Maarten Wit
February – July 2006

DBL

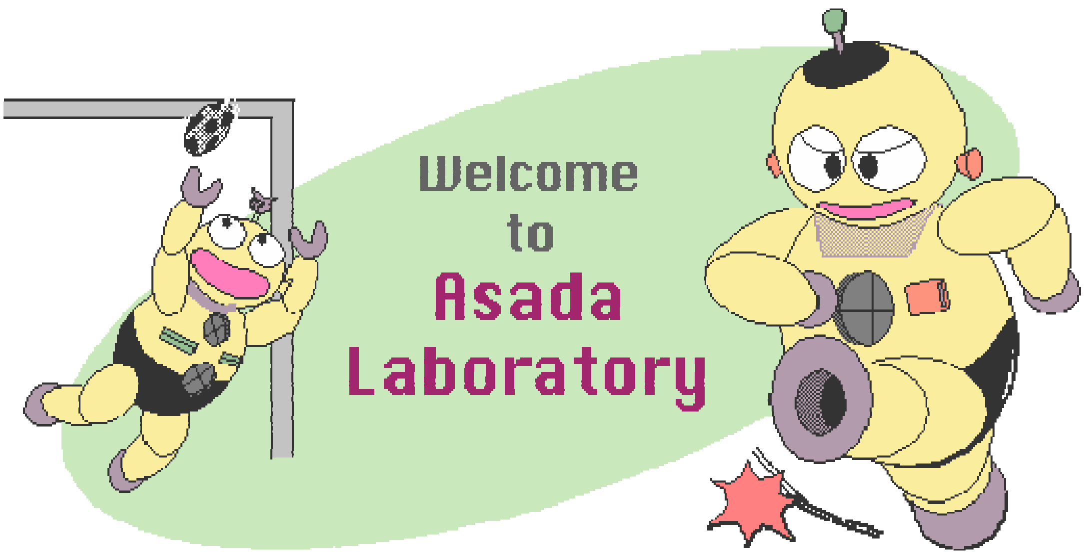
TU Delft

Delft University of Technology

Delft Center for Systems and Control

DeMaMech Exchange project Europe <> Japan

大阪大學 OSAKA UNIVERSITY



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Links

Delft University of Technology: www.tudelft.nl
Delft Center for Systems and Control: www.dcsc.tudelft.nl
Delft Biorobotics Lab: dbl.tudelft.nl

Osaka University: www.osaka-u.ac.jp/eng/index.html
Asada laboratory: www.er.ams.eng.osaka-u.ac.jp/index-eg.html
Hosoda laboratory: www.robot.ams.eng.osaka-u.ac.jp (Japanese only)

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2. Executive Summary

The exchange project for students in Design and Manufacturer in Mechatronics, DeMaMech is exchanging students between four European universities and four Japanese universities. I am a student at Delft University of Technology (Netherlands) and went to Osaka University (Japan) for my final MSc project. I was offered the possibility to formulate a project, together with the Delft Biorobotics Lab (DBL) and professor Hosoda (at that moment he is assistant professor at the Asada laboratory)

The research interest in the Asada laboratory is mainly in robotics. One of the topics studied there is walking robots. Since this is also the main interest of the DBL we were able to formulate a project interesting for all parties.

3. Travel Schedule

January 27, 2006	Finnair	Amsterdam → Helsinki
		Helsinki → Beijing
February 13, 2006	Air China	Beijing → Osaka
July 24, 2006	Air China	Osaka → Beijing
July 25, 2006	Finnair	Beijing → Helsinki
		Helsinki → Amsterdam

For this trip I used two return tickets instead of three single way tickets since it is cheaper in general. The drawback, especially for the flight back is the additional switches of airplane you need. In my case the Osaka-Beijing flight got 5 hours delay making the stay in China (outside the airplane) very short. In January/ February I stayed in Beijing for two weeks to celebrate Chinese New Year there. I stayed in Japan for 5 months and two weeks.

4. Research

The exchange to Japan is used to do my final master project. Before this I finished all my courses and did a literature survey. After the project in Hosoda laboratory I write my thesis back in the Netherlands. My research topic is **“Limit Cycle Control for Dynamic Robot Walking”**; I will briefly discuss the project in this text.

