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EINDHOVEN UNIVERSITY OF TECHNOLOGY

STICKMAN CONTROL

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Management summary

The goal of this project is to create a simple humanoid robot called a stickman. This robot should be able to walk down a shallow slope without any actuation and walk horizontally using an electromotor with control system. Stickman is built in the previous phase. The actual stickman is weighted and its mass is lower than the mass computed in the previous project phase. This is corrected with additional masses, which makes it possible to position the center of mass at the correct height.

A surface is constructed to make passive and actuated walking possible. This surface consists of two plates on which several pads are mounted. The plates are mounted to some tables to ensure a rigid base. Experiments are performed with this setup in order to achieve passive walking. It was possible to walk about 2.5 meters down a slope of $0.02rad$. The angle of the table and the distance between the pads is slightly changed to achieve this result.

The experimental setup for actuated design is established too. Measurement data is processed real time by Matlab/Simulink model which is running in a Linux environment. The setup furthermore consists out of an electromotor, two rotary encoders, three amplifiers, a data-acquisition device and a converter.

A controller is designed to minimize the tracking error with respect to a predetermined reference signal. This reference signal is derived from simulations with the dynamic model from the previous phase. The controller consists of a basic PD-controller improved with an algorithm for finite time convergence. Besides, feed forward is part of the control scheme. This controller makes it possible to track the reference signal with an error smaller than 3%.

A successful experiment on actuated walking is performed in which the stickman walked about $2.2m$. The maximum error during this walking motion was approximately 5% of the maximum angular position. The torque of this experiment is compared with the torque calculated with the dynamic model. The torque during the experiment is higher than calculated. The model does not represent the real walking motion; it is an approximation so this difference was expected.

List of symbols

Variable	Quantity	Unit
a	Amplitude of sine	$-$
b	Angular frequency of sine	$-$
c	Phase shift of sine	$-$
C_t	Torque constant	$Nm\ A^{-1}$
E	Energy	J
F	Sine function	$-$
h	Height	m
I	Current	A
i	Transmission	$-$
l	Length	m
m	Mass	kg
n	Number of amplifiers	$-$
P	Power	W
T	Torque	Nm
t	Time	s
U	Voltage	V
V	Volume	m^3
w	Width	m
x	Distance	m
ρ	Density	$kg\ m^{-3}$
$\dot{\varphi}$	Angular velocity	$rad\ s^{-1}$
Subscript		
tot	Total	$-$
add	Added	$-$
leg	Leg	$-$
ref	Reference	$-$
i	Index	$-$
n	Total number	$-$
max	Maximum	$-$

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Introduction

The purpose of this report is to continue the work done in the previous project phase. The goal of the whole project is to design and build a two legged robot with one degree of freedom (a stickman) and conduct experiments on the walking motion of the stickman. This robot is built in the previous phase of this project which is summarized in the next chapter. After the research from this report the stickman can be used to research the human walking gait because it is the most basic form that represents the human walking motion. For example, the key concept of falling before making a step can be analyzed with this stickman. The purpose for the authors of this report is to get acquainted with a project as a whole and to experience each project phase and its challenges.

The stickman is a very simplified version of the human legs. It has two inner legs and two outer legs joined in the hip with only one degree of freedom. The walking motion of the stickman will look like the motion of a gorilla or a man on crutches. The goal is to get the stickman walking without actuation down a slope and with actuation on a horizontal surface. The stickman is designed in the previous phase and the main dimensions and properties are stated in the chapter below. The actual build stickman has to meet the determined requirements which are analyzed in Chapter 1. An experimental set-up is designed in Chapter 2 which has some special features to make passive and active walking possible. After Chapter 1 the stickman has the correct properties and should be able to walk down a slope which is experimented in Chapter 3. The connection between a laptop and the stickman is designed to control the actuated walking. This connection is elaborated in Chapter 4. The control of the stickman is managed by a controller. This controller is designed in Chapter 5 and implemented in Chapter 6 for the actuated walking motion. Chapter 6 also describes the results which are compared to simulations done in previous the phase of this project. Finally, recommendations are stated in Chapter 7 for further use of the stickman and the experimental set-up.

Iets over bepalen van factor van counts naar graden ergens in het verslag?

Summary of the previous phase

The main subject of this report is the walking motion of a stickman. This is a simplification of the human legs with one degree of freedom. The stickman used for this report is made in a previous project phase which is summarized here.

The global geometry is defined by six parameters: Leg length, foot radius, horizontal and vertical position of the CoM and total weight of the legs. The length of the legs and the total mass is chosen. The center of mass (CoM) should be as high as possible according to the client. The values of the other two parameters and the initial state are varied in a simulation with a verified dynamic model. The testing criterion of this simulation is the number of successful steps made by the stickman. The limit cycle is analyzed to determine the actual stability. The most stable configuration is chosen.

The electromotor and other controlling equipment are chosen based on the overall geometry. The torque required is computed to determine a suitable motor. This is done using the dynamic model and with an approximation of this model to check the results. The motor is chosen based on a velocity-torque plot. It has a power of $60W$ which reaches a safety factor of 8 regarding the torque. The minimum gear ratio is 52:1 however a motor with a gear ratio of 111:1 was available and is chosen for the stickman. This combination is appropriate regarding the torque and rotational speed.

Two sensors are used to measure the angle between the legs on the main axle and the position of the motor on the motor axle respectively. Rotary encoders are chosen based on their accuracy. The encoder on the axle is a 12bit single turn absolute encoder and the encoder on the motor a 9bit multi turn incremental encoder. The encoder on the motor is part of the motor provided by the client. The accuracy of the encoder on the axle is determined based on a requirement of the client which holds that the angle between the legs should be measured with a minimum accuracy of 0.1°. This accuracy is needed to determine the first and second derivative of the position data. These represent the velocity and acceleration respectively.

The final specifications (theoretically) are listed in Table 0.1.

Table 0.1: Basic parameters of the stickman determined using the dynamic model

Parameter	**Value**	**Unit**	**Description**
Length	400	$[mm]$	From the foot to the hip joint
Foot radius	400	$[mm]$	
Horizontal pos. CoM	0.0	$[mm]$	With respect to the vertical symmetry axis
Vertical pos. CoM	100	$[mm]$	With respect to the hip joint
Total weight	6.0	$[kg]$	For both legs, electrical equipment included

Chapter 1

Stickman properties

The whole geometry including the position of the centre of mass (CoM) is determined with a model as stated in the summary of the previous phase. Experiments are done to check if this position is correct for the actual stickman. The computed position is $100mm$ below the axle and the mass of each leg must be $3kg$. These are important properties because they determine the stability of the walking gait. The initial conditions do not significantly influence the gait if it is stable. Each leg of the stickman weights purposely less than $3kg$ so additional mass has to be added. This provides us the freedom to position the CoM. The CoM of the original stickman is determined so the position of the additional mass can be computed. The amount of space on both legs to place the additional mass determines the geometry. Three options are analyzed to find the feasible position and geometry of the additional mass.

Original stickman

The position of the CoM of the actual stickman is determined experimentally and each leg is weighted with a scale which has a resolution of $5g$. The experiment is described in Figure 1.1. Basically, each leg is analyzed separately by laying it on a bar with a small radius and balancing it. When the leg is balanced on the horizontal bar the CoM lies exactly above the bar. However, the leg cannot be placed exactly perpendicular to the cylinder so it is placed at different angles as shown in Figure 1.2. The contact points of the leg with the bar are marked on the leg and are later on combined to determine the position of the CoM.

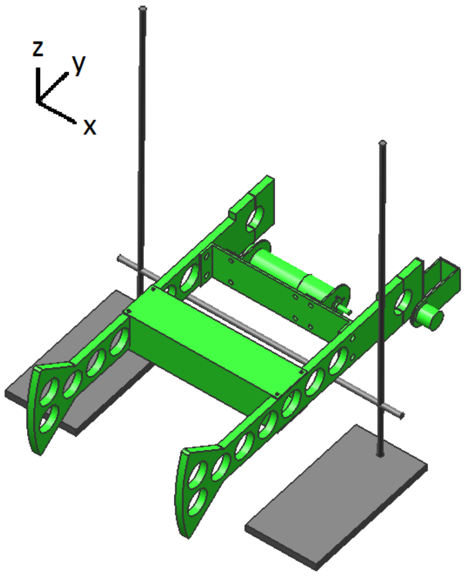

Figure 1.1: Balancing the leg perpendicular to support

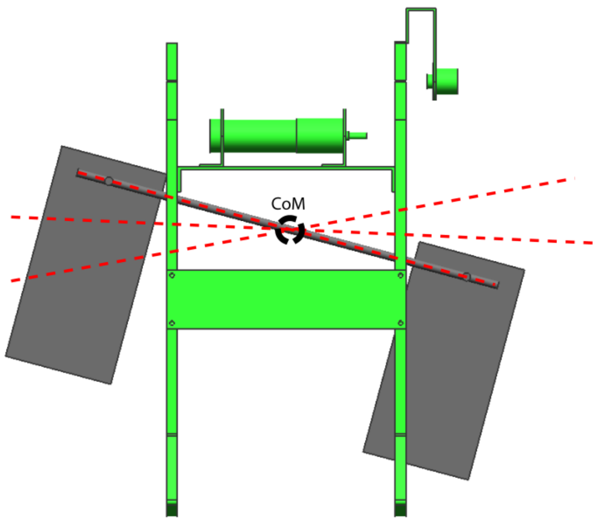

Figure 1.2: Balancing the leg at an angle

Only the position along the y-axis (from Figure 1.1) is important for the case described in this report because moving sideways is not taken into account. The position of the CoM with respect to the axle for the inner leg is $-137.5mm$ and for the outer leg $100mm$. So the CoM of the outer legs is correctly positioned and the additional mass to reach the desired weight of $3kg$ per leg is placed at the same height as the CoM.

Positioning the CoM

The CoM is positioned by adding the correct amount of mass at the correct position. Three possibilities to add mass on the inner leg are shown in Figure 1.3. The black rectangles are the additional masses in this figure. Option 1: Adding a plate on top of the middle leg (P1). Option 2: Adding mass next to the motor (P2). Option 3: Weight on top of the middle leg and below the motor mount (P1+P3). The total stickman including the outer leg and the additional weight is shown in Figure 1.4.

