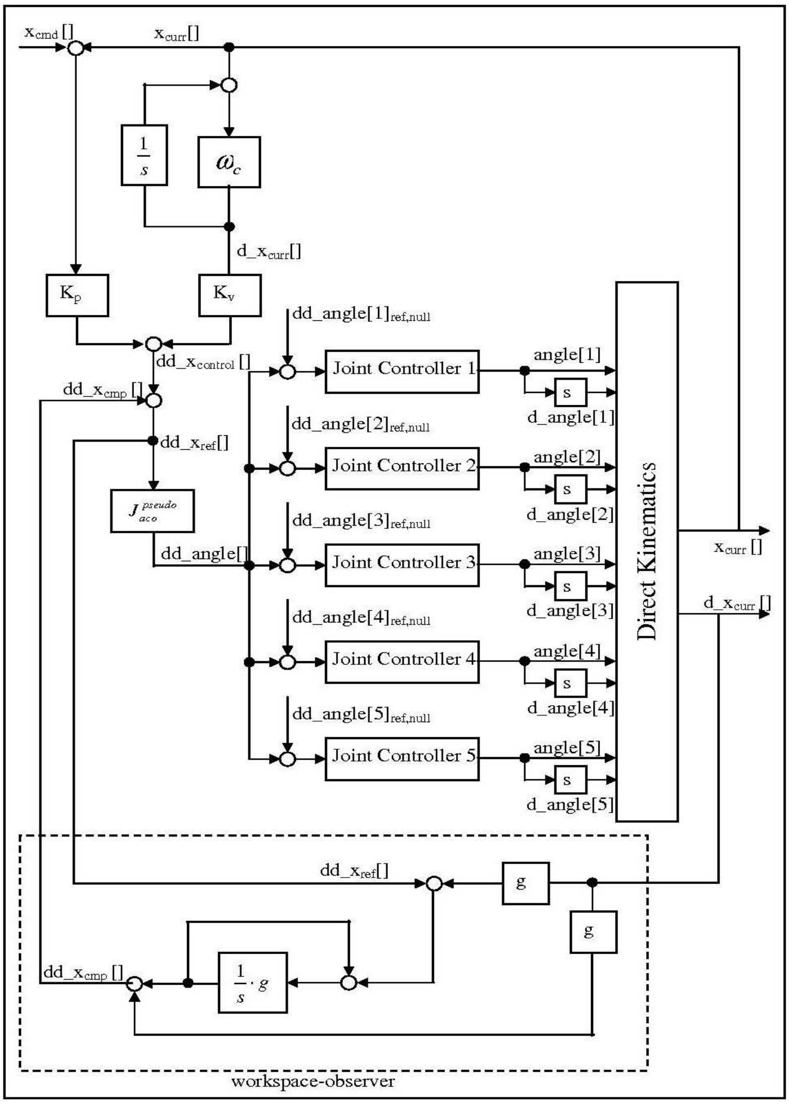

Fig. 3 Control-circle for the simulation

joint-space observers are assumed to perform perfect results so that no disturbance forces need to be regarded.

A more detailed view explains the mathematical relations behind the algorithm and goes as follows:

In a general system (currently without a workspace-observer), the Jacobian matrix is used to create the relation between the work-space motion $\dot{x}$ and the joint-space motion $\dot{q}$:

$$\dot{x} = J_{aco} \cdot \dot{q} \quad (5)$$

The relationship between the acceleration in work- and joint-space results from the derivation of this relationship. It can be simplified for slow motions by neglecting the part with the differentiated Jacobian, since it becomes very small.

$$\begin{aligned} &\ddot{x} = J_{aco}\ddot{q} + \dot{J}_{aco}\dot{q} \\ &\approx\triangleright\ \ddot{x} = J_{aco}\ddot{q} \qquad (6) \end{aligned}$$

According to this formula, the position of the end-effector is directly depending on the joint acceleration, which in this case consists of the referring workspace- and nullspace joint acceleration $\ddot{q}_x^{ref}$ and $\ddot{q}_{null}^{ref}$: $\ddot{q}^{ref} = \ddot{q}_x^{ref} + \ddot{q}_{null}^{ref}$.

The position of the end-effector can be calculated by

$$\begin{aligned} \ddot{x} &= J_{aco}\ddot{q}^{ref} \\ &= J_{aco}\ddot{q}_x^{ref} + J_{aco}\ddot{q}_{null}^{ref} \\ &= \ddot{x}^{ref} + J_{aco}\ddot{q}_{null}^{ref} \qquad (7) \end{aligned}$$

, which again can be changed to receive the difference between the current and the referring acceleration of the workspace:

$$\ddot{x}^{ref} - \ddot{x} = -J_{aco}\ddot{q}_{null}^{ref} \quad (8)$$

If the workspace-observer is also regarded, the compensating acceleration $\ddot{x}^{cmp} = J_{aco} \cdot \ddot{q}^{cmp}$ is added.