4.1. Introduction

Walking is an activity that costs little conscious effort for humans. This turns out to be quite difficult to achieve with robots. The walking of robots can *either* be made very robust and versatile *or* energy efficient but an ultimate combination of this has not yet been achieved. Much research has been done to static and zero moment point (ZMP) walking. In general they both result in stable but energy inefficient walking. Examples are the well-known robots made by the Japanese companies Honda and Sony.

A completely different approach is that of Passive Dynamic Walking (PDW) as first described by McGeer (1990). For such robots or models, no control or actuation is used. The energy to move forward is in most cases obtained by walking down a slope, see figure 1. The design of the robot should be done carefully in order to achieve stable walking. Research done to passive dynamic walking at several laboratories, shows that energy efficient walking is possible. It is made understandable by starting with the most simple robot model and gradually extending this to more complex and human-like models.

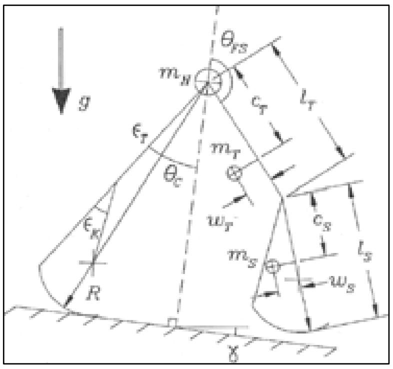

Figure 1 PDW model with knees walking down a slope [McGeer 1990]

PDW can be extended to walking on a level floor by adding actuation. The actuators should add the same amount of energy to the system as the gravity did before. Still the energy efficient natural dynamics of the robot are utilized; this walking strategy is called Actuated Dynamic Walking (ADW). The joints of the ADW robots are not controlled to track a trajectory but are only activated when needed. The natural walking motion can be described as limit cycles, which are periodic motions in phase space (e.g. the joint angle versus its angular velocity). There are different limit cycle control (LCC) strategies to actively control the system to a stable limit cycle.

At Hosoda laboratory of Osaka University as well as at Delft Biorobotics Lab (DBL), ADW is studied, and pneumatic McKibben muscles are used to actuate the robots. Due to the nonlinear nature of the actuators exact movements are hard to produce. Using expert knowledge and tuning, desired behavior of the robot is obtained.

4.2. Goal and motivation

The subject of my project is “Limit Cycle Control for Dynamic Robot Walking.” Dynamic walking robots use the natural dynamics of the hardware. During walking these robots typically exhibit limit cycle behavior. Dynamic walking has the advantages that it is energy efficient and the control is simpler compared to the traditional ZMP control. Drawbacks of dynamic walking include the stability problem; the limit cycle of the robot has a limited range of convergence (Basin of attraction).
Goal of this research is to make a dynamic simulation of an ADW robot and to use this to improve the control of the real robot. The controller should use the natural properties of the robot to control the robot to a stable limit cycle for different environments and in presence of disturbances.