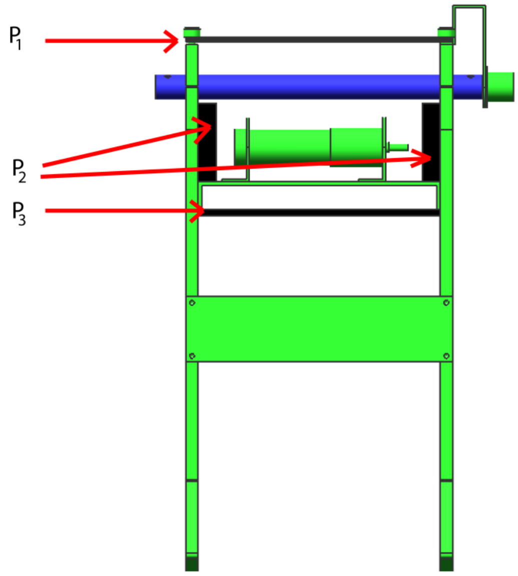

Figure 1.3: Mass distribution of the middle leg

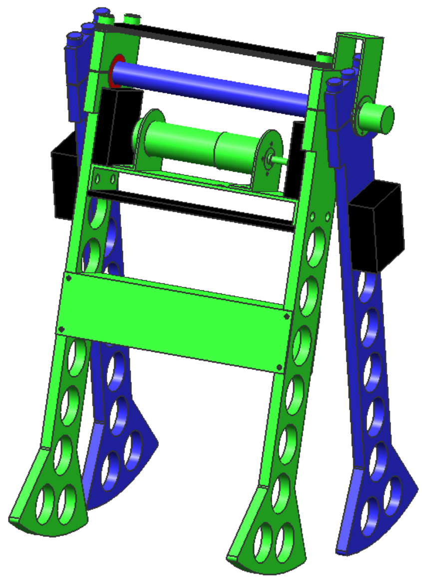

Figure 1.4: Total stickman with additional masses

The masses are determined using (1.1) and (1.2). These equations describe the requirement on the total mass of each leg and the requirement on the position of the CoM respectively. The position of each mass in (1.2) is determined with respect to a reference value. This reference value is set at the required height for the centre of mass ($0.1m$ below the axle). Equation (1.2) is described in Figure 1.5 as well.

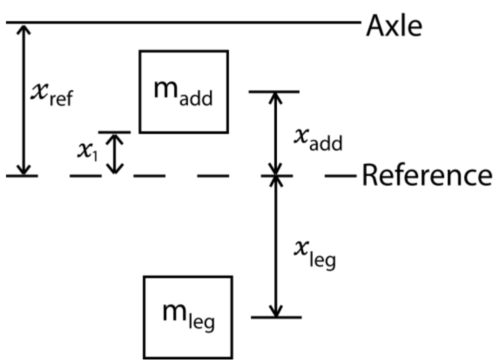

Figure 1.5: Computation of the total center of mass

$$m_{tot} = m_{leg} + m_{add} = 3kg \qquad (1.1)$$

$$m_{tot} \cdot x_{ref} = m_{leg} \cdot x_{leg} + m_{add} \cdot x_{add} = 300 \qquad (1.2)$$

$$m_{add} = \rho \cdot V = \rho \cdot l \cdot b \cdot h$$

$$x_{add} = x_1 + \frac{1}{2}h$$

Applying the requirements described at the beginning of this chapter only the height of the additional masses is variable. This results in (1.3) and (1.4).Using these equations the three different options can be analyzed to see if they are possible. This analysis is done based on the equation of the CoM. The CoM is positioned at the correct height followed by a verification of the total mass.

$$\rho lb \cdot h + m_{leg} - m_{tot} = 0 \tag{1.3}$$

$$\frac{1}{2}\rho lb \cdot h^2 + \rho lb x_1 \cdot h + m_{leg}x_{leg} - m_{tot}x_{ref} = 0 \tag{1.4}$$

Option 1 results in a total mass of $2860g$ which is too low and when Option 2 is chosen the total centre of mass lies $19mm$ above the requested position. The available space is too small to hold the total needed mass at one single position. More design freedom is acquired by adding mass below and above the reference height for the CoM. The size of the additional masses from Option 3 is determined by solving the system of equations. The result is shown in Table 1.1.

Table 1.1: The final geometry of the additional masses

Part	Mass $[g]$	Distance to axle $[mm]$	Size $[mm]$
Inner leg	2030	-137.5	-
Extra mass below motor	356	-107.25	$20 \times 50 \times 4.5$
Extra mass top inner leg	573	37	$22 \times 70 \times 4.7$
Outer leg	1885	100	-
Extra mass (2x)	1115	100	$70 \times 50 \times 20$

Conclusion

The actual stickman is weighted and its mass is lower than the mass computed in the previous project phase. This is done on purpose to be able to position the CoM. The mass distribution of the inner and outer leg has to be the same to ensure a fluent walking gait. The vertical position of the CoM of the outer leg lies $100mm$ below the axle of the stickman, as required. The mass of the outer leg is $1885g$ which is less than the required $3kg$ per leg. The total additional mass on the outer leg should weigh $1115g$ and can be placed $100mm$ below the axle. The mass distribution for the inner leg is slightly more complicated because of the limited space. The position of the CoM of the inner leg lies $137.5mm$ below the axle and its total mass is $2030g$ which is $970g$ less than required. An additional mass of $573g$ is placed on top of the inner leg and a mass of $356g$ is placed underneath the motor mount. The position of the CoM for both legs is now placed $100mm$ below the axle of the stickman and both legs weigh $3kg$. These specifications are computed in the previous project phase.

Chapter 2

Walking surface

A surface is constructed to make passive walking possible. The stickman has only one degree of freedom (the hip joint) so the walking motion on a completely flat surface is not possible. The legs of the stickman have the same length so during a step the swing leg will scuff. However, when the stickman is walking on pads there is no problem. The dimensions of these pads are based on the geometry of the stickman. The surface can be tilted to provide a slope for passive walking.

Padding

The length of a pad is taken equal to the arc length of the foot of the stickman. The arc length is equal to $142mm$ which is rounded to $145mm$. The height is chosen small, to prevent stickman from falling too far when it steps besides a block. The width of the blocks is set to $50mm$. Regarding ease of production the pads for the inner leg are the same as for the outer leg. The dimensions of the blocks are listed below.

Length = $145mm$
Width = $50mm$
Height = $10mm$

The required number of pads depends on the step size and the length of the slope. A step is defined as shown in Figure 2.1. The step begins with a double support phase. During the single support phase there is a stance leg and a swing leg. Finally the legs are switched in the double support phase of the following step.

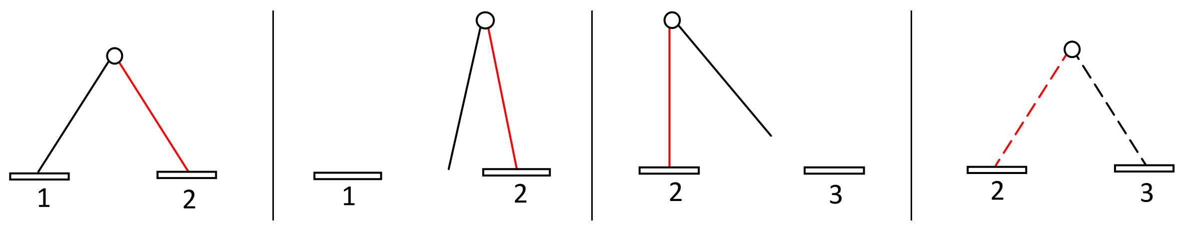

Figure 2.1: The visualization of a step

The distance covered during a step is calculated using the contact points. The feet of the actual stickman are round which is taken into account. The total distance of a step consists of the distance between the contact points during the double support phase and the arc length of the foot during the single support phase. The distance between the contact points and the arc length depend on the angle between the legs during the double support phase. This angle is determined using the dynamic model from the previous phase of this project. So the total step distance is determined based on a simulation which results in a distance of approximately $35cm$.

Surface

The pads are placed on a wooden plate which has the dimensions $1500 \times 400 \times 10mm$. The pads are not fixed at first so the step size can be varied during the experiments. Two of these wooden plates are used for the experiments. This provides a total walking distance of $3m$ which is sufficient for the experiments.

The wooden plates are placed onto three tables because these tables are rigid. Building a new rigid frame is more expensive and not necessary. The slope can be adjusted easily by raising one side of the table. The height each table leg should be lifted to provide the required slope can be calculated using the length of the table and simple trigonometry.

The final set-up for the experiments is shown in Figure 2.2. This is the set-up for a passive walking experiment. The tables are placed horizontally for actuated walking experiments.

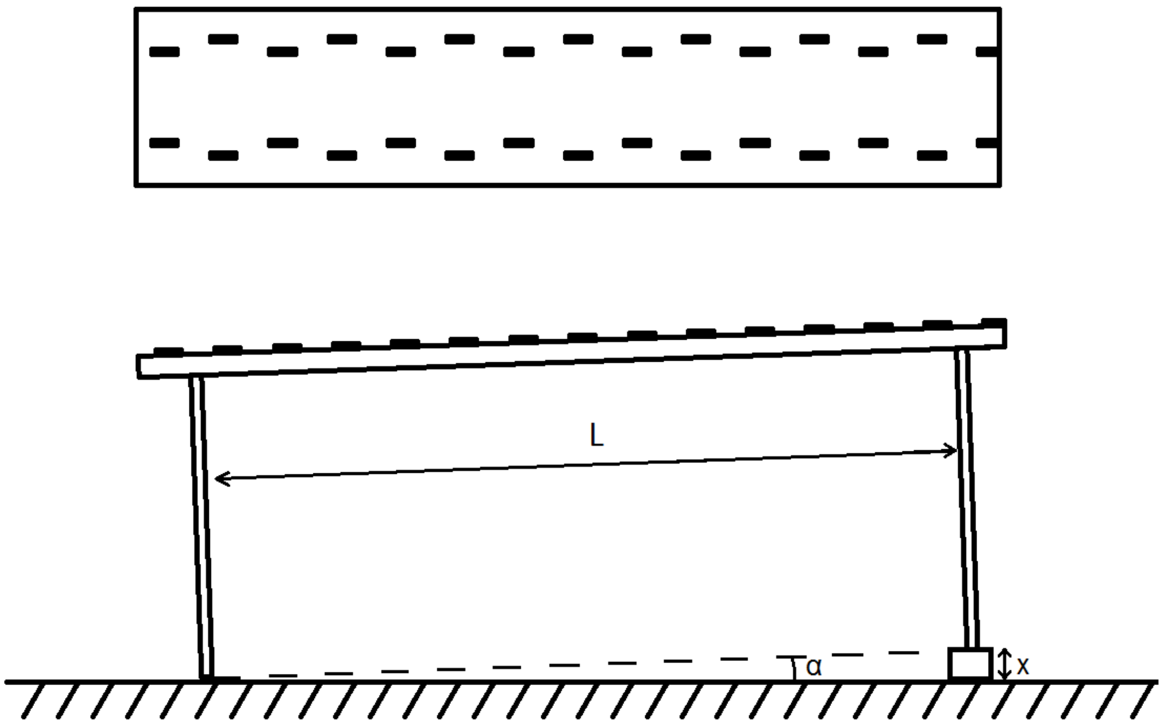

Figure 2.2: The setup of the passive walking (showing pads wooden surface and tables)

Chapter 3

Passive walking

Now that the stickman is adjusted to meet the design specifications as elaborated in Chapter 1, it should be possible to walk down the slope from the previous chapter without actuation. The experimental setup is described in the previous chapter. In this chapter the approach and results of the passive walking experiments are treated.

Experimental setup

The initial settings for the experiment are obtained from the simulations done in the previous phase of this project. The adjustable parameter values for the experiment are the step size and the slope angle. Changing the step size will obviously change the total number of steps as well. The slope angle used in the simulations is equal to $0.015rad$ and the step size based on the simulations is $35cm$. These are the initial settings for the experiments on passive walking. The number of steps within a track range of $3m$ is estimated by the step length and is equal to 15 steps.