$$\begin{aligned} &\ddot{q}^{ref} = \ddot{q}_x^{ref} + \ddot{q}^{cmp} + q_{null}^{ref} \\ &\Rightarrow \ddot{q}^{ref} = J_{aco}^{pseudo}\ddot{x}_x^{ref} + J_{aco}^{pseudo}\ddot{x}^{cmp} + \ddot{q}_{null}^{ref} \quad (9) \end{aligned}$$

According to (8), the nullspace-acceleration can be regarded like a disturbance which needs to be compensated by the observer. Added to (9), it follows from the above

$$\begin{aligned} &\ddot{q}^{ref} \\ &= J_{aco}^{pseudo}\ddot{x}_x^{ref} + J_{aco}^{pseudo}(-J_{aco}\ddot{q}_{null}^{ref}) + \ddot{q}_{null}^{ref} \\ &= J_{aco}^{pseudo}\ddot{x}_x^{ref} + (I - J_{aco}^{pseudo}J_{aco})\ddot{q}_{null}^{ref} \qquad (10) \end{aligned}$$

Finally, it can be proven that the null-space input does not have an influence on the workspace by assuming a general reference acceleration $\ddot{q}^{ref} = J_{aco}^{pseudo} \cdot \ddot{x}^{ref}$:

$$
\begin{aligned}
&\ddot{x} \\
&= J_{aco} \cdot J_{aco}^{pseudo} \cdot \ddot{x}^{ref} + (J_{aco} - J_{aco} J_{aco}^{pseudo} J_{aco}) \ddot{q}_{null}^{ref} \\
&= \ddot{x}^{ref} + (J_{aco} - J_{aco}) \ddot{q}_{null}^{ref} \\
&= \ddot{x}^{ref}
\end{aligned} \quad (11)
$$

The transformations of those equation shows, that the added null-space influence has no effect on the end-effector thanks to the workspace-observer.

4.5 Null-space task

The constraint to keep the last two links horizontal was chosen as a null-space task.

The orientation of the last links depends on the joints number two, three and four. Only if the sum of those three joints equals 0, the last links` pitch stays zero.

$$\Theta_2 + \Theta_3 + \Theta_4 = 0 = \Theta_{link} \quad (12)$$

This constraint is transformed to obtain the equation for the joint which is supposed to be controlled, in this case joint 4:

$$\Theta_4^{cmd} = 0 - \Theta_2 - \Theta_3 \quad (13)$$

A PD-controller is chosen to create the control algorithm for the null-space constraint.

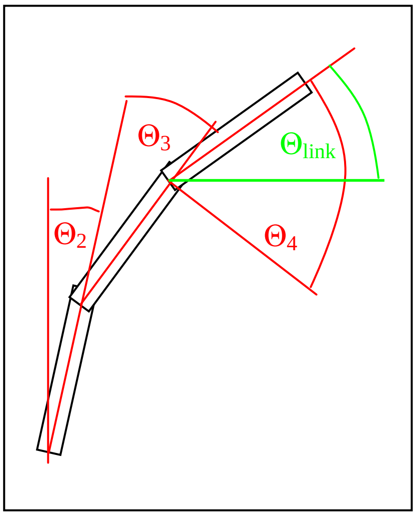

Fig. 4 Angles 2, 3 and 4

$$
\begin{aligned}
&q_{null,4}^{ref} \\
&= K_p^{null} (\Theta_4^{cmd} - \Theta_4) - K_v^{null} \dot{\Theta}_4 \\
&= K_p^{null} (-\Theta_2 - \Theta_3 - \Theta_4) - K_v^{null} \dot{\Theta}_4
\end{aligned} \quad (14)
$$

4.6 Conclusion

During my stay, I implemented a simulation for the control of a redundant manipulator to test its performance. I started to program it from scratch and realized the manipulator's kinematics by working independently and reading books, papers and lecture notes. This way, I learned many new things, but also spend too much time for tasks, which later turned out to be unimportant.
After the basis was created, Prof. Murakami explained the control algorithm to me, which I explored and implemented during the rest of the time.
Although I did not make it to run tests on the laboratory's manipulator, I still learned very much by mastering the upcoming challenges and problems. My comprehension and knowledge about robotics have increased a lot and I am looking forward to use and increase both in classes or future projects.

5. Exchange Student Life

My life in Japan mostly took place in Hiyoshi, a part of Yokohama, where the Keio University's Yagami and Hiyoshi campus are located. The Hiyoshi station is part of the Tokyu Toyoko line, which connects Yokohama and Tokyo's Shibuya. It only takes about 15 minutes to go to Yokohama and 25 minutes to Shibuya.
Besides my daily life and trips to Tokyo on the week-end, I also did some sightseeing in other parts of Japan.

5.1 Dormitory

Along with the other DeMaMech-Students at Keio University, I was living in the "Hiyoshi International House". This dormitory consists of four houses with about 15 apartments each. Each apartment was shared by two people and had 2 private rooms, a shared kitchen, toilet, bathroom with washing machine and a balcony. The private rooms were well furnished and even had their own refrigerator. Everything was very new and clean. Furthermore, the dormitory had two so called lounges, where we could meet with friends or have parties. The Japanese resident assistances, who were also living in these four houses, used the lounges for a welcome party, a BBQ, a farewell-party and other activities for the residents, so that it was easy to meet the other international students from all over the world. Since there also was a TV in one of the lounges, many people gathered there to watch the matches of the soccer world cup, which always was a lot of fun.
The support by the resident managers Mr. and Mrs. Arahari was also very nice and friendly.

I shared my apartment with Yutaro Takahashi, a fellow DeMaMech exchange student from Delft, whom I had already met during the workshop in Berlin. We got along very well and sometimes went out to parties or to have dinner together. Especially since I did not cook very often, I mostly went out to eat in the university cafeteria or to local restaurants.

The location of the dormitory was very convenient. It only took about 10 minutes by foot to go to Hiyoshi station, where many stores and restaurants are located. The Yagami campus was also just a 8 minute walk away. Altogether, the Hiyoshi International House was the perfect place to live.

Since I extended my stay until the end of September, but could only stay in the International House until the end of August, I had to find a new place. Therefore I moved into a guest-house in Hiyoshi. This house was the home of 5 people, who each had their own room but shared a kitchen and bathroom. It was okay to stay there for a month, but sadly further away from the campus, not as clean as the International House and also way more expensive.

5.2 University life

Prof Murakami's laboratory is located on Yagami Campus and consists of two rooms, whereof the so called "motor-room" was the one where I and 12 other students had their desk. Hence there was almost always someone in the laboratory and I experienced a life at university which is unknown in Germany. Along with students from other laboratories a large group of people studied in the same room, took breaks and went to lunch together or joined sports and other activities. Although my lack of Japanese often hampered the conversations, I soon felt accepted in the group, yet always regretted to know only a few Japanese words. Nevertheless the other students kept inviting me to join different group activities, which I always enjoyed. I want to thank my lab-members especially for the nice welcome and farewell parties along with my last night in Japan. During that night, they rented a van and showed me the colourful skylines of Tokyo and Yokohama before taking me to the Narita airport.

But there were also times, when the motor-room was just too small for the number of people. Along with a noisy server and many storage shelves, the room soon was too full and working became difficult. During the busiest weeks, working with other students during the night became a nice alternative. Than the atmosphere was more relaxed and especially during the soccer world-cup, night-shifts were a good way to stay awake for the early morning games.

The group organisation also showed during the SUM-meetings. SUM is an alliance of five laboratories, which meet twice a week for at least 3 hours each time. During those meetings, the students have to give reports about their work and afterwards have to answer questions to the professor. In the beginning of august, I also joined the SUM summer-camp, a week-end trip to Keio Tateshina cottage, where the new bachelor students had to give their first reports.

5.3 Travelling and Sightseeing

The stay in Japan was also a great opportunity to travel and see the country.

During the first weeks, I spend most of my free time to explore Tokyo and Yokohama. The whole area with the many people living in it is very amazing. Especially since everything is tidy and organized.

Some other places were also close enough to visit them on a day-trip. Like Kamakura with the Big Buddha statue or Nikko and its world heritage. Other trips required a little more time, like the climbing of Fuji-san. I joined two German friends and their lab-members on their 2 day trip and enjoyed the sunrise on top of the mountain.

Yet the longest trip was to Kyoto, Hiroshima and Miyajima. While Kyoto with all its historical places was very beautiful and interesting, Hiroshima and its history were very emotional, sad, but also interesting. Especially since a man of a victim’s organisation gave us a free tour around the Peace Memorial Park and explained and told us many things.
In Kyoto we also received a free guided tour through the Kyoto Castle. Five students from an English circle offer these tours to foreign tourists to practice English. We enjoyed it very much and used the opportunity to chat with them.

Travelling in Japan is a great thing to do. It is not very cheap, but the country and the people are very nice. I always felt safe and the Shinkansen allows to travel long distances in short times.

6. Summary

Taking part in the DeMaMech exchange program was an exciting and wonderful thing to do.

Joining Prof. Murakami's laboratory was a great opportunity. It allowed me to learn much about robotics and control theory, but also gave me the chance to make valuable experiences while working on my own project with its ups and downs. Besides that, the laboratory became the place where I met many people and made new friends.

Furthermore the stay gave me the chance to get to know Japan with its people, culture and language. Before my arrival, I only had a basic knowledge about the country. But thanks to its friendly people and the safe environment, it was no problem to find out about its advantages and disadvantages. Especially the backing by all the people involved along with the financial support allowed me to concentrate on my project and experience the life in Japan without having to worry too much.

Therefore I want to thank Prof. Murakami and everybody else involved for giving me this great opportunity!