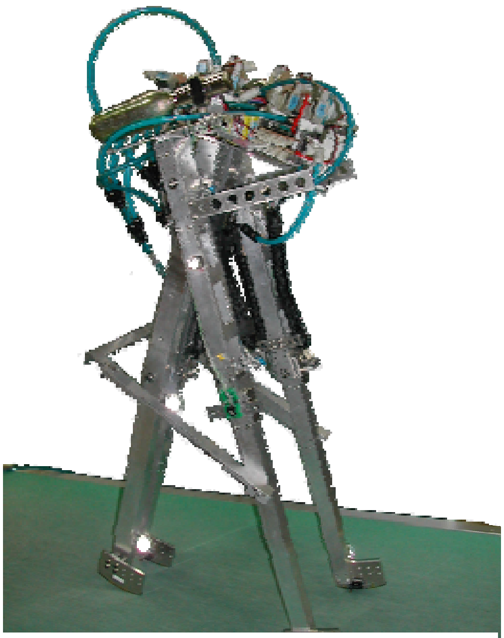

Figure 2 Pneumatic robot Que-kaku built at Hosoda laboratory

4.3. Que-kaku robot

One of the robots of Hosoda laboratory was the subject of this project: a 2D walking robot with McKibben muscles, shown in Figure 2. The name of the robot: 空脚, Que-kaku means “air legs” in Japanese. This refers to the pneumatic McKibben actuators used for walking.
As can be seen in the picture, the robot consists of four legs, symmetrically connected in pairs, resulting in a so-called 2 dimensional robot. Que-kaku is powered by 2 gas canisters and pressure regulators that are mounted on top of the hip joint. McKibben muscles actuate the robot’s hip and knee joints. Since this type of actuator, like human muscles, can only exert pulling forces they are connected in antagonistic pairs, resulting in six actuators, all controlled by a three-state solenoid valve. The control of the robot is done by a microcontroller board, also mounted on the hip. A USB-interface enables fast experimenting by controlling the robot directly from a pc. Also an external air supply can be used for convenience.
Que-kaku is equipped with three potentiometers at the hip and knees joints, measuring the joint angles. Contact switches are mounted on the circular feet to detect ground contact. The moment the foot touches the ground is called heel strike. This is used to initiate the next step during walking. An overview of the robot’s inputs and outputs if given here:

Inputs	Outputs
6 x Control signal to the air valves, selecting supply, close or exhaust state	3 x joint angles signal of hip joint and the knees 2 x foot contact switch signal

4.4. Method

First a dynamic simulation in MATLAB has been made with a robot model including a model of the used actuators. The feed-forward controller as used on the robot is implemented. Next, feedback is introduced to regulate the step time during walking. A controller is designed on the simulation and later implemented on the robot. The behavior of the robot can converge to a (feasible) desired walking motion (limit cycle) after a few steps. The asymmetry of the robot between the inner and outer legs causes the steps of Que-kaku to be periodic after two steps, this is called a walking cycle.

4.4.1. Robot model

A simple 2d model is build, consisting of four parts: the inner and outer leg, both consisting of an upper and bottom leg. For the four parts of the robot, these parameters were determined:

- Length - from knee-joint to hip-joint or to the floor.
- Mass
- Center of Mass (distance of CoM to higher joint)
- Inertia
- For the lower legs: Shape and location of the feet

The systems states of the robot are shown in figure 3 and include the coordinates of the hip joint (x_h, y_h); the angles of the upper legs are φ_i and φ_o for the inner and outer legs respectively; the angles of the two knees are θ_i and θ_o.

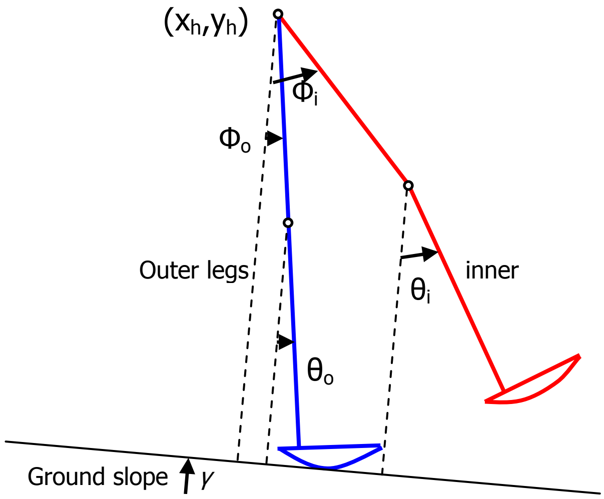

Figure 3 Model of Que-kaku showing its states

4.4.2. McKibben muscle model

A complex task is to make a comprehensive model of the used pneumatic actuators due to the nonlinearity and complex behavior. The pressure in the McKibben muscles is increased when the valve is opened to the supply pressure. The increasing pressure causes the muscle to expand and to shorten. This way it can exert a pulling force, comparable to the functioning of the human muscle. The muscle force is measured for different muscle pressures and extensions and a linear model is made. The measurements and linear model are shown in figure 4b.

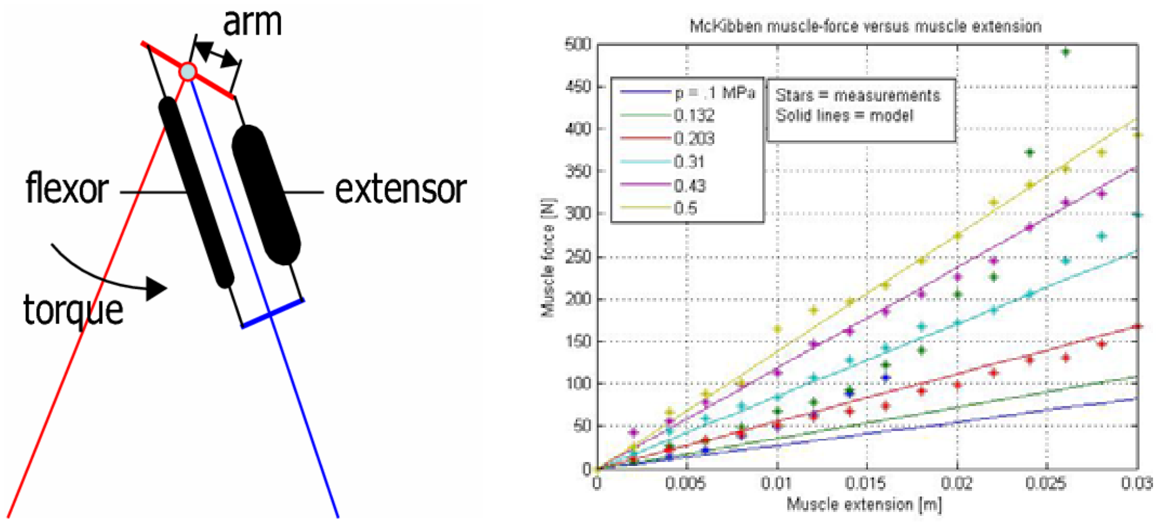

Figure 4 (a) McKibben muscle antagonistic pair actuating a robot joint. (b) Force measurement and linear model for different muscle pressures and extensions

The valve opening durations are the inputs to the system, controlling the six three-state valves. The valve states are: Supply (s) from the pressure source (0.55 MPa), close (c) or exhaust (e) to the environment (0.10 MPa). The important properties and relationships are discussed here:

- **Internal pressure** of the actuator. This depends on the supply pressure and the duration of the valve opening. While the valve is opened to supply air to the muscle, the pressure increases quadratic until the reference pressure is reached. The speed of increasing and decreasing pressure is different. This is modeled using exponential increase or decrease over time. The pressure is controlled by the valve opening durations to supply and exhaust.
- **Natural length** of the actuator. This is depending on the muscle properties and the muscle pressure. If the muscle is not pressurized, the length is about 20 cm. The length of the muscle changes nonlinearly with the internal pressure. This is modeled by curve fitting.
- The **extension** is the length of the muscle due to the joint angle minus the natural length.
- The **force** of the muscles is approximated by: $F = S + K \cdot e + D \cdot \dot{e}$ where F is the resulting muscle force; e and $\dot{e}$ are the extension of the muscle and its velocity. S is the static muscle force. K is the stiffness and D represents damping, they are both depending on the muscle pressure p. Force measurements showed that the static parameter $S = 0$, and stiffness $K = 27571p$. The two parameters of damping $D = D_f p + D_{f0}$ need to be decided based on simulations. The muscle force is given by: $F = (27571p)e + (1000p + 300)\dot{e}$

A joint actuated by an antagonistic muscle pair as shown in figure 4a is influenced by the resulting muscle torque τ depending on the forces of the extensor and flexor muscle, f_e and f_f respectively and the moment arm a being the perpendicular distance between the muscle and the joint. The joint torque is given by: $\tau = a\cos(\phi_i - \phi_o)(f_e - f_f)$

4.5. Controller

The Que-kaku robot is this far controlled using a feed-forward controller. The valve opening durations to supply air to the flexor muscle and to exhaust the extensor muscle S_f and S_e are both equal to 200 ms.

Due to the well designed hardware, Que-kaku can perform stable walking without using feedback. The control parameters are decided offline and the walking behavior depends on the environment.

A simple feedback controller is implemented to actively regulate the step time of the robot using the air valve opening durations as control inputs. The controller enables the user to decide on the walking behavior in terms of the step time. The controller rule is given by:
$S_f(k+1) = S_e(k+1) = S_e(k) + P\left(T_d - T(k)\right)$ where *k* indicates the current time step, T_d and *T(k)* are the desired step time and the step time of the last step. *P* is the controller gain. The controller can make the natural walking behavior converge to a desired walking behavior after a few steps.

4.6. Simulation

Based on an existing MATLAB simulation of a PDW model by Martijn Wisse (DBL) I made a simulation of the Que-kaku robot. First the robot was simulated as a PDW model walking down a slope. Adding the McKibben muscle model resulted in an ADW model, walking on a level surface. For simplicity the knees were not used in the actuated model and only the two hip muscles were actively controlled. The knees were locked, i.e. $\theta_i = \varphi_i$ and $\theta_o = \varphi_o$. Since the lower legs are relatively light compared to the upper legs it is assumed that the motions of the knees do not have a large influence on the walking behavior. A phase plot of the hip angle and its velocity are shown in figure 5a and figure 5b shows the duration of every step.

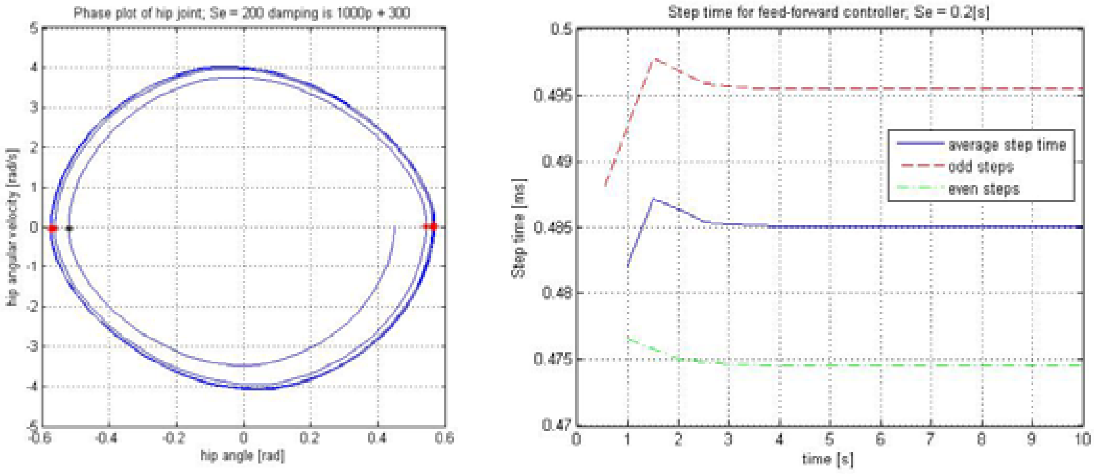

Figure 5 Plots of ADW with feed forward controller. (a) The phase plot shows that the walking behavior converges to a limit cycle. (b) The average step time converges to a fixed value; note the asymmetry.

The input signals to be used are the opening durations of the air valves for the hip-muscles. The value of these time constants has been changed and the resulting walking behavior is measured for the following conditions: Walking on a treadmill with low velocity; high velocity and walking on the floor.

4.7. Experiments

In the laboratory several experiments with the robot have been carried out. First walking experiments are done to obtain sufficient measurement data of walking with the feed-forward controller and the influence of the valve opening times on the walking behavior. Also the influence of walking on the linoleum floor and on carpet is compared to walking on a relatively fast or slow moving treadmill. The valve opening durations are varied independently and the resulting step time is shown in figure 5b.

4.8. Conclusions

- A dynamic simulation of the Que-kaku robot has been made in MATLAB. It can be used to simulate the effect of a different controller or changing of the hardware. The model can be easily adapted to a different type of robot and can be used to design new types of controllers.
- A feedback controller is implemented on the simulation and also applied to the robot.
- Using a feedback controller the walking behavior can be actively controlled.

5. Exchange student life

I will briefly say something about my life in Japan, fist about the everyday life in the dormitory and laboratory and then something about my spare time.

5.1. Living

During my stay in Japan I lived in an international dormitory called “Senri International House”. The only international aspects of the dormitory are the inhabitants. Besides the eighty percent Chinese people there is a mixture of some nationalities but the few DeMaMech students living here are almost the only western people. Surprisingly the staff only knew a few words of English or nothing at all.
Good points of the dormitory are the location near a train station, cycling distance to the university. It also offers a nice view from the rooftop and the dirty windows. My room itself was quite ok but I have to admit I was lucky and did not have to kill as many cockroaches as some of my friends. The rooms all have a bed, desk and air-conditioning and the rent is fairly low.

The rules in the dormitory are very strict. Some rules do not make sense to me. Examples are the curfew at 1 am every night when the front door is locked. Officially this is even 10 pm and you would need to call in advance and write down your name when you come home later. For the rooms nobody is allowed in it except yourself. A reason for this might be the poor isolation between the rooms. In general the place and especially the kitchen and toilets are very dirty. This is the reason why we have never used the kitchen.

5.2. Spare time

Like many Japanese people I adapted to the habit of spending long days in the lab and having both lunch and dinner in the cafeteria on the campus. Since I got a key of the lab I could enter whenever I wanted. Any time of the week, even in the night or weekends you are likely to find other people either working or relaxing/ sleeping in the lab.

I joined a beginner course of Japanese for a few months and learned some basic language and the character sets katakana and hiragana. This proved to be useful in everyday life to order food and understand signs on the street and in shops.
To relax me and my friends go out for dinner, drinking and to go to clubs. I also joined a fitness club in Osaka. And of course I did sight seeing in the neighborhood of the dormitory, the city of Osaka and the other places I visited as mentioned in the next section.

5.3. Traveling

Of course, besides study and research I also had or made time for traveling and sightseeing, sometimes together with other DeMaMech students and sometimes with my friendly colleagues. Here is a list of places I visited during my traveling:

Osaka is a very large city and consists of several smaller cities. I lived in Suita, 20 minutes cycling from the University's Suita campus. Since the public transportation is very good in Japan it is easy to reach most places of the city in an easy way.

Shikoku is one of the big islands of Japan. Together with some lab members I traveled there with two cars for three days. The landscape is nice and there are many tunnels and bridges to travel through and between the mountain landscapes. We stayed in two different Japanese style hotels and used the onsen = hot baths.

Hiroshima and **Miyajima** were the goal of a trip I made with Hareld (also Dutch DeMaMech student). Hiroshima is most known due to the first atomic bomb attack in WWII. The memorial park with the A-dome building and the museum there were impressive to visit. We spent the night in a 'manga café' where people can rent a small box with internet-pc and television to enjoy movies, manga books and some relaxing. Miyajima is a small island near Hiroshima and worth visiting for its beautiful and old temples and shrines. Mainly the big red gate in front of the island is very famous.

Tokyo I could visit with the lab to go to the RoboMec Conference at Waseda University. This was a unique opportunity to travel by the shinkansen train and sleep in a hotel in the famous Shinjuku area. The good thing is that everything was paid for by the lab. Since I left one day before the conference started I had some time for looking around in Tokyo and join a sightseeing tour.

Okinawa is a group of islands in the far south of Japan. We went there with four DeMaMech students from Osaka for one-week holiday. Although the weather was not good, due to the starting rain season it was a nice experience. We could do snorkeling and sightseeing on the islands.

6. Summary

This report can only cover a little bit of the total experience I had in Japan but I hope it gives you some idea. During my stay and traveling in Japan I made many pictures. I put a selection of them on Internet, ordered by category. You can find them at 360.yahoo.com/maartenwit. Feel free to contact me for any questions or remarks at the address in the first section.

This exchange has been a wonderful and unforgettable experience. I have learned a lot and I am grateful to everybody who made this possible.