Experiments and results

Experiments are started with the setup as described above. By trial and error, it seemed that friction had a very large influence on the possibility to walk a long distance. Every step, the step size initially decreased. One cause for this phenomenon can be the fact that the feet hit the side of the blocks, which causes loss of energy. This happened in most cases after the third step and resulted in a decrease in walking motion and step size. The total amount of energy provided to stickman could therefore be too small. For this reason, the slope was slightly made steeper. Finally, an angle of $0.02rad$ appeared to be the most appropriate configuration. Nevertheless, the decreasing step size is also part of converging to a limit cycle gait. This is confirmed by the fact that the step size was almost equal after about five steps.

The distance between the blocks was initially set to $12cm$ as a result of the simulation output. Nevertheless, this distance between the blocks appeared to be too big. Again, trial and error and video analysis provided the optimal track configuration with this specific slope angle and stickman. The distance between the first four pairs of blocks should be equal to $8cm$. The other blocks are placed at intervals of $6cm$. This setup made it possible to walk eleven steps in a repetitive way. However, a reproducible set-up needs a mechanism to launch the stickman, since the initial step size, angles and angular velocities influence the measurement. The big influence of these parameters explains why it is very difficult to make the system reliable and repetitive, without such a launching system.

However, with some minor changes to the stickman a more reliable setup is possible, as one of the main causes for falling is a slight deflection from the track. This is elaborated in the recommendation section.

Chapter 4

Laptop connection

The second goal of this project phase is to motorize the stickman and make actuated walking possible. The choice of software is elaborated in this chapter together with the specifications of the hardware components. The required hardware components are listed in the summary of the previous phase but will shortly be summarized here.

Software

The stickman will be controlled using real time simulation. A computer is used to process measurement data from the encoders and compute a control signal. The real time simulation has to be connected to the stickman while experimenting without interruption and high sample rates are needed to fluently control the stickman. Based on these requirements a Linux operating system is chosen instead of Windows because Linux ensures a stable connection. Windows always performs multiple tasks at the same time which can interfere with the main task. Linux gives a focus to the main process and delays all other tasks.

Secondly, a program or programming language is needed to process the measurement data. The design of a controller is the focus of this project and there is no time to learn a programming language to program the controller from scratch. So Matlab Simulink is chosen because block schemes can be used to build and test a controller.

Hardware

An overview of the whole hardware system is shown in Figure 4.1. The processed measurement data $y(t)$ is converted to a control signal $u(t)$ in the software. This signal represents the output voltage of the data-acquisition system (TUeDacs MicroGiant [1]). The signal is sent through a USB 2.0 cable to the TUeDacs which converts the digital signal into an analog voltage in a range of $\pm 10V$.

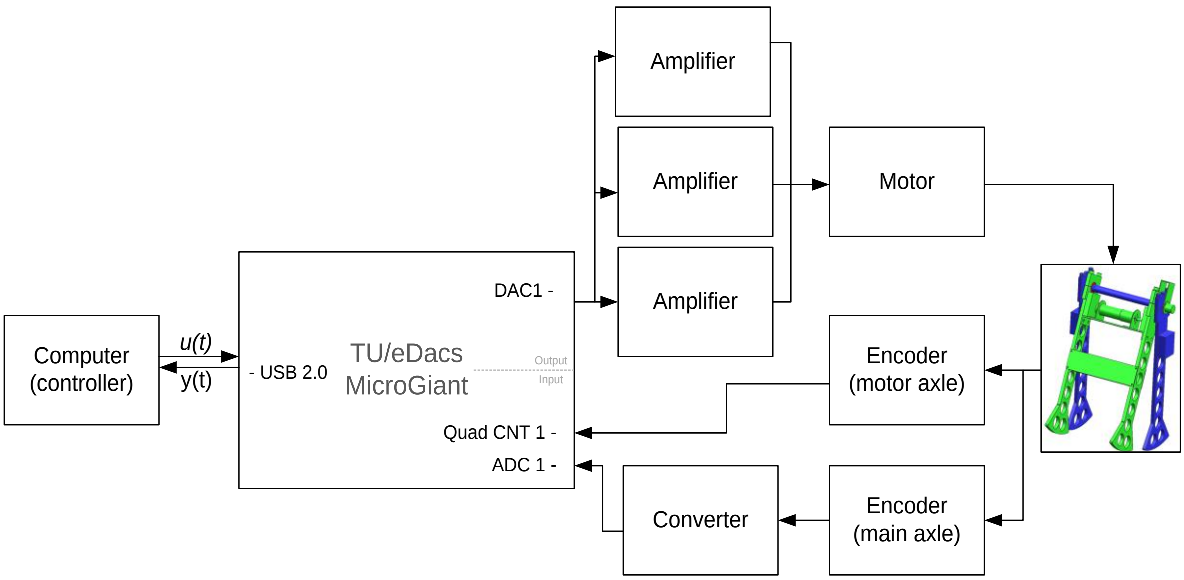

Figure 4.1: A schematic overview of the hardware components and the connections.

This voltage is applied to three amplifiers, which have an input voltage range of $\pm 2.5V$. Normally, one amplifier would be chosen which is compatible with the used motor. The choice of this kind of amplifier is explained in the report from the previous phase of this project. These amplifiers have a fixed output voltage of $24V$ and a variable output current, depending on the input voltage. The current is limited to $1.3A$. The parallel configuration of the three amplifiers makes it possible to get the maximum torque out of the electromotor. Specifications of the motor can be found in [2].

The position of the legs of the stickman with respect to each other is measured by an absolute encoder on the main axle. This encoder cannot be connected on its own to the TU/eDacs device because it provides a SSI signal [3]. An extra converter [4] is installed which converts the digital SSI-signal to an analogous voltage in the range of $\pm 10V$. This voltage is supplied to one of the ADC-connectors on the TU/eDacs MicroGiant. This is not the usual way to connect such an encoder but the use of the TUeDacs and the Simulink software makes this necessary. The digital signal can be converted to a position number and then sent via an USB cable to the laptop which is more accurate than conversion to an analog signal and back. However, it would take a lot of time to get the signal correctly from the USB port into the Simulink environment.

Furthermore, there is an incremental motor-side encoder [5]. This encoder is directly connected to the Quad CNT port on the TUeDacs and the data is converted into a digital signal. This signal is sent via the USB cable of the TUeDacs to the laptop.

Chapter 5

Control system analysis

One of the goals is to make sure the stickman can walk by itself. A controller is designed to accomplish this. The current position is compared with a reference signal which results in an error. This error is converted by the controller and the output signal drives the motor. This is a standard feedback control strategy and is shown in Figure 5.1. The stickman shown in Figure 5.1 can be replaced by a model. This model describes the response of the robot and is determined experimentally.

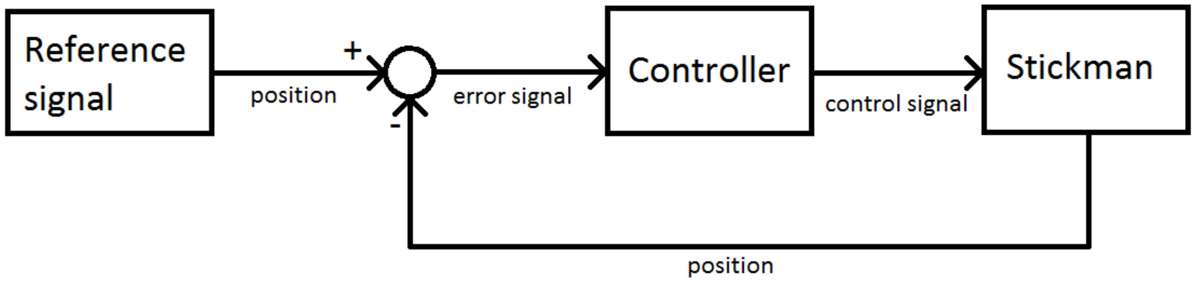

Figure 5.1: Schematic view of the standard feedback control strategy

There are different ways to design a controller. The controller can be designed based on the transfer function so the response of the robot is taken into account and so the error should theoretically converge to zero. However, only a linear transfer function can be determined so non-linear movements are not taken into account. Secondly, to make sure the error converges to zero the inverse of the transfer function is needed. The inverse of the transfer function does not always exist. A second method to design a controller is based on the dynamic behavior of the robot and the physics involved. The standard approach is based on the transfer function and this is the first method explained below. This includes experiments to determine the transfer function and an explanation on the non-linear movement of our robot. Then the second method is described which includes the design of and the improvements on the controller.

Transfer function

The transfer function describes the response of the system in the Laplace domain. The function can be used to determine the amplitude and phase of the response for all frequencies. A suitable controller can be designed based on this response. The transfer function is determined using a random signal called white noise. This is very efficient because this signal has almost each possible frequency while the power is the same for each frequency. Only one short experiment is needed to determine the transfer function instead of testing each frequency to compute the amplitude and phase.

The experiment is done twice. Firstly the stickman is lying on its side and secondly it is standing upright in walking position. This is done to analyze the influence of gravity on the leg. One of the legs is fixed while the other leg can move freely. The results of the experiments are shown in Figure 5.2 and 5.3. The smooth line is an estimate of the transfer function which is manually adjusted (using the breakpoints) to fit over the experimental data.

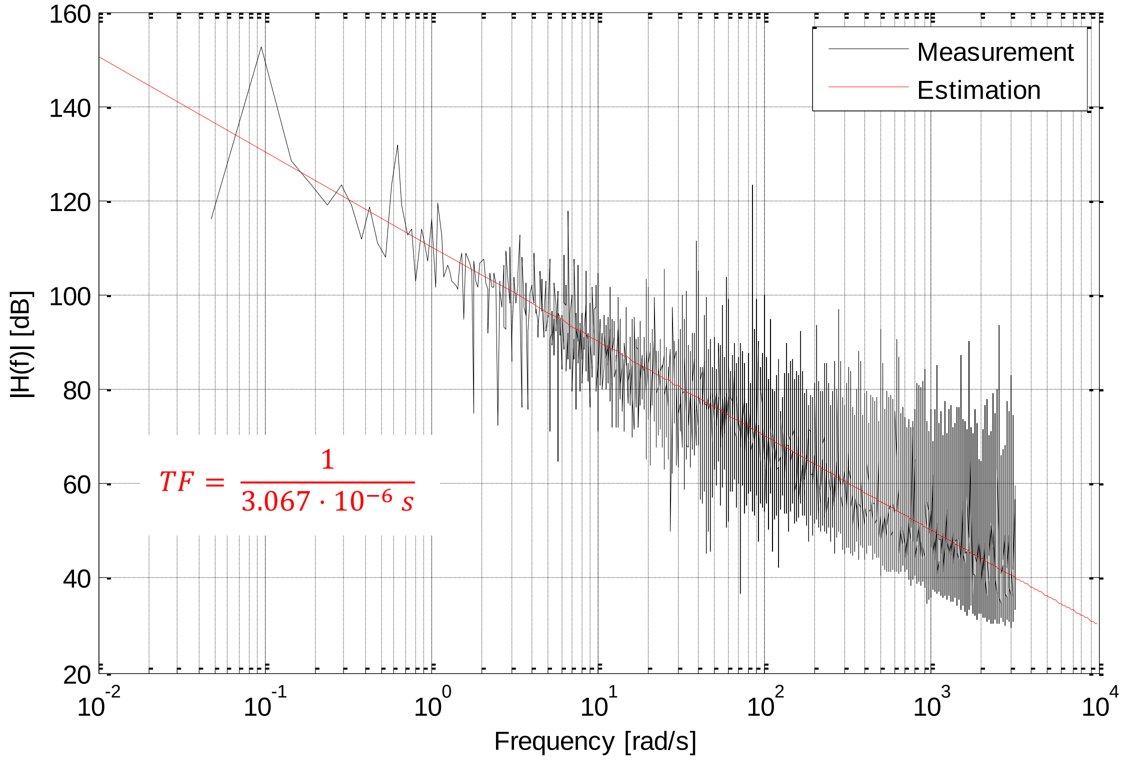

Figure 5.2: Transfer function experiment with the stickman on its side.

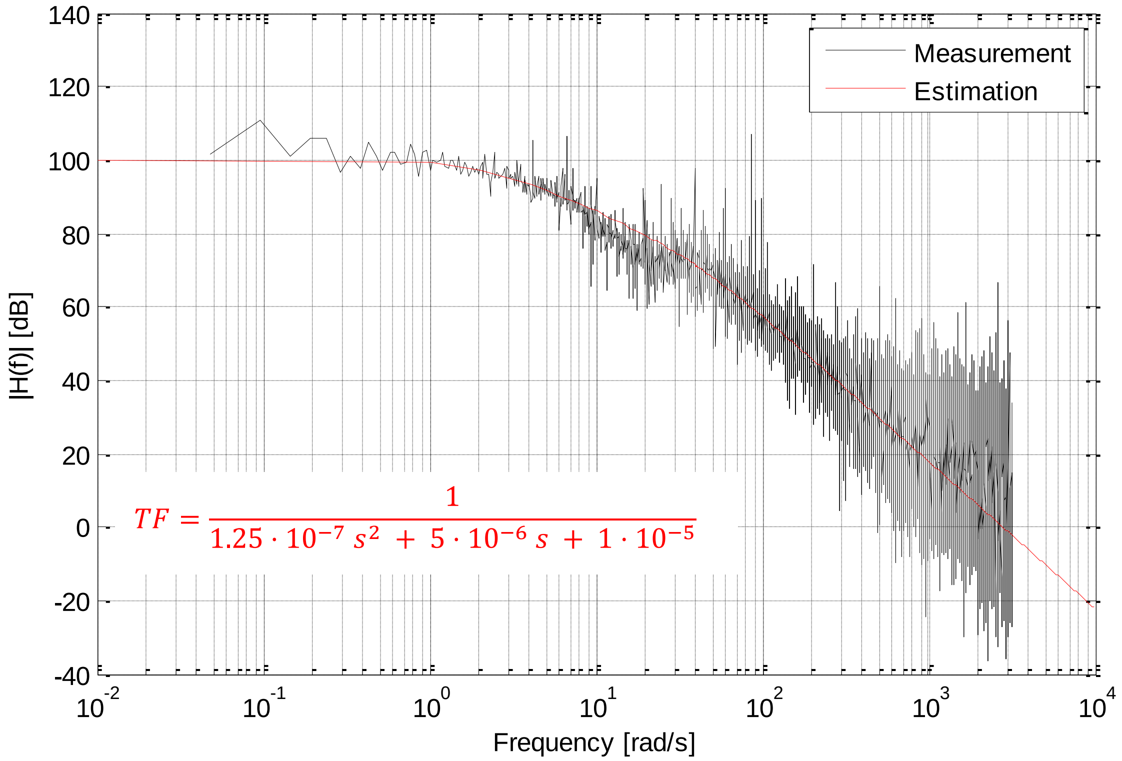

Figure 5.3: Transfer function experiment with the stickman in standing position.

Non-linear system

These transfer functions are determined in a non-realistic situation. The stickman was not actually walking during these experiments. The experimental situations described above do not account for the impact at each step during the walking gait. This non-linear behavior in the actual movement is not described by the transfer function and even worse the transfer function only represents a linearization around the equilibrium point. So these transfer functions give an idea of the response but do not give a solid basis for the design of a controller.

Design by dynamic behavior

As said above, the controller could not be designed using the standard method based on the transfer function. Therefore the controller is designed based on the dynamic behavior of the stickman. The procedure for designing the controller is described below.

Figure 5.4 shows that the controller is placed before the plant. The signal which is sent to the plant is in Volts. If $2.5V$ is send to the amplifier, a current of $1.3A$ is send to the motor. So the motor delivers its maximum torque when a voltage of $2.5V$ is sent to the TUeDacs. A controller needs to be designed which sends the correct voltage dependent on the error. The feedback of the plant is the position in counts. First the position in counts is converted to degrees, this is not necessary, but it makes the design of the controller easier. In order to compare the feedback to the reference they both need to be converted to the same unit, in this case this will be degrees. Now after comparing these two the error in degrees is obtained.

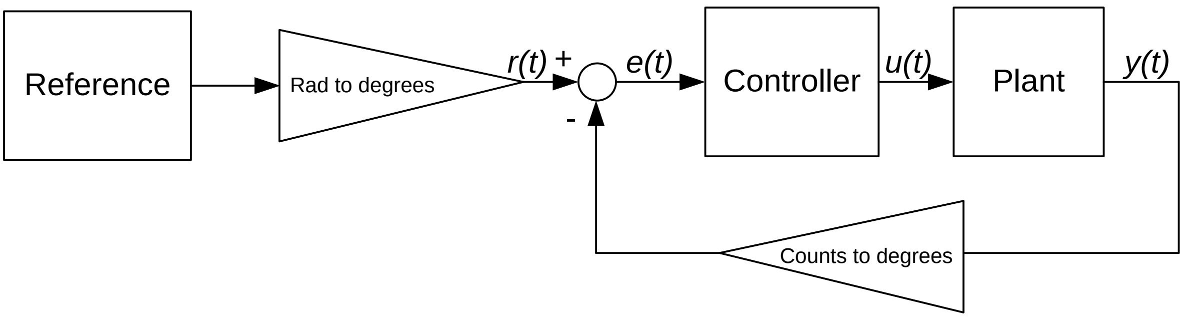

Figure 5.4: The control scheme

Reference signal

A walking motion that is controlled by a motor and sensor needs a proper reference; this is a target value for the position at each moment in time. The reference signal is based on the simulations done with the dynamic model from the previous project phase. The angle for each leg is defined with respect to the walking surface. The motor in the stickman only controls the angle between the legs, so to compute the reference signal the angles of both of the legs during one step are subtracted. This provides us with a periodic trajectory that describes the angle between the legs. Figure 5.5 shows the simulation data (the red line) during two steps, the blue and green line represent the angles of each leg during simulation with respect to the walking surface. There is also the possibility to generate a similar trajectory based on measurements with the encoder on the main axle during passive walking. Ideally, this would be the same as shown in 5.5.

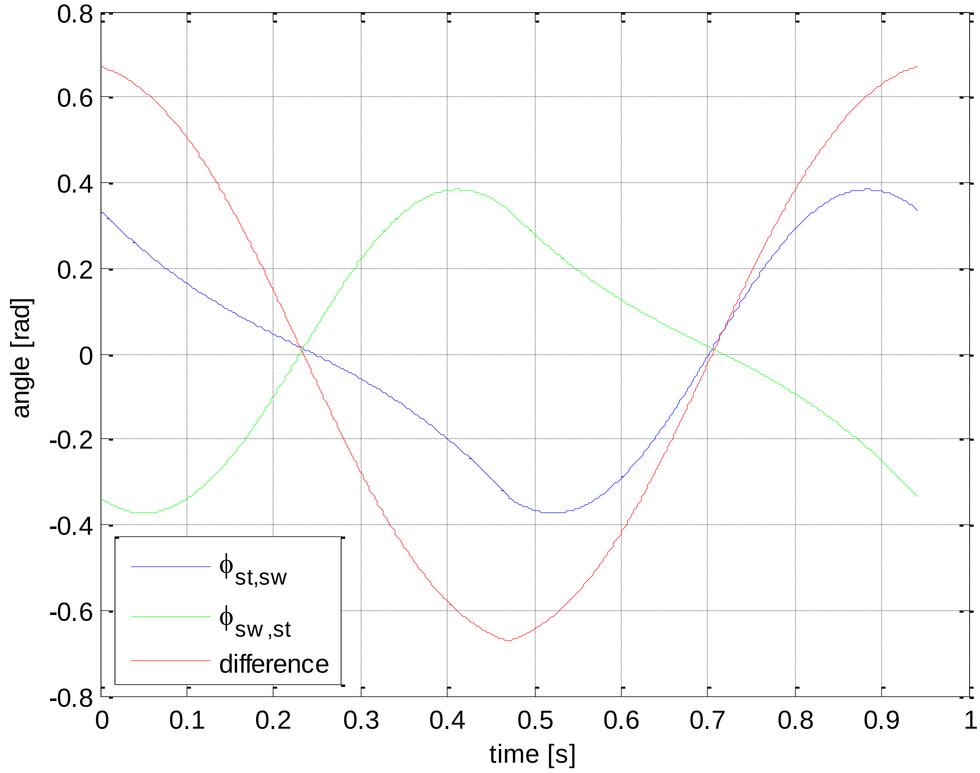

Figure 5.5: The periodic function of the leg angles during two steps

It is possible to fit a function through the simulation or measurement data which is implemented as a reference into the controller. This function approximates the real value of the angle between the swing and stance leg. Since the movement is recurrent, as shown in Figure …, a periodic function will give an appropriate approximation. The most basic periodic function is a sine function and a sum of sine functions can reproduce any function. This will give an approximation as shown in (1.1) with the coefficients displayed in Table 5.1.

$$F(t) = \sum_{i=1}^{n} a_i \sin(b_i t + c_i) \tag{1.1}$$

Table 5.1: Values of parameters in the function *F(t)*.

Variable	Value	Lower bound (95%-confidence interval)	Upper bound (95%-confidene interval)
a_1	0.6545	0.6542	0.6547
b_1	6.667	6.666	6.668
c_1	1.580	1.579	1.581
a_2	0.005245	0.005034	0.005456
b_2	19.73	19.58	19.89
c_2	1.517	1.435	1.599
a_3	0.004499	0.004298	0.004700
b_3	32.62	32.45	32.79
c_3	1.885	1.794	1.976

The correctness of the fit through the data can be increased by increasing the number of sine functions. First, a function which consists out of three sine functions is examined on correctness. The quality of the fitted function in comparison to the reference signal can be expressed in terms of an

R-squared value. For the function described by the parameter values stated in Table, the R-square is equal to 1. This is a rounded number because the R-square value of one means a perfect fit. However, the fit is nearly perfect so it will be used as the reference signal. The error between the simulation and the composed sine function is shown in Figure 5.6b. The absolute value of the angle is plotted against time for both the simulation and the sine function.

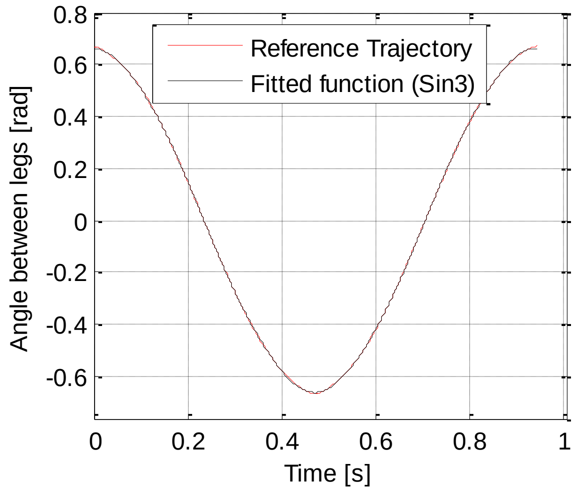

Figure 5.6a: The reference trajectory and the fitted function

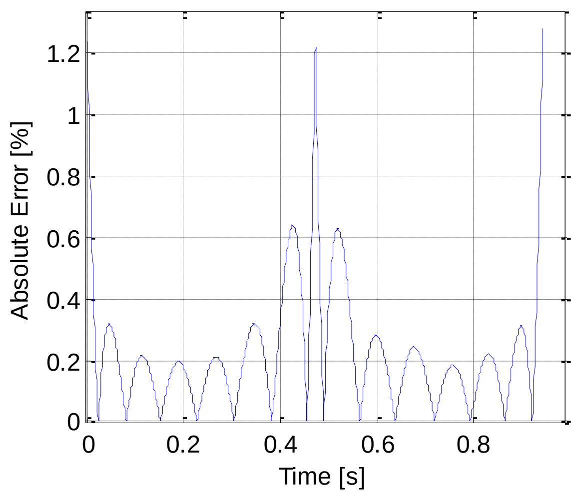

Figure 5.6b: The absolute error of the fitted function

PD controller

The reference signal is compared with the actual motor position as shown in Figure 5.7. This results in an error which is converted into the right amount of Voltage to reduce this error. This is done by a controller. First a PD-controller will be used, which is based on the error in angular position (P-action) and the error in angular velocity (D-action). Only the gain of the P and the D-action need to be determined. At first a very conservative controller is designed where stability is the most important criteria and not the performance. First the maximum angle and angular velocity of the legs are determined from the simulation, these are respectively $38°$ and $200°/s$. In this project there was not enough time and knowledge to make quantitative calculations which validate stability because it is a non-linear system. However it is possible to make a qualitative analysis which implies stability.

A controller is made which sends its maximum voltage of $2.5V$ to the plant if the maximum error in angle or angular velocity is obtained. So the gain of the P action is set to $\frac{2.5}{38}$ and de D action is set to $\frac{2.5}{200}$. Results are as shown in Figure 5.7. It is a very weak controller with large errors, but it will never have overshoot.

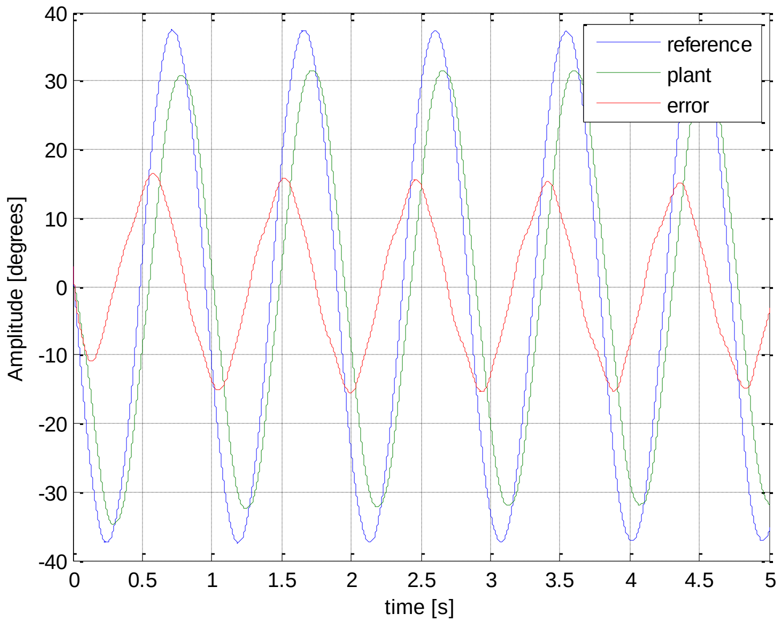

Figure 5.7: Reference signal, plant signal and the error versus time with $P = \frac{2.5}{38}$ and $D = \frac{2.5}{200}$

This controller does not give a good tracking behavior and has a large phase lag, but it is always stable. To improve the performance of the controller the gain of the P action and the gain of the D action can be raised. If only the P action is raised the controller will control more based on the error in angle resulting in better tracking behavior in the maximum, but increased phase lag. On the other hand if only the D action is raised the controller will control more based on the angular velocity resulting in worse following behavior in the maximum, but a decreased phase lag. The performance of the most optimal configuration with $P = \frac{2.5}{38}$ and $D = \frac{2.5}{20}$ is shown in Figure 5.8.

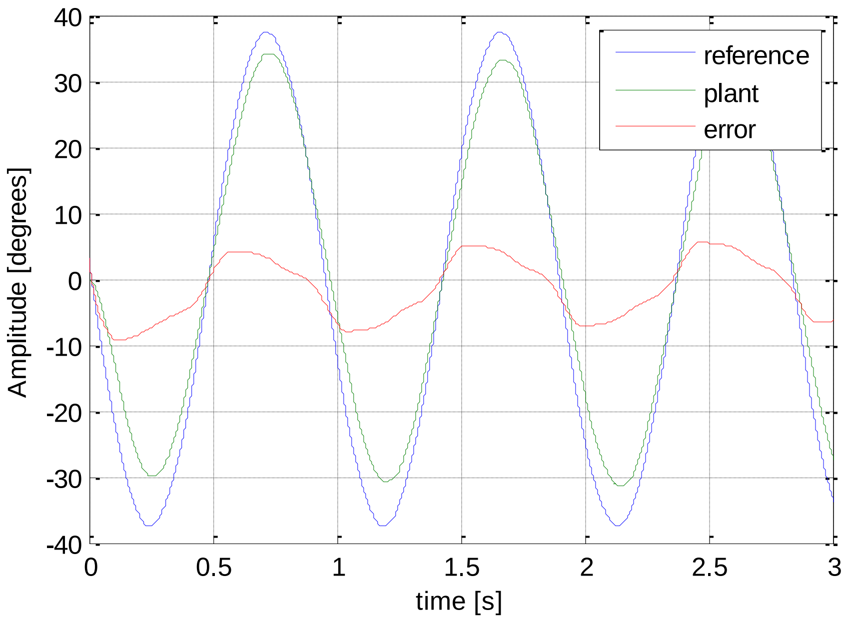

Figure 5.8: Reference signal, plant signal and the error versus time with $P = \frac{2.5}{38}$ and $D = \frac{2.5}{20}$

Increased power

After raising the P and the D action the conclusion can be drawn that the amplifier did not give enough power to the motor, this can be seen in Figure 5.9. The voltage applied to the amplifiers may not exceed $\pm 2.5V$, otherwise it is saturated at this level. It is obvious that the voltage exceeds this level. Two more amplifiers were added parallel in order to solve this. This is possible because the TUeDacs sends a voltage to the amplifiers. If the amplifiers are parallel they all receive the same voltage and they all send a similar current to the motor dependent on the voltage applied. The voltage output of the amplifier is constant. Therefore these can work parallel. Using three amplifiers gives a maximum current of $3.9A$ at a voltage of $2.5V$ while the motor can only handle $3.2A$. Therefore the voltage send from the controller to the TUeDacs should never exceed $2V$ because when this happens the amplifiers generate more power than the motor can handle. So to maintain safety a saturation with a maximum voltage of $\pm 2V$ should be placed between the controller and the plant.

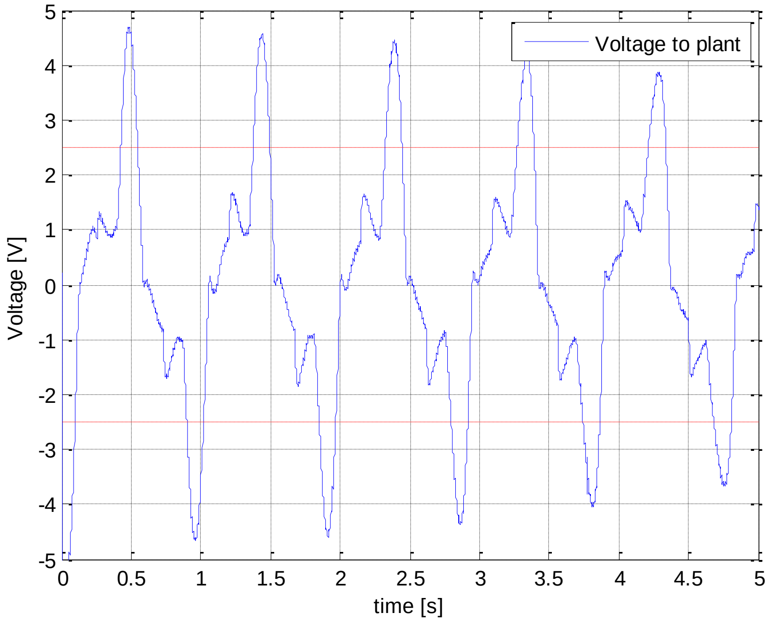

Figure 5.9: Voltage to plant, the amplifier cannot deliver enough power if more than $\pm 2.5V$ is applied

Increased speed

When the amplifiers were added, the error became smaller. Reducing the error further cannot be done with increasing the current from the amplifiers. After analyzing results the conclusion could be drawn that the problem was not a lack of torque, but a lack of motor speed. The motor could not reach the maximum speed of the reference signal which caused an increased error. The controller tries to add speed by increasing torque, but this is useless because the maximum speed is already obtained. For this reason the transmission between the motor shaft and the main axle is changed from 222:1 to 111:1. This means that the leg can move twice as fast, but the maximum torque becomes twice as small. There is enough torque present after adding the amplifiers so the torque decrease is not restrictive.

Scattering

After adding the amplifiers the P and D action can be raised more with significant result. But if both the P and the D action are raised too much chattering will occur. Chattering means that the controller controls too hard so will constantly overshoot. This results in a fluctuation of the plant signal around the reference signal. The error does become smaller, but chattering is not desirable. The chattering and the fluctuation of the error can be seen in Figure 5.10 a and b.

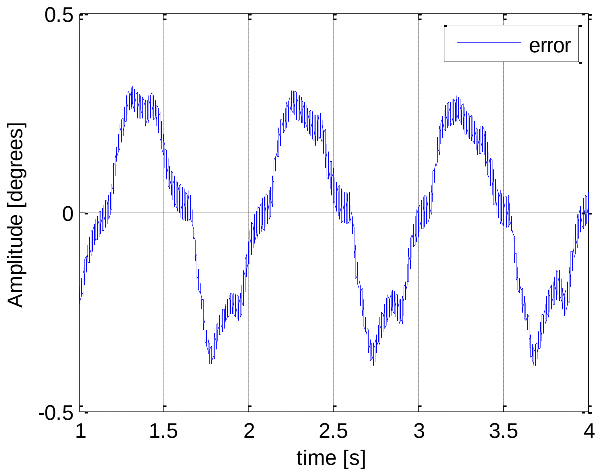

Figure 5.10 a: The error versus time of a controller with chattering

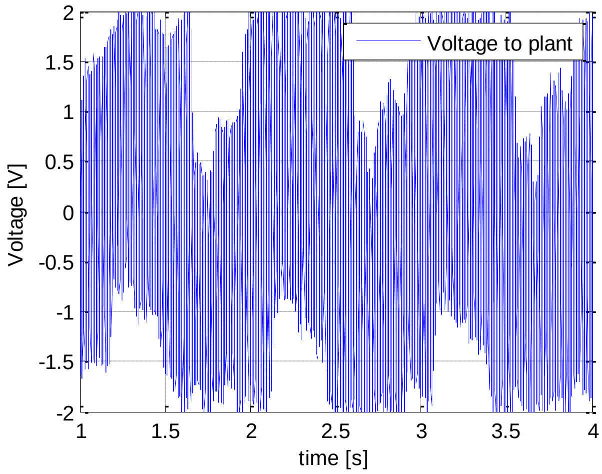

Figure 5.10 b: Voltage to plant of a chattering controller

There are two ways to reduce chattering. First the sample frequency can be raised so the controller controls faster which allows less overshoot. Furthermore a low-pass filter can be added to remove the high frequencies of chattering. These solutions are not used because there is no need for a very accurate controller. It has to follow only the predetermined sine-function. Because this function is periodic phase lag is less important than the tracking behavior during the peaks.

For this reason a controller with a high robustness is designed which has a P-gain of $\frac{2.0}{20}$ and a D-gain of $\frac{2.0}{100}$. The following behavior, error and the voltage to plant can be seen in Figure 5.11 a, b and c. This controller does not give any chattering and gives a nice tracking behavior in the peaks. The maximum error is 5°. Potential phase lag can generate a high error however, phase lag is not a problem for the walking motion and when the phase lag is compensated the remaining error is 2°. This means there is less than 5% deviation compared to the maximum position. This is an acceptable error. In the next section a sign function will be introduced for finite time convergence in order to further decrease the error.

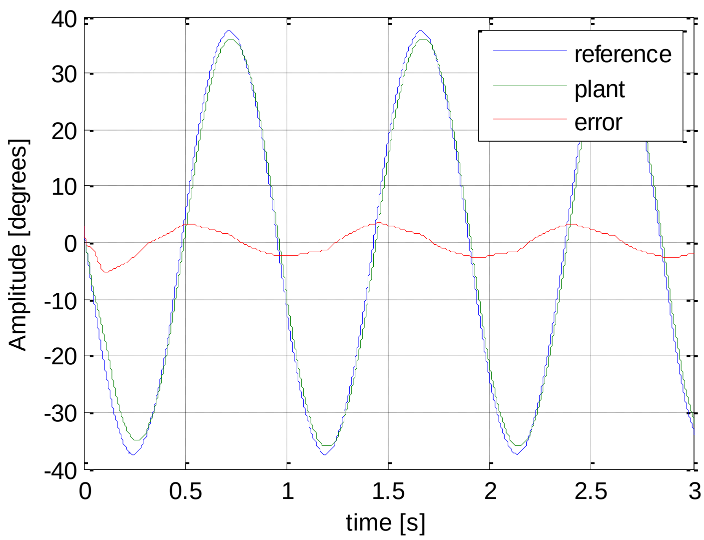

Figure 5.11 a: Reference, plant signal and the error versus time of final controller ($P = \frac{2}{20}$ and $D = \frac{2}{100}$)

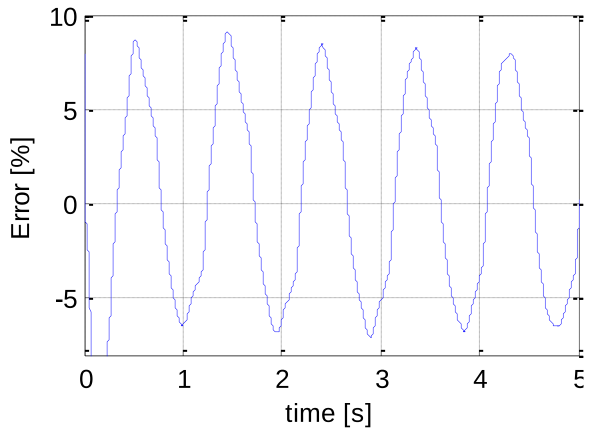

Figure 5.11 b: The error in % versus time of the final PD-controller

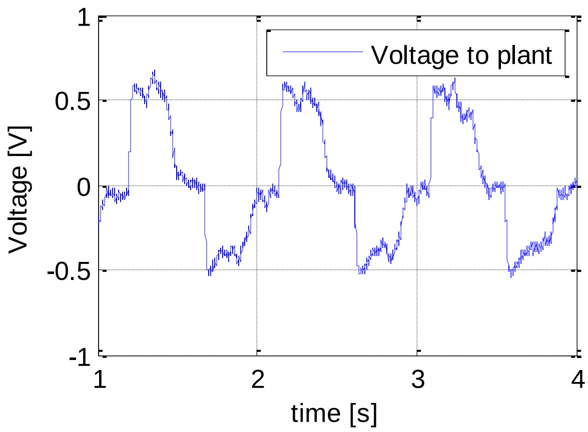

Figure 5.11 c: Voltage to plant of the final PD-controller

Sign function

For finite time convergence and decreasing the error there is experimented with a sign function on the PD controller from the last section. A sign function uses a power between zero and one for increasing the performance if the error is smaller than one. But the tracking behavior becomes worse if the error is (a lot) larger than one because of the power smaller than one. Implementing the sign function gives the control scheme as shown in Figure 5.12.

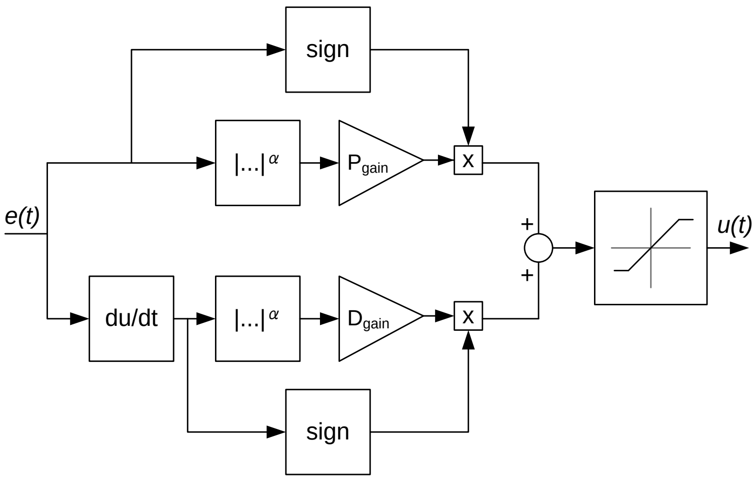

Figure 5.12: The controller with sign function

For finding the optimal value for the power of the P and the D action the power is varied from 0.9 till 0.6. It can be concluded that if the power becomes smaller the error increases slightly and chattering decreases slightly. Eventually an optimum is chosen between chattering and tracking error. A power of 0.6 gives the best result as shown in Figure 5.13 a and b. Once the phase lag is corrected, the maximal error is about 2.4° which means 6% and there is almost no chattering. Once experimenting, this gives the most reliable results concerning energy usage. Further improvements can be achieved by feed forward, as explained in the following section.

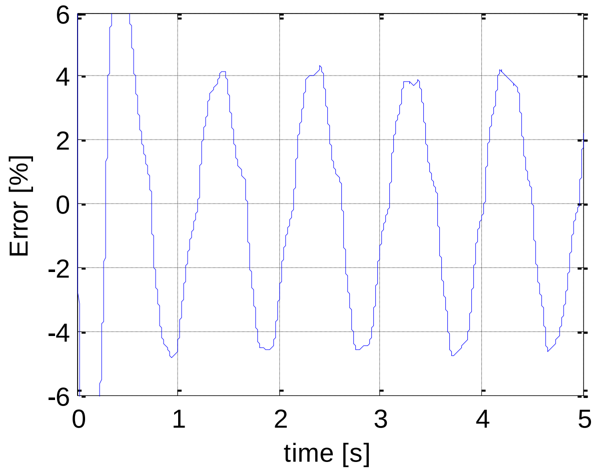

Figure 5.13 a: The error in % versus time of the controller with sign function

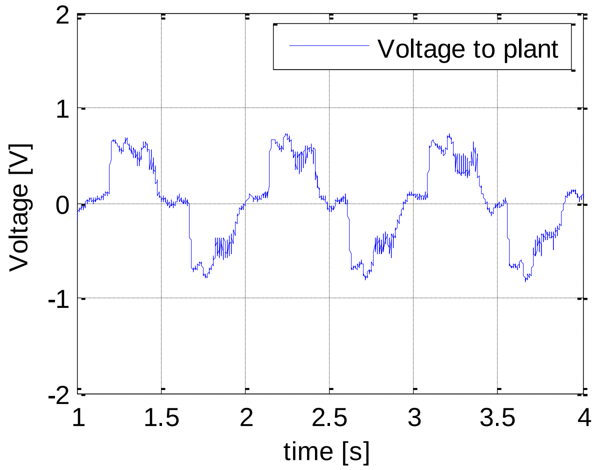

Figure 5.13 b: Voltage to plant of the controller with sign function

Feed forward

Another way to increase performance without the risk of influencing stability is by adding feed forward to the control scheme. Feed forward is based on observations with respect to the error in relation to the reference position, velocity and acceleration. In Figure 5.14 the scheme of feed forward is shown.

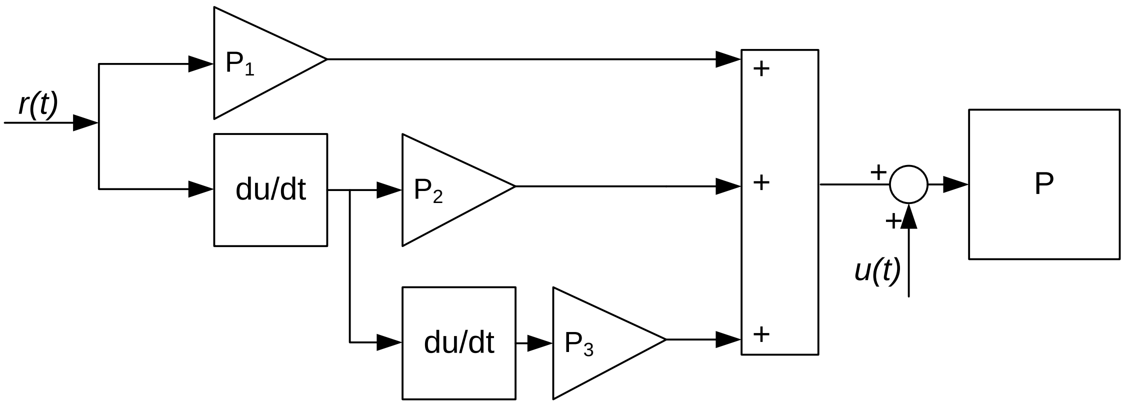

Figure 5.14: The feed forward scheme

The values of the three different gains are determined by experimenting and are optimized for the particular reference signal from the simulations. The best results are obtained with $P_1 = 0.2$, $P_2 = 0.06$ and $P_3 = 0.013$. The results are shown in Figure 5.15 a, b and c. The phase lag is manually removed to obtain the actual tracking error without the phase error. It can be seen in 5.14 c that there is still no chattering. The feed forward does not influence chattering because it works parallel with the controller.

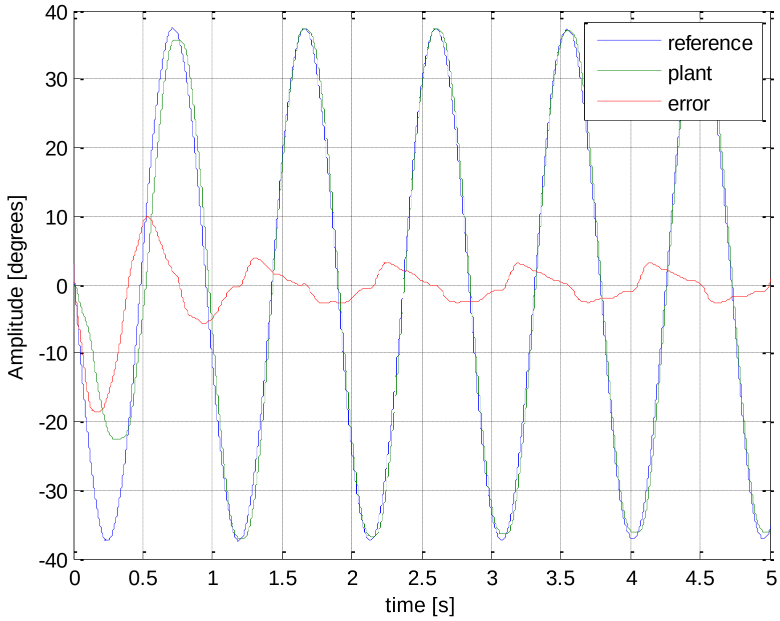

Figure 5.15 a: Reference, plant signal and the error versus time of final controller with sign function and feed forward

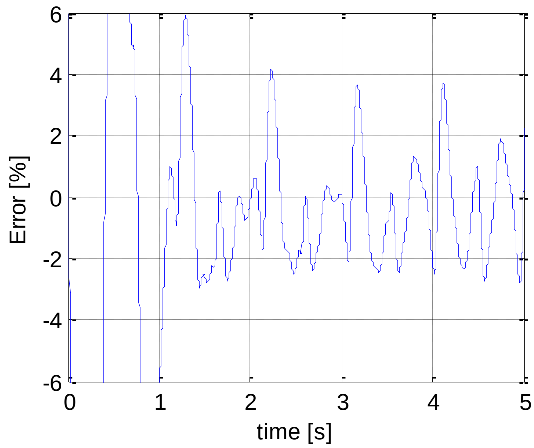

Figure 5.15 b: The error in % versus time of the controller with sign function and feed forward

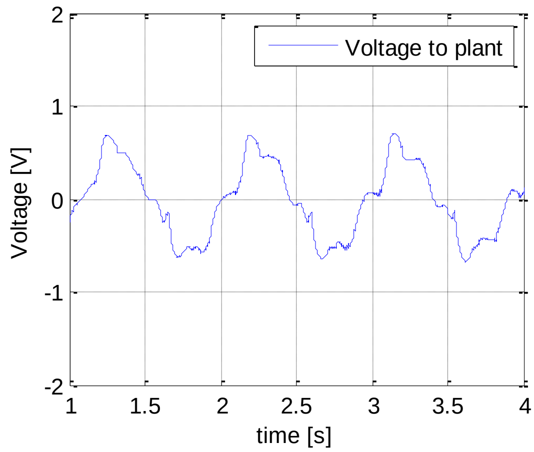

Figure 5.15 c: Voltage to plant of the controller with sign function and feed forward

Conclusion

The overall conclusion which can be drawn is that with a standard PD controller a choice has to be made between increased controller performance and scattering. With an implemented sign function the tracking behavior can be increased for errors smaller than one, here also a choise between chattering and increased controller performance must be made. By using smaller gearing the maximum speed of the legs is increased and by using more amplifiers the maximum power of the motor can be used. With feed forward the performance is increased for a specific reference signal without increased scattering.

Chapter 6

Actuated walking

It is possible to let the stickman walk on a horizontal surface after a satisfying controller is designed. The results of experiments and the experimental settings are discussed in this chapter. Simulations done with the computer model are compared with the results. The comparison is made for the energy usage and required torque.

Modifications and settings

The walking gait is mainly based on the reference signal and all the settings determined in the previous chapters. However, the experiments made it clear that not all these settings were usable for a successful walking gait. For this reason, some modifications to the control scheme are applied. First of all, the gains of the PD-controller are slightly changed so that the P-gain is equal to $\frac{2.0}{6}$ and the D-gain is set to $\frac{2.0}{100}$. Also, an extra gain is added right before the saturation of $\pm 2V$. This is done to ensure that stickman's movement is powerful enough, since experiments showed that the movement without this gain was not powerful enough. Last, the amplitude of the reference signal is set to 120% of the original setting. This adaption makes it possible to walk on the blocks which were placed at the predetermined intervals of $12cm$. Other parameters have the values that are determined in the previous sections.

Walking gait analysis

Figure 6.1 shows the target amplitude of the legs, the actual amplitude of the legs and the error for a simulation in which stickman was able to walk 7 steps. This is equal to a distance of about $2.2m$. For this walking gait, the blocks are placed at intervals of $12cm$, which is equal to the length estimated based on the simulations with the dynamic model. The surface is placed fully horizontally. The motion can now be analyzed to determine the error, energy consumption and the required torque during the walking motion.

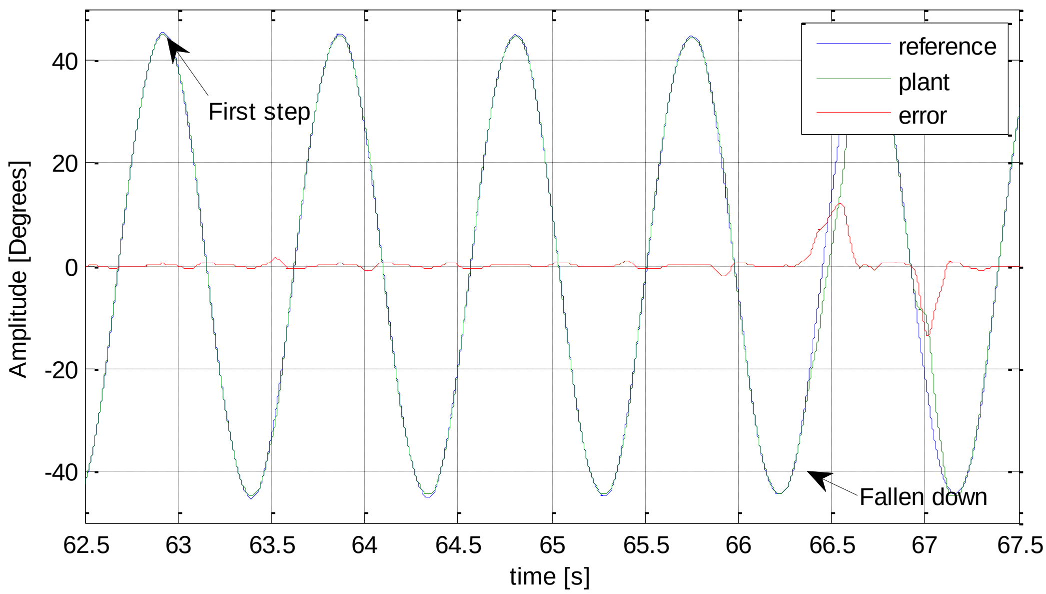

Figure 6.1: Amplitude of the legs, amplitude of the reference and error as function of time during an experiment

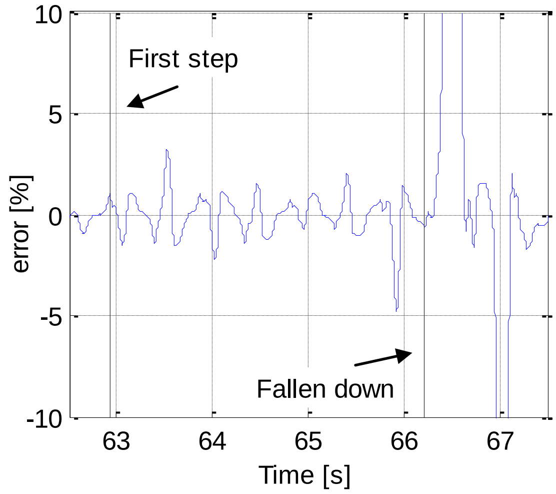

Figure 6.2: Error during a measurement of 7 steps

Figure 6.3: Energy consumption during a measurement

The error in Figure 6.2 is defined as the error in degrees divided by the maximum amplitude of the reference signal in degrees and multiplied by 100%. This makes it possible to evaluate the error with respect to the amplitude of the motion so this figure shows the relative error. Figure 6.3 shows the total amount of energy consumed during the experiment. The energy usage is dependent on the torque and angular speed. Torque is computed by the voltage sent to the amplifiers (U), the number of amplifiers (n) and the torque constant (C_t) as specified in [2]. The gear ratio (i) and the maximum output current of the amplifiers are involved as well. The relation between these parameters is given in (6.1). In this situation, C_t has a value of $25.9 \cdot 10^{-3} NmA^{-1}$, the maximum output current of one amplifier is equal to $1.3A$, the total number of amplifiers is 3 and the gear ratio is $1{:}\,111$.

$$T = \frac{U}{2.5} \cdot n \cdot I_{max} \cdot C_t \cdot i \tag{6.1}$$

The power (P) required can be computed by (6.2) and the energy by (6.3), with the above computed torque (T), $\dot{\varphi}$ is the difference in angular velocity between both of the legs and t is the sample time.

$$P = T \cdot \dot{\varphi} \tag{6.2}$$

$$E = P \cdot t \tag{6.3}$$

The obtained results can be compared to the simulations with the dynamic model. This will give some insight in the additional amount of power that is needed once the stickman walks on a flat surface instead of a shallow slope. Figure 6.4 shows the difference in angular velocity of the two legs as function of the torque required for both the simulation and the experiment. The trajectory is not completely as expected, but some things can be declared. The required torque at the maximum angular velocity is higher than in simulation. It seems that both the gravity and friction forces in the transmission and on the foot surface have a great influence on the behavior. This is confirmed by the observation that when stickman is going to fall, torque increases over the complete cycle. This is caused by the fact that the gravity forces increase when the stickman is in the wrong position. The movement has a bigger amplitude to make it walk more reliable. This will also cause an increase of the required torque.

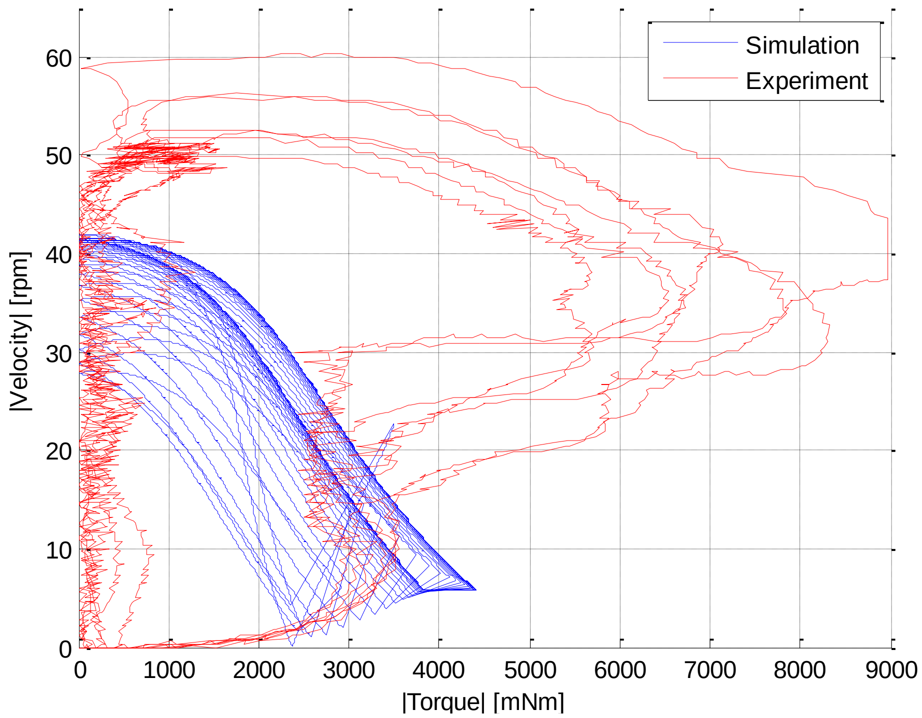

Figure 6.4: Angular velocity as function of Torque for seven steps computed in simulation and experiment

The energy usage is also higher than expected based on the simulations. This is obvious because torque is proportional to energy. As the torque is higher for most of the time, energy usage will be higher. During the experiment it was about 5.1 times higher than during simulation. It must be marked that the controller has a certain influence on the energy usage. When the controller tries to minimize the error all the way to zero it will use a lot of energy. However, the error does not have to be zero to achieve an active walking motion. The energy used is shown in Figure 6.5.

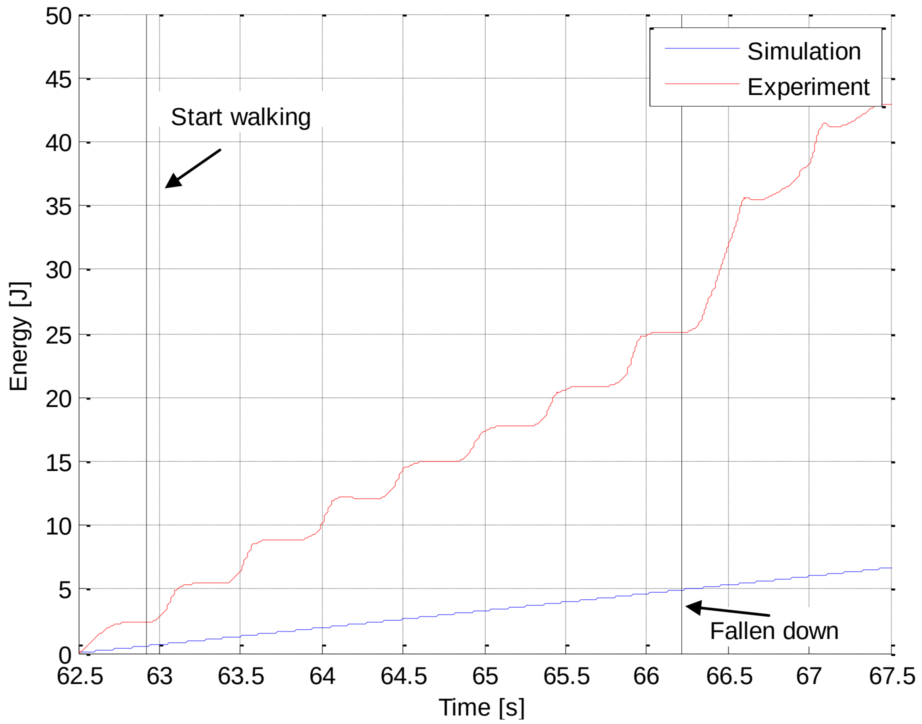

Figure 6.5: Energy consumption during an experiment and a simulation

Conclusion

A successful experiment is performed in which the stickman walked about $2.2m$. The maximum error during this walking motion was approximately 5% of the maximum angular position. The torque of this experiment is compared with the torque calculated with the dynamic model. The torque during the experiment is higher than calculated. The model does not represent the real walking motion; it is an approximation so this difference was expected. The torque during a real time experiment is probably higher because of friction between the feet and the walking surface. When the motion is not exactly correct the stickman kicks against the pads on the walking surface which results in a higher needed torque. The energy usage of the stickman is higher as well because this is proportionally with the torque. The progress in the energy usage is gradually and the usage per step can be seen clearly from the graph.

Chapter 7

Recommendations

While walking passively and actuated a number of problems were encountered. Because of the time span and the budget of this project these could not be solved. Therefore the following recommendations are named in this section instead of implemented in the experimental setup.

Set-up

The set-up which was used was a low cost option. It was entirely made of materials available, although the set-up could be improved very well using other materials. The most desirable improvement is another walking surface which is a lot more rigid, because the wooden plate warps a lot which causes the stickman to walk crooked or stumble. The second useful improvement is to construct the fixing of the walking pad so that they are movable. Now the walking pads are fixed with tape, this is not very recommendable because the position of the pads is changes a lot. Although the slope could be adjusted very well by raising the table on one side it would be better to construct a construction which allows exact and fast adjustment of the slope. This could be done by supporting the rigid surface on one side by a fixed support point while the height of the other side is adjustable by a rope. A reference point (exact horizontal position) could be found by using a level. From the reference point the slope can be adjusted.

Passive walking

The analysis of the walking motion showed some points of improvement, which are not easy to realize in a very short amount of time. The main point of improvement is a larger distance between the inner legs and the outer legs. This distance is set to $1cm$ and causes falling if stickman is not started aligned with the track. More space between the legs, for instance $3cm$ at each side, would give a far more reliable system. Another way of increasing reliability is a launching system, which makes it possible to launch stickman with the right leg angles and angular velocities. And it is possible to do it in identical way at every launch. At last, if it is possible to read out the information of the encoder on the main axle, there is an extra tool for analyzing the walking motion and the cause of falling.

Hardware and software

Although the stickman and its controller are designed with great precaution there are still some faults in the design and problems with the data acquisition. The first and most obstructive problem is the absolute encoder which not works. A lot of effort is put in trying to make the data acquisition of the encoder possible, but without any result. If it is possible to get the signal of the encoder in Simulink there can be controlled a lot better because the slack in the transmission could be taken into account. For safety reasons a compatible amplifier could be bought so the engine never receives more current than it can handle. Now this is done in Simulink by using a saturation. This is not wrong, but a compatible amplifier is safer.

There are two notable improvements to the stickman itself possible. First as said above, the inner and outer legs should be placed more apart. By doing this the system becomes less sensitive to misalignment. Second, the axle of the motor bends if a great amount of torque is delivered by the motor. There are different solutions to prevent this. One option is the use of a smaller gearbox and a larger ratio between the motor axle and the main axle. This helps in two ways, on one hand less torque is transferred trough the axle and on the other hand the axle rotates more. Because of the increase in rotation the force will not permanently be applied in almost the same direction of the axle. Another option is using bearings on both sides of the axle from the gearbox to prevent bending of the axle.

Active walking

All the above recommendations apply for active walking, but there are still some additional recommendations which can be made regarding to active walking and the energy experiments. First of all a foot surface which has a lot of friction and is durable should be found. This high friction is necessary to achieve active walking. If the friction is too less, stickman will simply loose his footing. Grip tape was used for these experiments, but it wore out after about 10 experiments. Second a cable guidance construction should be made which ensures the cables to the stickman do not interfere with the stickman while it is walking. Another more complex option is to make the stickman wireless.

In the energy experiment a lot of improvement could be made. It was not possible with the used setup to walk many times reliable because of the above stated problems. If these problems are solved reliable results can be found with the energy experiments. But in order to do so an optimal controller should be made for each reference signal because now the controller is optimized with feed forward for a certain reference signal. Iterative learning control could be used for optimal controller performance with every reference signal. If this is implemented there could be walked with different frequencies and amplitudes of the reference signal in order to find a minimum value of the energy usage.

Conclusion

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Appendices

A.1. Manual

This manual describes the steps for both *passive* and *actuated* walking of the *Stickman*. If the cursive printed words are not clear see the terminology section of this manual for a short explanation of these words. However basically it is expected that the knowledge of the reader about this subject is sufficient enough that he or she understands these words. If this is not the case, it may be wise to first read the corresponding report about the *Stickman*.

First, in Chapter 1, the set-up for passive and actuated walking will be described. Then, in Chapter 2, there will be shown how to build a controller in *Simulink* in Linux. In Chapter 3 both passive walking and actuated walking will be discussed. In Chapter 4 possible errors will be discussed and as said before in Chapter 5 some terminology is explained.

1. Set-up

In this chapter first the set-up of the passive walking is discussed. The set-up of the actuated walking, which is an elaborated version of the passive walking set-up, will be discussed next. All necessary components will be summed and there will be shown how to connect all components to each other.

Passive walking

In order to walk passively you will need to prepare both the stickman and the walking surface. If you do not want measure the angle between the legs you can skip the part 'connecting encoder'.

<u>You will need the following components for passive walking:</u>

- Stickman
- Tables with a total length of 3 meters
- Material for raising the table
- The two wooden plates with blocks attached
- Clamps and/or weights

And if you would like to measure the angle between the legs you will need the following additional components:

- Converter (to convert the encoder signal)
- A TUe/DACs
- Laptop
- Cables for connecting

<u>First the Stickman needs to be prepared for passive walking. Follow the next steps to do so:</u>

1) Disconnect the motor and motor encoder cable from the Stickman. The encoder on the motor axle cannot be used for measuring the angle between the legs because the motor will be disconnected from the main axle. Remove the cables.

2) If you would like to walk without measuring the encoder signal you should tape the cables of the absolute encoder on the main axle somewhere on the Stickman where they not in the way (we have

taped them under the upper weights above the main axle). If you would like to measure the encoder signal you can leave the absolute encoder cable for now.

3) Remove the belt between the motor axle and main axle. This can be done by first unbolting the motor (4 screws), then removing the belt on the motor axle. Note that an additional mass is taped under the motor bridge. Remove this weight in order to unbolt the motor. You do not have to remove the belt from the main axle. Make sure to bolt the motor back in place and reattach the additional mass under the motor bridge because else the weight distribution will be wrong.

4) Make sure the weight distribution of the Stickman is okay. The whole Stickman should be $6\ kg$ and the center of mass should be $10\ cm$ under the main axle. If the Stickman is original state it will be sufficient to check whether the additional masses on the outer legs are placed on the correct place (the center of these weights should be 10 cm under the main axle). For measuring the center of gravity of the legs separately you can read chapter 1 of the corresponding report.

5) For walking passively no grip tape should be under the foot of the Stickman because the walking gait is badly affected by this. So remove the grip tape.

The Stickman is now ready for passive walking.

<u>Prepare the walking surface as followed:</u>

1) Place the wooden plates on the tables (with the blocks on the top side). Make sure the plates are in the right order.

2) