University of Twente

EEMCS / Electrical Engineering
Control Engineering

Ankle actuation for planar bipedal robots

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MSc Report

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April 2007

Report nr. 012CE2007
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Abstract

This study focusses on ankle actuation of planar bipedal robots based on passive dynamic walkers. Simulations have been used to analyze the design characteristics which are necessary in robots fully powered by ankle actuation. The mass distribution between upper and lower and the shape of the foot have been found to be of major influence on the existence of a stable limit cycle. Simulation results show that pushing off before the swing leg collides with the floor is energetically more efficient than pushing off after the impact.

The results were used to design and construct an ankle actuation system for the walking robot 'Dribbel', which is developed at the Control Engineering group of the University of Twente. Mechanical requirements of the system were determined by means of simulations of a detailed 20-sim model. CAD tool packages were used to design the custom mechanical parts and electronics. The electronics interfaced to the TWI bus system already present at the robot.

The realized system is not yet operational. This is due to several implementation issues which could not be resolved within the available time for this project. Possible solutions to the various problems are discussed and will be implemented in the near future. As soon as the system is fully operational experimental data will be gathered to validate the dynamic models used in the design process. A comparison will also be made to the previous configuration with respect to energy efficiency and robustness.

Preface

If you are reading this, it means that my time as a MSc. student at the University of Twente has ended. It took me a few months under 6 years to finish my study, but it feels like time has flown by. It really has been an amazing and 'learning' experience and I enjoyed every moment, or at least most, of it!

First of all I'd like to thank the supervisors of my MSc project. Prof. Stefano Stramigioli, MSc. Gijs van Oort and ir. Edwin Dertien thanks for all your support and help during this project. I like to think that I learned quite a lot from you and that this project really is the master piece of my study!

I would also like to thank professor Soemers and Marcel Schwirtz for their help. They made sure that the construction would not brake after the first run, or that the circuitry fried immediatly. All other employees and students of the CE laboratory under supervision of prof. van Amerongen are greatly appreciated for the fun working atmoshpere of the last months!

The people of TCO really did a great job on fabricating all the mechanical parts. I owe special thanks to Klaas Smit for giving me a crash course in making technical drawings and all his advice in how the design could be altered whenever there was a 'small' problem.

Special thanks go to my family. You always supported me and gave me the oppurtunity to do what I really wanted. Without you I don't think I would have gotten to where I am now.

Last but not least, there are a lot of people I want to thank for making the past years one big party and helping me to relax whenever I tended to become a workaholic. Unfortunately I don't have space to name you all, but I count myself lucky to call you my friends!

Enschede, April 2007

Michel Franken

Contents

Introduction

Robots have become more and more important in society over the past decades. The first working robot was installed in the General Motors plant in Ewing Township [7]. It was an automated die-casting mold that dropped red-hot door handles and other such car parts into pools of cooling liquid on a line that moved them along to workers for trimming and buffing. From this first automated machinery, robots have evolved into an 11 billion dollar market and are involved in the manufacturing of almost every consumer good. It is predicted that the next hot field will be household robotics [4].

Household robots differ from industrial robots in that they have to be mobile and must adhere to much more severe safety requirements. Where in a plant it is possible to design the entire manufacturing line around the robot, a household robot has to perform tasks at various unknown locations. One of the most basic tasks a mobile robot has to perform is move from location A to location B. The environment in which these robot have to operate is shaped to suite humans, so a logical choice for their shape would therefore be to resemble a human.

Many commercial and academic research facilities are working to create humanoid robots. This has resulted in stunning robots which are actually capable of working together with humans on simple tasks. Probably the most well known example is Honda's Asimo. Robots like Asimo however suffer one major drawback and that is their energy consumption. Large motors are used to precisely control the position of the joints at all times. As a fully autonomous robot is required to carry its own power supply an energy efficient robot is capable of prolonged autonomous operation which increases its productivity and therefore its use.

Tad McGeer demonstrated a completely passive walking frame in 1990 that walked stably down a declining slope [6]. Since then several academic institutions have been doing research on energy efficient walking. The research at the Control Engineering department has been focused on determining the important dynamic characteristics of the structure of such robots and the development of robust control strategies. To validate the results of these research projects a physical robot has been constructed.

Planar bipedal robot project

The robotic research at the CE group is under the supervision of professor Stramigioli. The research on energy efficient walking robots started with the PhD-project of Vincent Duindam in 2001. He worked on the port-based modelling and control of such robots [3]. Several MSc projects were carried out to aid his work and are listed below:

1. Analyis and development of a 2D walking machine [1]
2. Realisation of an energy-efficient walking robot [2]
3. Strategies for stabilizing a 3D dynamically walking robot [8]
4. Foot shapes and ankle actuation for a walking robot [9]
5. Dynamic effects of an upper body on a 2D bipedal robot [10]
6. Feed-back control for biped underactuated walking robots [5]

Goal

This project is an extension of the work discussed in [9]. The benefits of walking with actuated feet and the necessary design constraints will be researched and a physical implementation will be realized for the 2D bipedal robot present at the CE group. First a conceptual design will be validated with simulations. The following topics will be addressed:

1. The influence of the shape of the feet and the mass distribution of the additional actuators
2. Design of the control strategy for walking using ankle actuation
3. Determination of the specifications of the actuator system
4. Modelling the designed actuator system

After the model with ankle actuation has been validated with simulations it will be physically realized and implemented on the 2D bipedal robot. The design is preferably a modular design so that it is a suitable platform to experiment with different foot shapes and more complex control strategies.

Report ouline

This report contains two papers in which the results are presented. The first paper contains an analysis of planar bipedal robots which are fully powered by actuation of the ankles. Simulations have been used to derive design characteristics which are necessary for the existence of a stable limit cycle. A model of such a robot has been simulated to research the required mechanical energy.

The second paper is about the design and implementation of an ankle actuation system on the existing planar bipedal robot Dribbel. The results of the first paper placed restrictions on the design of the system. Simulations were carried out to determine motor and mechanical requirements. The realized system is not yet operational so a comparison between the simulation models and the physical system was impossible. As soon as the realized system is fully operational this paper will be rewritten to include information about the energy efficiency of the realized system. A comparison will also made with the previous configuration of the robot.

More information and a discussion about the electronic and mechanical design can be found in the appendices. A discussion of the implementation of the code for the microcontrollers is also present in the appendices.

Part I

Analysis of fully ankle actuated planar robots

Analysis of fully ankle actuated planar bipedal robots

Michel Franken, Gijs van Oort and Stefano Stramigioli

***Abstract*— In this paper planar bipedal robots, based on passive dynamic walkers, are analyzed by means of simulations. In these models, the energy that is needed to sustain a stable limit cycle is generated by actuation of the ankles. The mass distribution between upper and lower leg and the shape of the foot have been found to be of major influence on the existence of a stable limit cycle. The results can be used in designing robots which are fully powered by ankle actuation. A model of such a robot has been simulated to investigate the resulting gait. The simulated model exhibits a very natural looking gait and walks with a wide range of velocities at low mechanical cost of transport. Simulation results are provided which show that pushing off before the swing leg collides with the floor is energetically more efficient than pushing off after the impact.**

***Index Terms*— Bipedal, passive dynamic, ankle actuation, moment of push-off, foot shape, mass distribution.**

I. Introduction

At the Control Engineering group of the University of Twente research is being conducted in the field of bipedal robots inspired by passive dynamic walkers. Passive dynamic walkers are unactuated walking frames that exhibit a stable and human like gait walking down a slight slope [13]. These robots require only the energy supplied by the reduction in potential energy due to the declining slope and gravity to sustain a stable gait.

The main incentive for the research at the Control Engineering group is the desire to build an energy efficient humanoid robot which is capable of working together with humans. Existing humanoid robots like Honda's Asimo are to some extend already capable of working together with humans. These robots use powerful servo motors to control the position of each limb so that a stable configuration is maintained while moving forward. This consumes a lot of energy (Asimo drains a 50kg battery in 30 minutes while walking [5]).

For a stable limit cycle however it is not necessary that the configuration of the robot is stable at alle times. This is demonstrated by the human gait, which basically consists of a series of unstable falling motions [10]. This is also demonstrated by passive dynamic walkers. These walkers rely on the dynamics of the structure for the motion itself and the energy generated by walking down a slope to compensate the loss of energy occuring at each impact of the swing leg with the ground (heel strike).

Powered passive dynamic walkers are walking frames that are capable of walking on level ground and use one or more actuators instead of gravity to compensate for the energy lost at heel strike. These robots still rely on the natural dynamics of the frame for walking and only add enough energy to the system to sustain a stable limit cycle. The resulting robots are therefore highly energy efficient. Some examples are presented in [4][5][6][17].

The current robot, Dribbel, at the CE group [6] uses a hip actuator to swing the new swing leg forward after heel strike. Energy however can also be added to the system by pushing off from the ground with the foot of the stance leg. Several studies [12][11] showed that adding energy to the system by means of a push off before impact should be more energetically efficient than other forms of actuation. This study was performed to analyze the necessary design characteristics of a robot fully powered by ankle actuation.

In section II the model of the planar bipedal robot used in this paper is discussed. The design characteristics of the model which allow it to walk fully powered by ankle actuation are analyzed in section III. Sections IV and V contain the results of the simulations and the paper finishes with conclusions about the presented work and a discussion of future work.

II. Simulation environment

To construct and simulate dynamic models the simulation software 20-sim is used [3]. The internal 3D Mechanics Editor can be used to generate code of complex linkages of rigid bodies.

A. Robot model

A model of a 5 d.o.f. bipedal robot was constructed. The model consists of 6 ideal point masses representing the center of mass (c.o.m.) of the legs and feet. The hip and the suspension are assumed massless. The suspension allows planar movement of the robot, but restricts sideway movement. Figure 1 shows the pointmass model and graphic scenery of the robot. The c.o.m. of the upper and lower leg is located in the middle of each link and the c.o.m. of the foot has a forward displacement with respect to the ankle. The dimensions of the robot are discussed in section IV.

The hip and knee joints are passive and the ankle joints are actively powered by the controller. A PD-controller at the knee is used to simulate a passive locking mechanism which can lock the knee when it is straight. In the c.o.m. of the foot a position/orientation sensor and power port are present. The position/orientation sensor is used in combination with a model of the shape of the foot to determine when and where the foot collides with the floor. For reasons discussed in section III a circular foot shape is used.

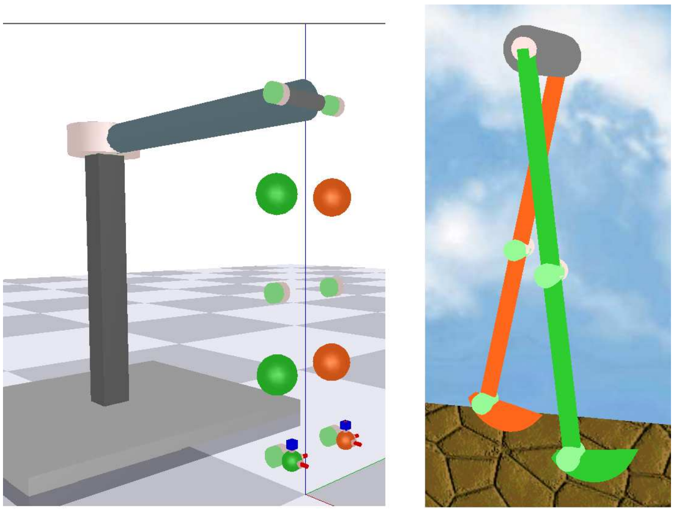

Fig. 1. Robot model

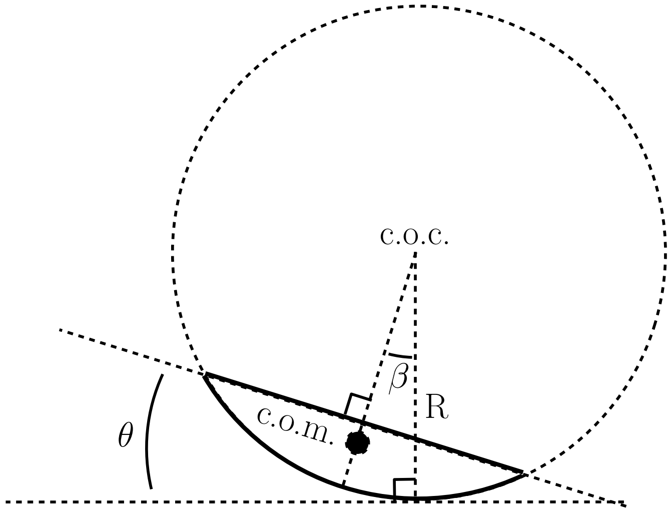

Fig. 2. Contact point calculation

B. Contact model

The impact of the foot with the floor is modelled as an elastic collision. In [15] it was shown that compliant contact with the ground results in less energy loss at impact and results in a more energy efficient gait. The Hunt-Crossley contact model [9] is used to calculate the normal force which is exerted on the foot by the ground. The Hunt-Crossley model contains a non-linear damper. The damping decreases as the penetration into the ground decreases. This prevents sticking of the foot to the ground, which is present in the linear Kelvin-Voight model. The Hunt-Crossley model is given in equation 1 where K is the spring constant D the dampening factor, z the lowest point of the foot, $\dot{z}$ the vertical velocity of the lowest point of the foot and H_f the height of the ground.

$$F_{(N)} = \begin{cases} -K(z - H_f) + (z - H_f)D\dot{z} & \text{if } z \leq H_f, \\ 0 & \text{if } z > H_f. \end{cases} \quad (1)$$

Single point contact at the position on the foot which is closed to the ground is assumed. In [7] it was shown how for circular feet the lowest point with respect to the ground can ce calculated. The used geometry is shown in figure 2 in which R is the radius of the roll over shape and c.o.c. the center of the circle spanned by the roll over shape. The calculated ground reaction force is transformed into a torque and force vector applied to the c.o.m. of the foot using the homogeneous transformation matrix of the contact point to the c.o.m. of the foot.

C. Controller

One of the characteristics of robots based on passive dynamics is that they can produce a stable gait with very simple controllers. The push off is generated by a P-controller which drives the ankle towards a setpoint. A P-controller can be used because actually reaching the setpoint itself is not important. What needs to be regulated is the energy introduced in the system by the push off and this energy can be regulated by the combination of setpoint and controller gain.

When the setpoint has been reached a PD-controller is used to retract the ankle towards the stationary position. The differential action is needed because the foot needs to be retracted relatively fast. With a pure P-controller this would result in oscillations around the setpoint. A vibrating foot during the swing phase is undesirable because it might decrease ground clearance and looks unnatural.

At the beginning of the simulation the model is in rest. Energy needs to be introduced in the system to make it start walking. The robot is started in an initial position and a small push is applied at the hip through the translational joint of the suspension. This is comparable to the manual launching of passive dynamic walkers.

III. Analysis

Ankle actuation is used to compensate for the energy loss which occurs at heel strike. In this section first the functions of the push off will be discussed and afterwards three important characteristics related to energy efficiency and the natural dynamics of the system. At the end of this section a comparison will be made to human dynamics.

As was mentioned the limit cycle of robots based on passive dynamics consists of a series of falling motions. When the swing leg hits the ground the c.o.m. of the robot is redirected from a downward rotation around the trailing leg to an upward rotation around the new stance leg due to the momentum of the c.o.m. The collision with the ground of the swing leg results in negative work on the c.o.m. so that the velocity after impact has decreased. Pushing off from the ground performs positive work on the c.o.m. which increases its velocity and makes up for the energy loss due to heel strike.

Another function of the push off is the addition of potential energy to the new swing leg. Actuation of the ankle causes the swing leg to rise. This additional potential energy is released when the foot is retracted and is transformed into kinetic energy during the swing phase. In robotic systems fully powered by ankle actuation the swing phase is completely passive.

A. Moment of push-off

The collision of the swing leg with the ground results in negative work being performed on the c.o.m. and therefore in a loss of kinetic energy of the c.o.m.. The amount of energy loss depends both on the velocity and the angle at which the swing leg hits the ground.

In [12] and [11] the energetic consequences of the moment of push-off are analyzed for the simplest walker model with an impulsive push along the stance leg. It is shown that for that model the impact loss is four times smaller with an impulsive push along the stance leg just before heel strike (modelled as instantaneous and perfectly inelastic). Pushing off just before impact with the foot of the stance leg results in less energy loss because the rotation of the foot decreases the impact angle of the swing leg and decreases the downward component of its velocity, this is sketched in figure 3.

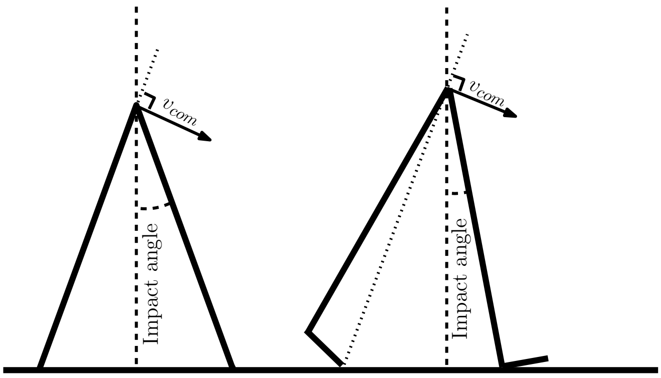

Fig. 3. Effects of a push off with the foot on the impact angle and velocity

The timing of the push off is very important. Pushing off too late results in a greater energy loss, but if the push off occurs too early the energy loss is also increased due to an increased downward velocity of the swing leg under the influence of gravity.

In human gait the push off also takes place before heel strike. Precise information about what triggers the human push off could not be found, but it is the author's believe that it is triggered by pressure loading of the fore foot, which occurs after heel rise.

B. Mass distribution

An important determinant of the robustness of the system is the ground clearance during swing phase. With very little ground clearance the robot will already stumble and fall due to small disturbances or objects on the ground. The most effective way to achieve ground clearance is to bend the knee during the swing phase. Bending of the knee is obtained if the rotational acceleration of the c.o.m. of the upper leg is higher than the rotational accleration of the c.o.m. of the lower leg with respect to the hip joint.

When the swing phase is fully passive the swing response of the leg is determined by the dynamics of the leg under the influence of gravity and its initial state. The dynamics in turn depend on the configuration of masses in the system.

To determine the optimal mass distribution one of the legs with dimensions as given in section II was simulated as a double pendulum (the ankle is kept rigid). The hip was given an initial angle (0.5rad) and velocity (-1rad/s), which is assumed to correspond with a normal human walking speed [16]. The mass of the upper leg was fixed at 5kg and a parameter sweep was performed on the mass of the lower leg and foot. During each sweep the minimum ground clearance was recorded. The absolute ground clearance of course also depends on the chosen initial state of the hip.

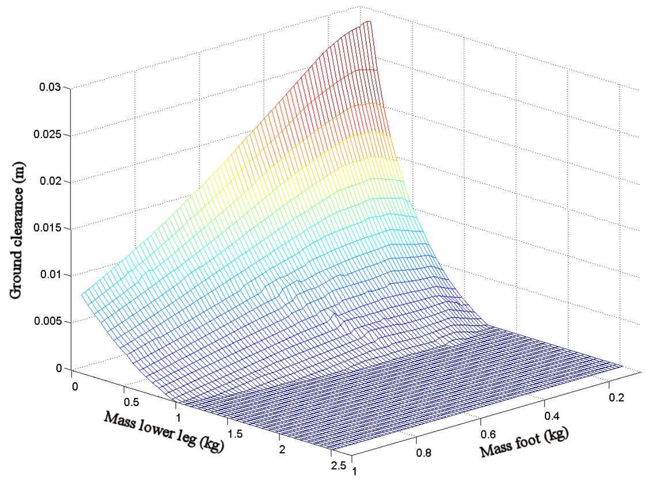

Fig. 4. Ground clearance as function of mass distribution

Figure 4 illustrates that when the mass ratio between upper and lower leg is low there will be no ground clearance and that maximum ground clearance is achieved for the highest ratio. From a practicle point of view a good mass ratio is assumed to be 10:1 at which the mass of the foot is chosen to be 0.4kg. This mass distribution results in a ground clearance of something more than 1 cm, which is about the same as the ground clearance in human gait [2].

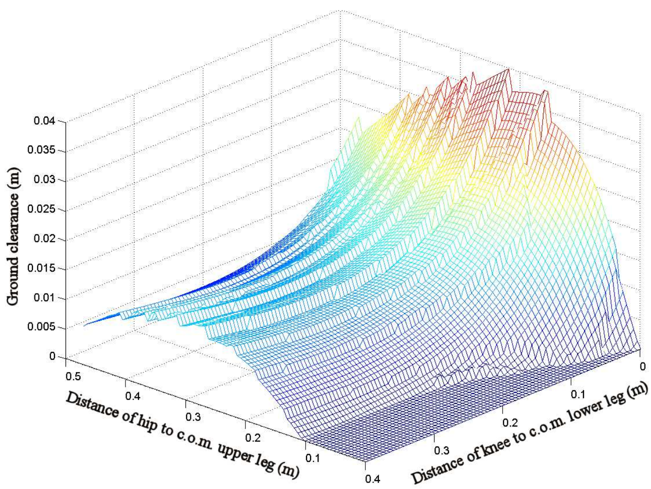

Fig. 5. Ground clearance as function of location of limb c.o.m.

A second parameter sweep has been performed with the chosen mass ratio, but with variable locations of the c.o.m. within the upper and lower leg. In a physical design the location of the c.o.m. of the foot can be influenced the least because the construction has to be strong and it is the smallest in size. Figure 5 shows the dependency of the ground clearance on the locations of the c.o.m. in the upper and lower leg.

Figure 5 shows that for the most ground clearance the c.o.m. of the lower leg should lie very close to the knee. This can be explained with the energy balance of the system. The balance is composed of potential energy and kinetic co-energy (since the swing phase is passive there is no energy addition during the swing phase). The Euler-Lagrange equation describing the angular acceleration of the knee angle is given in equations 2 and 3. The moment of inertia of a point mass rotating around an axis is calculated as $I_x = m_x l_x^2$. The meaning of the symbols are shown in figure 6.

$$\begin{aligned} L &= E_k^* - E_p \\ 0 &= \frac{d}{dt}\frac{\delta L}{\delta \dot{\theta}} - \frac{\delta L}{\delta \theta} \end{aligned} \tag{2}$$

$$\ddot{\theta}_2 = \frac{f(m_f, m_l, l_f, l_{l1}, l_l, l_u, \ddot{\theta}_1, \dot{\theta}_1, \theta_1, \dot{\theta}_2, \theta_2, g)}{I_f + m_f l_{l1}^2 + I_l} \tag{3}$$

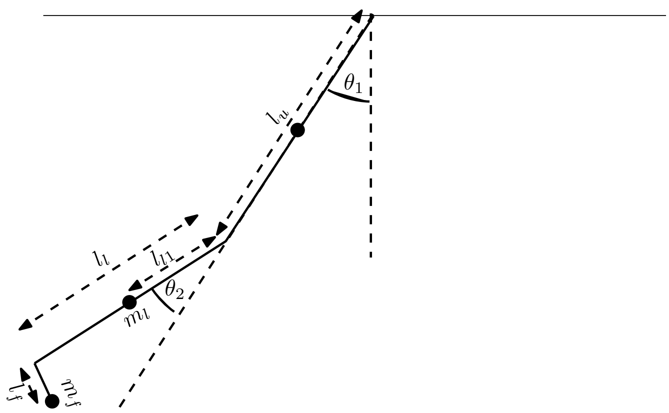

Fig. 6. Symbolic representation of the swing leg

For maximum knee flexion the angular acceleration of the knee should be maximized. Equation 3 shows that this is the case when the moment of inertia of the lower leg around the knee is minimized, i.e. minimizing the distance of the c.o.m. of the lower leg to the knee.

The location of the c.o.m. of the upper leg is a trade-off. On the one hand maximum energy is introduced in the system due to the initial angular velocity of the hip when the c.o.m. is located near the knee. On the other hand angular acceleration due to gravity is maximized when the c.o.m. is located near the hip (smallest moment of inertia).

C. *Foot shape*

The foot is of great importance during walking. It carries the weight of the body forward during the stance phase and it acts as a rigid lever during push off. During the stance phase the foot undergoes an elastic deformation while it carries the body weight forward. This elastic deformation results in a particular roll over shape. Intersubject biomechanical studies have shown that this roll over shape has a low variance and has a curvature of 30-35cm [8]. This was found this by applying a coordinate transformation on the center of pressure (c.o.p.) during walking from the world frame to the ankle frame. Figure 7 shows the resulting roll over shape.

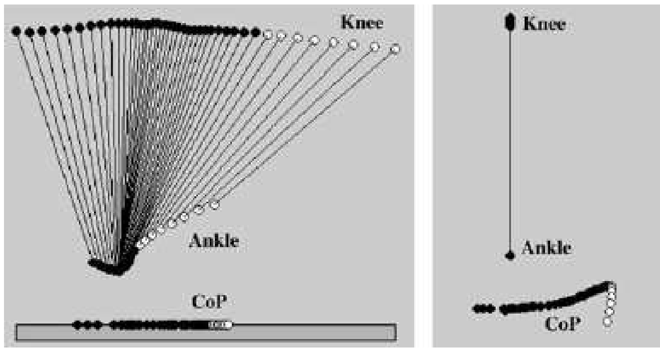

Fig. 7. Human roll over shape of the foot, source [8]

In [13] computer models were used to analyze how the foot curvature influences the local stability of passive dynamic walkers. The optimal curvature was found to be 1/3 of the leg length, which corresponds approximately to the human roll over shape. In [1] a model of a powered passive dynamic walker with knees and curved feet was analyzed. They used this model to deterimine the influence of the curvature of the foot on the mechanical work needed per step. They concluded that for the model with knees and curved feet the optimal curvature was 38% of the leg length.

The nadir of the curvature (lowest point of the foot when it is parallel to the ground) of the foot is often shifted forward with respect to the ankle, which is not present in the human roll-over shape. In [13] it was concluded that with this offset the passive reaction torque helps to keep the knee locked during the stance phase.

Powered dynamic walkers have a locking mechanism in the knee and therefore wouldn't need this offset in the nadir. In [17] an offset in the nadir is however found to increase the stability of that walker. The increase in stability is due to the passive reaction torque, but at a different location. This will be demonstrated with the robot discussed in [4] as example. That robot is fully powered by ankle actuation and has an offset of the nadir.

As was discussed earlier the upperleg should be much heavier than the lower leg to avoid foot scuffing during the swing phase. This is the case with this robot as most mass is either located on the upper leg or is connected to it and moves in phase with it. At approximately 50% of the swing phase the upperleg of the swing leg passes the stance leg. As the upper leg is much heavier than the lower leg this causes the c.o.m. of the entire robot to shift forward and is no longer above the ankle. If this robot was equipped with circular feet without an offset in the nadir, the stance leg would immediatly start to rotate forward due to the gravitional force acting on the c.o.m., figure 8. This causes the effective step length to be decreased (the angle of the hip will be smaller at the end of the step than at the beginning). This is a vicious cycle and will eventually cause the robot to trip and fall.

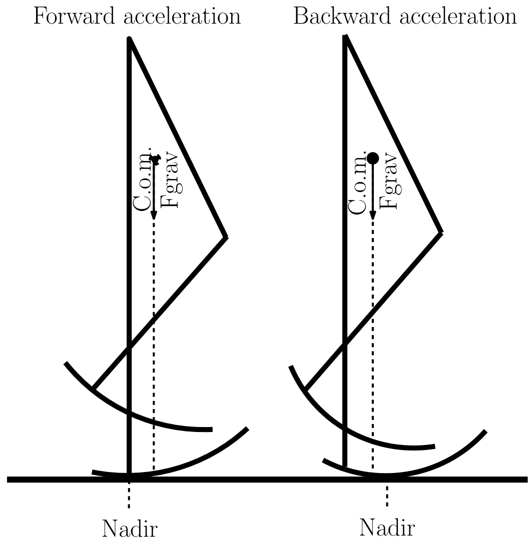

Fig. 8. Rolling of stance leg due to location of c.o.m.

With an offset of the nadir the c.o.m. is kept behind the nadir longer, figure 8. When the c.o.m. is behind the nadir the gravitional force on the c.o.m. works to decelerate the stance leg. This effectively decreases the velocity of the c.o.m. in the direction of movement and provides the extra time needed for the swing leg to finish it complete swing phase. If the offset is too large the stance leg will start to rotate backwards due to the larger lever of the gravitational force.

D. Human dynamics

Ankle actuation is very important in the human gait. Studies have shown that 80%-85% of the mechanical energy generated in the gait cycle is generated in the ankle during the push off of the stance leg [16]. There exist however large differences between the dynamics of the human body and the results presented in this section.

The most prominent difference is the mass distribution in the humans legs. In this it was shown that for sufficient ground clearance is achieved with a mass ratio of 10:1 between upper and lower leg. The mass ratio between the human upper and lower leg is however only 2:1 [14] with which on basis of figure 4 no ground clearance would be achieved. Several reasons why humans can walk mostly powered by ankle actuation and a low mass ratio are:

1) *The presence of joint spanning muscles*
   Push off in the human gait is obtained by contraction of the soleus and the gastrocnemius muscles (the deep and superficial calf muscles)[10]. Contraction of the gastrocnemius muscle however will also result in bending of the knee as it is attached to the femur. Since there is an initial bending of the knee at the beginning of the swing phase less angular acceleration is required and a lower mass ratio suffices.
2) *The swing phase is not completely passive*
   Human use the muscles in their thighs to thrust the swing leg forward [16]. The acceleration of the upper leg causes the knee to bend.

Another difference, as can be seen in figure 7, is that the offset of the nadir is not present in the human roll-over shape. Three contributing factors that this offset is not needed in the human roll-over shape are:

1) *The elastic deformation of the foot during the stance phase*
   Kinetic energy is stored in the elastic deformation of the foot which results in a decrease of the velocity of the c.o.m. of the robot
2) *The presence of an upper body*
   One leg constitutes just over 20% of the human body mass [14]. The passing of the upper part of the swing leg will therefore result in a smaller forward displacement of the c.o.m.
3) *The swing phase is not completely passive*
   Due to the forward acceleration of the swing leg a negative reaction torque is applied on the stance leg. This efficitvely slows down the stance leg.

IV. SIMULATION RESULTS

Based on the results described in section III, the dimensions of the robot model described in section II are chosen as in table I. The locations of the c.o.m. of the upper and lower leg are chosen in the middle of each part to conform to a physical realizable construction. The radius of the foot is chosen smaller than the theoretical optimal $1/3$ of the leg length. The offset of the nadir of the roll over shape flattens the foot in longitudinal direction, which decreases ground clearance during the swing phase. A stronger curvature of the foot was found to prevent scuffing of the foot during the swing phase.

	Length (m)		Mass (kg)	
Upper leg	0.47		5	
Lower leg	0.4		0.5	
	Radius (m)	Offset nadir (m)	Height (m)	Mass (kg)
Foot	0.106	0.05	0.05	0.4

TABLE I
DIMENSIONS OF ROBOT MODEL

Simulations have been performed with two different instants at which the push off is initiated. In the first type of simulations the push off was iniated as soon as the heel of the other foot collides with the floor. This moment can be determined very precisely in real life and is therefore often applied in physical systems [4][6][17].

In section III it was discussed that less mechanical work is required when the actuation takes place before impact. Simulations have been carried out in which the actuation is initiated when the foot was 1 cm above the floor. At slow walking speeds and in the beginning of the simulation the minimal ground clearance during the swing phase can be lower than 1 cm. To prevent premature actuation the absolute hip

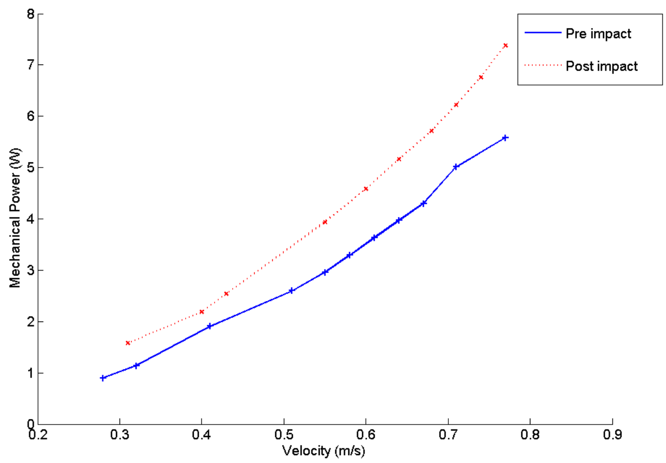

Fig. 9. Mechanical power as function of velocity

angle is required to exceed a specified angle before the push off is initiated. This guarantees that the swing leg is in the last stage of the swing phase.

The range of velocities at which these models produced a stable gait and the associated required mechanical power is shown in figure 9. The controller parameters which were changed to alter the velocity of the robot were the setpoint of the ankles and the gain of the P-controller gain. Also the parameters used to launch the robot (initial posture and magnitude of the push force) needed to be altered to achieve a stable limit cycle.

Figure 9 clearly shows that initiating the push-off before impact results in a gait requiring less energy to sustain. The required energy is about 75% of the energy required with post-impact actuation. This however is still much higher than the predicted 25% by [12] and [11]. The moment at which the actuation is initiated here has not been optimized, therefore it is assumed that more energy reduction can be achieved. As the mechanical power is not delivered instantaneous in this model, the maximum attainable energy reduction is probably higher than the 25% discussed in [12] and [11]. The setpoint of 1 cm was chosen because it could be applied during the entire experiments. When the robot is launched it has to converge to its limit cycle. During this convergence the ground clearance is less than in the limit cycle.

This method of pre-impact push off is not practical to implement because it requires the distance of the foot to the floor which is difficult to measure. A more efficient procedure is to define the instant of push off either in terms of a hip angle, or pressure loading of a certain area of the foot. The optimum instant of initiating the push off is also likely to depend on the velocity at which the robot walks. The instant of push off should therefore be adaptive.

The gait produced by especially the pre-impact push off model is very natural looking. In figure 10 a single step of the left leg is broken down into 5 composures. The model exhibits period-1 gaits, so both steps are symmetrical (except at speeds below 0.4m/s where the left and right step differed slightly).

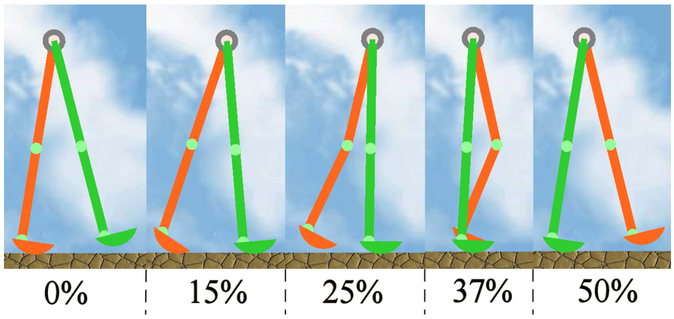

Fig. 10. Composure of robot at percentages of stride time

V. Specific Cost of Transport

Powered passive dynamic walkers are usually compared on the specific energetic and specific mechanical cost of transport (C_{et} and C_{mt}). The C_{et} uses the total energy required for walking and C_{mt} uses the mechanical work which omits the negative influence of the energy loss in the physical transmission. Only the C_{mt} can be used to compare the model with existing robots, because no physical drive system has been modelled. The C_{mt} is calculated as in equation 4, in which P_m is the mechanical power, g the gravitational constant, m the mass of the robot and v the forward velocity of the robot.

$$\begin{aligned} P_m &= \frac{\int_{t=0}^{t_0} T\omega dt}{t_0} \\ C_{mt} &= \frac{P_m}{gmv} \end{aligned} \qquad (4)$$

The strength of the C_{mt} is that it is a dimensionless number in which beside for the mechanical power also is accounted for the weight and velocity of the robot. The C_{mt} for each stable gait is given in figure 11. The C_{mt} ranges from 0.03 to 0.08, which makes the model very energy efficient [5].

These simulation results are approximately confirmed by experimental results discussed in [4]. An ankle actuated robot is discussed which weighs 12.7kg and walks at 0.44m/s with 3 Watts of mechanical power. If the absence of friction is taken into account this agrees with the results presented in figure 11.

VI. Conclusions

In this paper simulation results have been presented which show that robots can walk fully powered by ankle actuation. The analysis of mass distribution and foot shape resulted in a robot which was capable of walking with low mechanical cost of transport at a wide range of velocities. It has also been shown that pushing off when the swing leg was 1cm above the ground decreases the required mechanical energy by 25%.

VII. Future Work

The simulation model will be extended to facilitate the evaluation of more advanced and practical methods of determining when the push off should be initiated. Adaptive solutions are desired so that the robot can walk at different speeds. Pressure

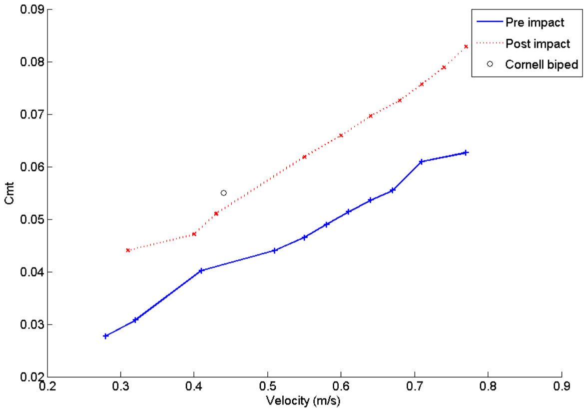

Fig. 11. Specific mechanical cost of transport as function of velocity

loading of an area of the fore foot is considered to be the most promising, because it directly relates to the composure of the robot with respect to the ground. If the fore foot is pressure loaded the swing leg must be about to hit the ground as the c.o.m. of the robot has moved forward.

The bipedal walker at the Control Engineering group of the University of Twente will be equiped with actuated ankles. It will be used to validate the results discussed in this paper. The walker will also be used as a test bed for new strategies of pre-impact push-off and hybrid combinations of ankle and hip actuation.

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Part II

Design and implementation of ankle actuation in a planar bipedal robot

Design and implementation of ankle actuation in a planar bipedal robot

Michel Franken, Edwin Dertien and Stefano Stramigioli

***Abstract*— In this paper the design and implementation of actuated ankles for a planar bipedal robot are discussed. This is a working paper as the system is not fully operational yet. Mechanical requirements of the system were determined by means of simulations of a detailed rigid body model. CAD tool packages were used to design the custom mechanical parts and electronics. The electronics interfaced to the TWI bus system already present at the robot. Simulations indicate that the robot is able to walk faster with the actuated feet than the previous point feet. A first comparison between full hip actuation and hybrid hip and ankle actuation indicate that the latter is more energy efficient at higher walking speeds.**

***Index Terms*— Bipedal, passive dynamic, ankle actuation, foot shape, mass distribution.**

I. Introduction

PREVIOUS projects at the Control Engineering group of the University of Twente have resulted in the realization of an energy efficient planar bipedal walker called Dribbel [2], [8], figure 1. This robot is powered by an actuator in the hip which swings the trailing legs forward after the leading leg collides with the floor (heel strike).

Fig. 1. Planar bipedal robot at the CE group

Several studies have shown that pushing off against the ground with the feet of the trailing leg has energetic benefits [5], [4]. When the actuation of the ankle takes place before heel strike the impact losses are decreased and less energy needs to be supplied to the system to sustain a stable limit cycle. The push off adds kinetic co-energy to the c.o.m. of the robot which compensates for the energy loss at heel strike. It also adds potential energy to the trailing leg which is released upon retraction of the foot. This causes the trailing leg to swing forward for the next step. In robots fully powered by ankle actuation the swing phase of the leg is completely passive. Such a robot is discussed in [1].

To research the effects of walking with actuated ankles the existing robot at the CE group will be equiped with such an actuation system. This paper describes the design and implementation of that system. In section II the design of the current robot and the requirements it places on the design of the additional actuator system is analyzed. Section III discusses the design and implementation of the actuation system. Section IV contains the control strategy for the robot. The system is not fully operational yet due to mechanical problems. A short overview of the current problems is given in section V. The paper ends with conclusions about the presented work and a discussion of future work.

II. Analysis and design requirements

In this section the current configuration of the robot is analyzed. This analysis is used to determine what the design requirements for the actuation system are.

A. Mass distribution

The mass distribution of the robot determines the dynamic behaviour of the legs during the swing phase. Figure 2 shows an approximation of the weight distribution in the current configuration based on [8]. The hip is clearly the heaviest part of the robot. In the original configuration this lowered the required mechanical work during the swing phase as the moment of inertia around the hip is minimized.

One of the factors that determine the robustness of the robot is the ground clearance during the swing phase. A small ground clearance will cause the robot to trip and fall due to small disturbances as the foot will hit the floor during the swing phase. An efficient method to achieve ground clearance is by acceleration of the upper leg with respect to the lower leg.

In the original configuration the ground clearance can be controlled with the torque applied to the upper leg by the motor located in the hip. When the robot is to walk fully powered by actuated ankles the swing phase is completely passive. The dynamics of the leg determine how much knee flexion is obtained due to the potential energy added to the swing leg by the push off of the foot and the momentum of the robot.

A previous study at the CE group has shown that for robots fully powered by ankle actuation a mass ratio between upper

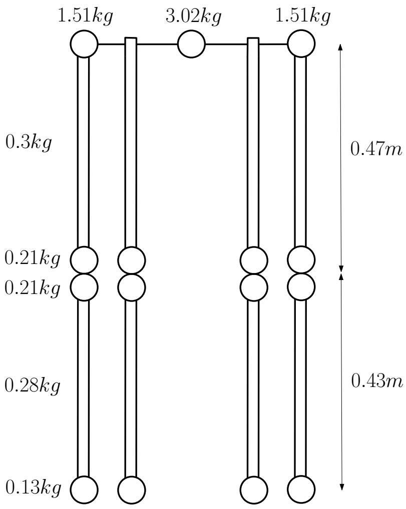

Fig. 2. Mass distribution in current configuration

and lower leg of 10:1 is a good choice. This ratio results in enough ground clearance during the passive swing phase over a wide range of velocities. From figure 2 the mass ratio in the current configuration is taken to be somewhere around 4:1. The heaviest parts of the new ankle actuators will therefore have to be connected to the upper leg to increase the mass ratio.

B. Hip motor

For a stable period-1 limit cycle the absolute hip angle at the end of the swing phase must be the same as at the beginning. This means that with a passive swing phase, the swing leg should swing freely with respect to the stance leg.

The actuator in the hip is composed of a servo motor with gearbox and is connected to both the legs. The innerlegs are connected to the housing of the motor and the outerlegs are connected to the shaft. This way all the legs can be actuated with a single motor and which legs are swing legs is determined by the direction in which the motor turns.

In a passive swing phase this hip motor is preferably not actuated as that improves the energy efficiency. That this is not possible will be demonstrated with the following example. Figure 3 shows a simple bondgraph model of a load under the influence of gravity connected to a servo motor. In this model τ_g is the torque due to gravity, U_m the voltage across the motor, R_{coil} is the electrical resistance of the coil, k_τ is the torque constant of the motor, gr is the reduction ratio of the gearbox, ω_{shaft} is the rotational velocity at the output of the gearbox and I_{gear} is the inertia of the rotor.

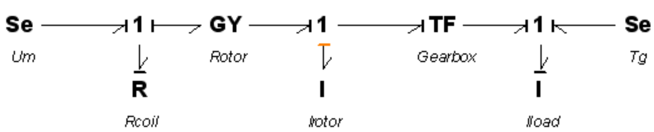

Fig. 3. Simple bondgraph model of a servo motor

Equation 1 describes the resulting torque on the load of figure 3. It is clearly visible that the presence of the gearbox degrades the backdriveability of the system. Both the mechanical inertia of the rotor and the electromechanical force resulting from the induced voltage due to the rotation of the rotor in the coil are divided by the squared reduction ratio, which amplifies their resistive effects. With a gearbox present in the hip the swing leg is clearly not able to swing freely with respect to the stance leg.

$$\tau_{load} = \tau_g + \frac{k_\tau U_m}{R_{coil} * gr} - \frac{k_\tau^2 * \omega_{shaft}}{R_{coil} * gr^2} - \frac{\frac{d}{dt}\omega_{shaft} * I_{rotor}}{gr^2} \quad (1)$$

The gearbox present in the hip has a reduction ratio of 1:73. Simulations have shown that this is enough to degrade the backdriveability to such a point that the swing leg is not capable of completing its swing phase. This problem can be solved by a controller which measures the torque at the output of the gearbox and controls this to zero. The motor is turning to facilitate the movement of the load, but not performing any mechanical work on it. A torque sensor intended for this purpose was already implemented in the original design [2].

C. Field bus

The current robot is controlled by a local controller network. One master module communicates with 9 slave modules over a single field bus using the TWI communication protocol. The functionality of each module is:

1) *Master module*
The master module gathers the data from the slave modules and gives commands to the slave modules according to the control algorithm.
2) *Motor module*
The motor module controls the motor located in the hip according to the commands received from the master module. It interfaces with an encoder which measures the angle between the legs. It also contains several safeguards which protect the bridge circuitry in case of an error.
3) *Knee joint module*
A slave module is present at each knee joint. It controls an electromagnet which can lock the knee when the leg is straight. It also interfaces with an encoder which measures the angle of the knee.
4) *Ankle joint module*
Each ankle has a slave module which can register if the foot is in contact with the ground by means of a switch. It also measures the orientation of the foot with respect to the ankle if a rotating foot with encoder is present.

The slave modules already present at the current robot measure the angles of all the joints in the robot. This means that only 4 extra modules need to be added to the field bus. These modules will control the motors of the ankle actuation system based on control signals transmitted by the main controller. The extra modules will need to be supplied with measurements about the position and velocity of the ankle joint they are controlling. This will increase the communication load on the field bus. The main control loop operates at 100 Hz and a worst case estimation is that for the control of the robot 150 bytes need to be transmitted over the field bus. The resulting communication speed of 120 kbit/s is still well below the maximum speed of 400 kbit/s of the TWI protocol. Part of the remaining capacity is used for data logging during operation.

III. Design & Implementation

In this section the physical design and implementation of the system will be discussed. The design is based on several requirements which were obtained by simulations. The complete robot is shown at the end of this section in figure 5.

A. *Foot shape*

The shape of the foot influences the way the c.o.m. moves forward during a step. A common choice for the shape of the foot of passive dynamic walkers is a round shape with a curvature of $1/3$ of the leg length. It was shown in [7] that this curvature is optimal for the local stability of those walking frames. This curvature also corresponds with the human roll over shape as shown in [3].

The lowest point of the curved foot (nadir) is often placed at an offset with respect to the ankle [9], [1]. A previous study at the CE group showed why that offset is necessary in robots fully powered by ankle actuation. The offset prevents the stance leg from rolling forward immediately after the upper leg of the swing leg passes the stance leg. This rolling movement occurs due to the gravitional force acting on the center of mass (c.o.m.) of the robot and effectively decreases the steplength of the robot causing it eventually to fall. With an offset in the nadir this rolling movement is delayed allowing the swing leg to complete its swing phase.

Simulation results showed that with the mass ratio of 4:1 a marginal ground clearance was achieved during a passive swing phase. In this simulation the hip was assumed to be perfectly backdriveable. To increase the ground clearance the backdriveability controller is used to exert a net torque on the swing leg by applying a non-zero setpoint. This torque accelerates the swing leg forward and increases the bending of the knee and thus the ground clearance. The net torque results in a negative reaction torque applied to the stance leg. This reaction torque is sufficient for preventing the robot from starting to roll forward as soon as the upper leg of the swing leg passes the stance leg. No offset of the nadir is therefore necessary in the footshape.

The energy loss during the collision of the foot and the ground is related to the impact velocity of the foot. By adding a compliant layer between the bottom of the foot and the ground the velocity at which the foot collides with the floor is reduced and therefore also the energy loss. The effectiveness of compliant contact is shown in [8]. The compliant layer is however also between the foot and the ground during push off. Energy of the push off is lost in the compression of that layer. This can be solved by reducing the thickness of the compliant material at the tip of the foot.

To achieve compliant contact with the ground an experimental layer of neoprene rubber (synthetic rubber) is attached to the bottom of the foot. The used layer of neoprene is $1.8cm$ thick. The thickness of the material is kept constant for now over the entire lenght of the foot. The energy loss in the push off phase is considered to be marginal, but experiments will be carried out to evaluate this.

The resulting foot and ankle joint are shown in figure 4. A HP 5640 A06 optical encoder is attached to the ankle joint which measures the angle between the foot and the lower leg.

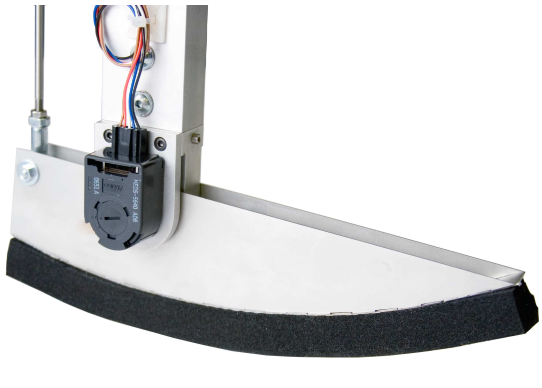

Fig. 4. Foot and ankle joint

B. *Actuator*

The type of motors that will be used are servo motors. Servo motors are used because unlike stepper motors the relationship between input (voltage/current) and output (torque/rotational velocity) is almost linear. This improves the modelling of the actuator and the controllability of the added energy. The energy added to the system depends on the applied torque, the resulting angular velocity and the time the torque is applied. High torques are required when impulse like actuation is desired and lower torques can be sufficient if the actuation takes place over a longer period of time. Based on simulations the motors should be capable of delivering an intermittent torque of 8 Nm at an angular velocity of 30 rpm.

Besides the required torque and rotating speed the ideal motor has several other characteristics. The ideal motor has a high stall torque, high torque constant and low terminal resistance. High torques can then be delivered at low currents and a low terminal resistance results in less energy dissipation in the motor itself. Its inteded placement is parallel to the upper leg. To protect the motor from being damaged in case the robot should fall it is desired that it is not wider than the upper leg.

It is not required that the system is backdriveable, so a gearbox can be used to alleviate the torque requirements on the motor. A high reduction ratio even helps passively to keep the ankle at the correct angle during the stance phase when there are high torques in the ankle due to the movement of the leg. However the rotation speed at the output of the gearbox compared to the rotation speed of the motor is decreased by the reduction ratio. This limits the speed at which a certain torque can be applied to the ankle joint.

The Maxon RE25 20 Watt 24 V version is chosen in combination with a GP32C 1:86 planetary gearhead, [6]. The chosen reduction ratio was the lowest, readily available, reduction ratio capable of handling the required output torque.

The complete combination offers the best overall compromise between the discussed characteristics.

C. Transmission

As was discussed the actuators will be connected parallel to the upper leg. A transmission is therefore required that is capable of transmitting torque over a perpendicular angle and a flexible joint (the knee). The requirements on the structure of the transmission come from the maximum angles of the system during operation. The maximum angle the foot can achieve with respect to the lower leg is 35^o. To generate the strongest push off possible, the transmission must be capable of actuating the foot up to this angle. During the swing phase the transmission should not load the bending of the knee with the foot in the neutral position. The maximum angle of the knee is taken from simulations to be 35^o. It is desired for storage purposes that the lower leg can be placed at a perpendicular angle with respect to the upper leg.

Such a transmission can be constructed for instance using cables and pulleys. However due to the forces acting on it, the cable will lengthen and will eventually break resulting in high maintainance. Also a complex system of pulleys and will be necessary to ensure that the cable will always be under tension when the knee is bend.

A second alternative which was considered was a transmission made of bowden cables. Steel bowden cables were considered so that it can withstand the forces acting on it without lenghtening. These cables however suffer from heavy internal drag when strongly curved, resulting in poor efficiency. A weaker curve improves efficiency, but runs the risk from getting snagged behind objects.

A rigid transmission which runs close to the legs is therefore desired. As the transmission is rigid the movement a coupling is make between the rotation of the knee and the rotation of the foot. This means that the motor will have to actively control the position of the foot during the swing phase to keep it in the neutral position as the knee bends. This is considered acceptable as the foot is not loaded during the swing phase and the energy dissipated to keep it in the neutral position during that phase are expected to be negligible compared to the energy dissipated during the push off.

Geometry dictates that a single bar transmission is not capable of satisfying all the requirements. The maximum angle the knee can make using such a construction depends on the location of the motor on the upper leg, but will never reach up to 90^o. An extra hingepoint is therefore created in the knee. This decouples the influence the position of the motor on the upper leg has on the maximum angle the knee can make. Figure 6 shows that this transmission is capable of satisfying all the requirements.

A perpendicular transmission is required to connect the two link system shown in figure 6 to the motor which is parallel to the upper leg. A combination of two straight bevel gear wheels is used for this purpose. A big surface of the secondary gear wheel is desired so that the pull levers of the transmission can be connected as a fork construction to its surface. The surface of the primary gear wheel should be small, because

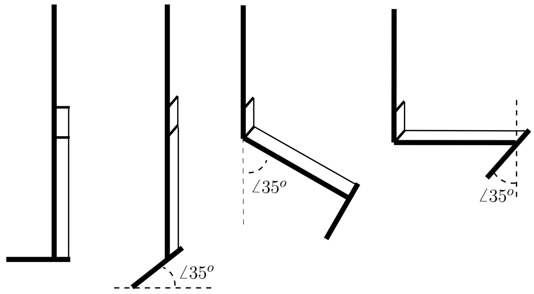

Fig. 6. Sketch of the transmission and its three extreme poses

the width of the transmission is limited due to the available space between the legs. A 1:3 reduction ratio between the primary and secondary gear is implemented to satisfy both requirements. A SolidWorks drawing Figure 7 shows the physical construction of this part of the transmission.

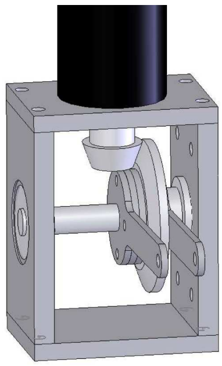

Fig. 7. Sketch of part of the transmission

Rods with steel ball-and-sockets at each end are used to connect the pull levers of the system in figure 7 with the hingepoint in the knee and the hingepoint to the foot. The bearings in the ball-and-sockets allow the rods to stay alligned when the the pull levers are rotated by the motor. Figure 8 shows the realized transmission.

D. Electronics

The motors actuating the ankles are controlled by a slave module connected to the field bus. An ATmega8 microcontroller is used to handle the TWI communication and generate the control signals (PWM and direction signals) for the motor driver. As a motor driver the VNH2SP30 full bridge chip by STMicroelectronics is used. This chip is capable of handling PWM frequencies up to 20 kHz and when properly cooled current peaks of 30 A. This single chip solution allows for a compact implementation so that the circuitry is protected when the robot should fall. Figure 8 shows the placement of the circuit board on the upper leg of the robot.

IV. Controller

It is shown in several papers [5], [4] that pushing off before heel strike is energetically more efficient than pushing off

Fig. 5. Dribbel with added feet and ankle actuation system (Photo taken by M.H. Schwirtz)

Fig. 8. Dedicated printed circuit board

after impact. In [1] experiments were carried out with pre impact push off, but this always led to gait instability. General methods of determining when the push off should be initiated still have to be developed. For now the robot will initiate the push off after heel strike. To that end switches have been connected to the feet which register if that foot is in contact with the ground.

Two types of controllers are present in the system. The first type of controller, discussed in section IV-A, are the controllers for the ankle actuators. The second type is the controller applied to the hip motor, discusses in IV-B. The function of this controller is to make the hip backdriveable.

A. Controller

The ankle actuators are controlled by very simple controllers. If the command to initiate the push off has been received from the main controller, upon a detection of heel strike, a proportional controller is used to drive the ankle towards the desired setpoint. This emulates actuation by a spring as is used in [1], but the amount of energy added to the system can now be controlled by the values of the controller gain and the setpoint. This allows the robot to walk at different velocities.

For the retraction of the foot a derivative action is added to the controller. The inclusion of the velocity of the ankle to the controller prevents the foot from oscillating during the swing phase. Oscillation of the foot can decrease the ground clearance of the foot and is therefore undesired.

B. Backdriveability controller

As mentioned in section II the torque at the output of the hipmotor should be actively controlled to facilitate the swing action of the legs. In case the ground clearance is insufficient a non-zero setpoint can be used to apply a small netforce on the upperleg of the swingleg which will increase the bending of the knee and thus the ground clearance.

The torque at the hip axis is measured and is used as input for the controller. A first prototype of such a controller was applied to a double pendulum with dimensions resembling a leg of the robot shown in figure 2. A PI controller, a discrete differentiating action made the controller unstable, was tuned on this model and was capable of controlling the torque at the hip axis.

When applied to the model of the walking robot however the controller was unable to regulate the torque at the output of the motor properly. The explanation for this is believed to be the non-stationary base of the motor. The robot was capable of walking with a non-zero setpoint of the controller so a further investigation of the backdriveability of such motors was postponed for a later study.

V. Implementation issues

The realized robot is not yet capable of walking by means of pushing off against the ground. The main problem at the moment is the connection of the feet to the ankle joint. The sides of the feet are 1mm thick and are stuck to the ankle encoder axis by means of a thight fit. The friction between the foot and the axis causes the axis to rotate when the foot rotates. This connection is sufficient when the foot has to be kept in a fixed position. However when a push off is made the friction force between the foot and the encoder axis is insufficient and causes the foot to rotate over the axis. In this situation the encoder position does not match the angle of the foot anymore and the controller fails. This problem can be solved by extending the encoder axis outside the foot and making a rigid connection with a setscrew between the encoder axis and a piece of aluminum which is mounted to the side of the foot.

A second issue is the strength of the knee lock mechanism. This mechanism consists of an electromagnet located at the upperleg which can lock a metal plate connected to the lower leg. All the force generated by the push off has to be transmitted to the center of mass of the robot (the hip) throug the leg. If the locking mechanism is not alligned properly the strain on the locking mechanism is increased. This causes the connection between the magnet and the metal plate to be broken during push off and subsequently the robot will immediately fall backwards.

After the complete system was assembled the layer of neoprene proved to be problematic. As the feet of the robot are very small the thick layer of neoprene reduced the sideway stiffness of the robot, which caused increased the strain on the knee joints. The asymmetric mass distribution of the legs (all the motors are connected to the same side of the legs) will cause the robot to deviate from its straight line of propagation. This was solved by decreasing the layer of neoprene to 7 mm, which still retains the benefits of compliant contact, but increases the sideways stiffness significantly.

Another implementation issues is that the torque sensor is not yet operational. This means that the hip is not back-driveable and that the control strategy discussed in section IV cannot be implemented.

VI. Conclusions

An existing planar bipedal robot has been equiped with actuated ankles. The analysis of the original configuration showed that in order to maintain a proper mass distribution the actuators had to be placed on the upper legs. A rigid transmission was developed which actuated the ankles over a flexible joint. The system has been realized, but is not yet operational. The main implementation issues and their solutions have been presented. In order to validate the models of the robot extensive tests will be done to gather experimental data as soon as the complete system is operational.

VII. Future Work

The robot is now equiped with a system to generate a push off with the feet. Future research will focus on the performance of hybrid control strategies with both actuation of the hip and the ankles. A comparison will be made the various control strategies with respect to energy efficiency and stability.

It is known that pre-impact push off decreases the energy losses at impact and therefore decreases the energy which needs to be introduced in the system to sustain a stable limit cycle. This system will be used to validate the effectiveness of different methods to determine the instant at which the push off is initiated.

Torque control is necessary in the hip to facilitate the swing action of the stance leg in the presence of a motor with gear-box. The discussed backdriveability controller worked well in simulations when the motor was connected to a stationary base, but its performance decreased significantly when the base could move (the stance leg). More advanced control strategies will be tested to increase the backdriveability of such systems.

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Mechanical design

In this appendix the design of the mechanical system is discussed.

Design and implementation

All the mechanical parts were designed in SolidWorks and are included on the project cd-rom. The mechanical drawings used by TCO for the fabrication are also available on the project cd-rom.

The conceptual design was altered during the fabrication process based on advice which was received from the people of TCO. The various remarks are listed below:

1. Securing of bearings
   All bearings have to be preferably secured by the mechanical construction itself. This way the bearings can always be replaced by taking the structure apart. Flanged bearings on axis should be secured on the one side by the material of the structure and on the other side by means of adjusting collars located on the axis. A small indentation has to be made on the axis where the adjusting collars are to be located. If adjusting collars cannot be used a space bus should be placed between the bearings to fix them in place.

2. Connection of several plates
   It should be avoid to use nuts and bolts to fix several plates together, because nuts and bolts will loosen due to vibrations. If the last plate is thick enough, screw thread should be fabricated in that plate. The bolt now tightens with respect to the last plate and the resulting connection is much stronger than with a nut behind the last plate.

3. Curved metal plates When curved metal plates have to be connected this should be realized with cut-aways in both plates which interlock. Spotwelds and glue are used to achieve a strong connection. A full weld connection of thin metal plates will leave those plates curved.

Material calculations

The width of the materials is based on calculations of the allowable bending forces on the parts. Parts that endure high forces should be made of steel, other parts are best made of aluminum.

The force used in the calculations is taken to be ten times the maximum occurring force in the simulations. The bending force for levers is calculated as:

$$\tau = \frac{F * l}{I/(h/2)} \tag{1}$$

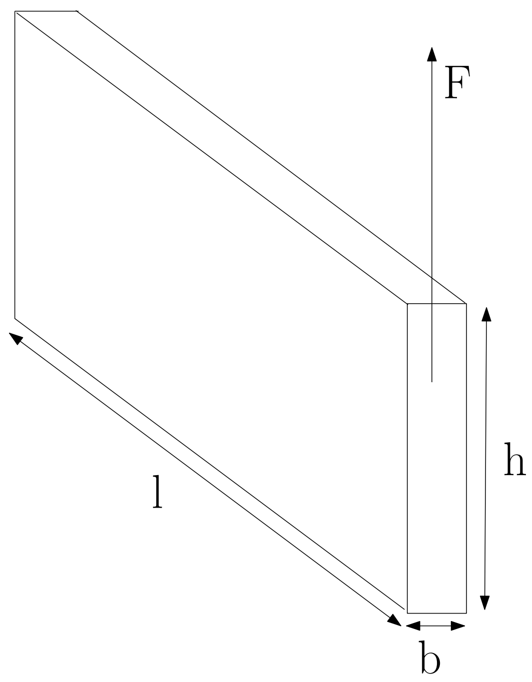


Figure 1: Bending force on levers

The diameter of the pull rods is based on calculations of the allowable push force. The force used in the calculations is taken to be ten times the maximum occurring force in the simulations. The push force for solid rods is calculated as:

$$P_k = \frac{\pi^2 * E * I}{l^2} \tag{2}$$

The diameter of the rods and the width of the levers based on these calculations is taken to be 2 mm.

Components

In table 1 a list is given from the various companies of which parts were purchased.

Supplier	Part
Boekholt Aandrijftechniek	Straight bevel gears
Eriks	Neoprene rubber
Neita	Bearings
Conrad	Ball-and-sockets
Farnell	Electronic Parts
Maxon	Motor units

Table 1: List of suppliers

Implementation issues

At the moment several implementation issues remain:

1. play on the axis of the gear wheel
   The location of the grooves on the axis is inaccurate. This causes a play of about 0.5 mm on the axis. At the moment this is solved by the position of the secondary gear wheel. This prevents the axis from sliding, but it also puts more strain on the motor shaft. A thin metal plate should be constructed which can fill the gap between the bearing and the adjusting collar.

2. Alignment of locking mechanism
   If the locking mechanism are not perfectly aligned, a problem can arise during the push off. The extra strain caused by the push off on the locking mechanism causes it to fail and thus the robot will fall backwards. Regular attention should therefore be paid to the alignment of the locking mechanism.

3. Connection of foot to encoder shaft
   At the moment only a tight fit connects the foot to the encoder shaft. During a push off a force is acting on the foot. The friction between the foot and the encode shaft is sometimes insufficient and the foot will start to rotate around the encoder shaft. The encoder position doesn't match the position of the foot anymore and this will cause the robot to fall. A solution to this problem is presented in the next section.

Recommendations

The ankle design can be improved by the addition of a brace. The encoder shaft should be extended outside the foot. A bar of aluminum is attached over the encoder shaft to the side of the foot by means of nuts and bolts. The bar of aluminum and thus the foot can now be securely fastened to the encoder shaft by means of a set screw. A picture of this system is shown in the following figure.

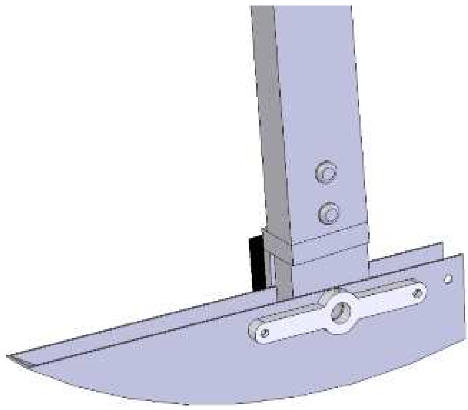


Figure 2: Solution to ankle problem

Electronics

In this appendix the schematics and implementation of the ankle controller are given.

Schematic

The schematic of the circuitry is depicted in figure 3

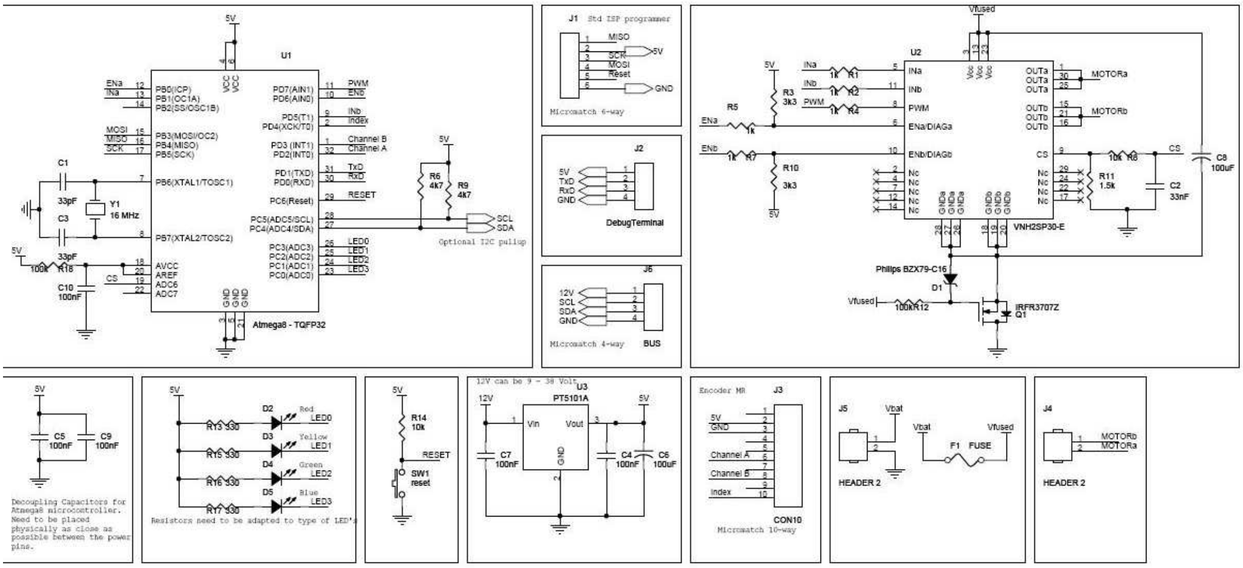
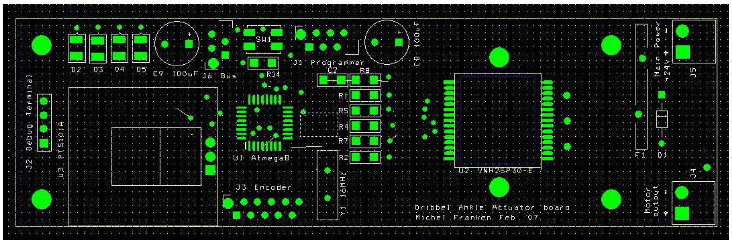


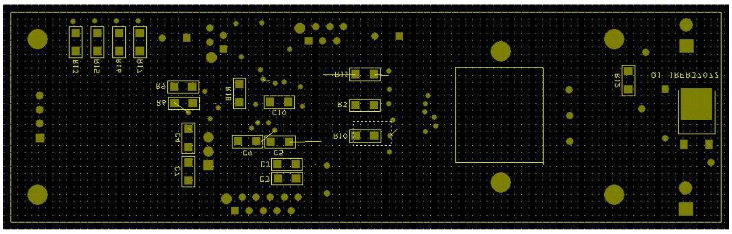
Figure 3: Schematic of electronic circuitry

Layout

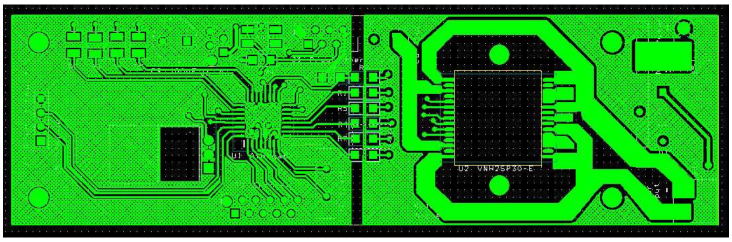
One of the demands on the dimensions of the board is that it should fit completely within the width of the leg which is 40mm. This is to prevent damage to the board if the robot falls down. The dimensions of the board are 38mm x129mm and the layout of both sides of the board are given in figure 4.



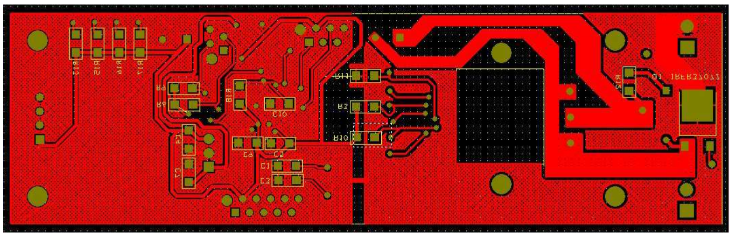
(a) Placement of the components on the top of the board



(b) Placement of the components on the bottom of the board



(c) Routing of tracks on the top of the board



(d) Routing of tracks on the bottom of the board

Figure 4: Board Layout

Revisions

In the above schematic the PWM signal is originating from an I/O pin of the ATmega8 microcontroller which is not capable of generating a PWM signal by hardware. To remedy this the PWM and INa signals switch I/O ports on the microcontroller. In the physical board the switch between the tracks is made by placing R1 and R4 in an upright position and reconnecting their output to the proper track.

Recommended alterations

If this design is recycled for other projects several suggestions can be made to improve the design:

1. Capacitor C6
   This capacitor is located right next next to the bus connector. If the board is not terminating the bus, the cable will have to be strongly bend to fit into the connector. It is therefore recommended to either select a capacitor with a lower profile so that it does not obstruct the bus cable, or move the capacitor to a different location on the board.

2. VNH2SP30-E This chip incorporates the H-bridge used to drive the motor. This chip is specified to have a maximum Vcc voltage of 41V. However it shuts down at 19V (some chips shut down already at 16V). If higher voltages are required it is possible to use the VNH3SP30-E chip which has the same lay-out. The VNH3SP30-E is specified to operate up to 30V, but does not incorporate a current sense circuitry and has a much lower maximum frequency for the PWM signal. It will also overheat 5 times faster than the VNH2SP30-E.

Code

In this appendix the implemented code is discussed.

Mode of operation

The code which controls Dribbel is largely the same as before, but it has been updated to include the 4 extra controllers. There are two modes of operation, one with stiff ankles and one in which a push off is generated with the feet after heel strike.

To initialize the system the robot should be placed with the feet against the ground with straight parallel legs. This initializes the hip encoder. Now the robot can be rotated over the feet so that the ankle encoders are initialized. After all four blue leds on the ankle encoder slave modules have started blinking the system is initialized.

The selection between the two modes is made after the initialization of the robot. Button A on the main controller selects the rigid ankle mode (green led is turned on) and Button B selects the active ankle mode (blue led is turned on). As before the black button next to the power socket starts and stops the selected walking mode.

Code

The code for the ankle controllers has been written with the free AVR GCC compiler. It is based on the motor controller written by ir. Edwin Dertien. Two extra functions have been implemented which allow the main controller to write the position and velocity of the ankle the slave module is controlling.

Two different controllers are present in the ankle controllers. A P-controller for generating the push off and a PD controller to keep the ankle in a rigid position. The switch between the two controllers is at the moment hard coded. The PD controller is selected when a zero setpoint is written and the P controller is selected for a non zero setpoint.

The interface to the current sense of the H-bridge chip and the MR-encoder attached to the ankle shaft are not yet implemented.

A very good manual on the use of AVR GCC can be found on the following URL: http://www.mikrokontroller.net/articles/AVR-GCC-Tutorial.

To do

The following list contains the work which has to be done on the overall control code.

1. Rewrite the code for the main controller and motor controller to AVR GCC
2. Test AVR GCC rewritten code for the joint interfaces
3. Update RS232 control and command procedure to include ankle controllers
4. Update datalogging to include data about the ankle controllers
5. Implement current sense interface and encoder interface on ankle controllers
6. Implement more general controller selection(P,PD or PID) in motor controllers

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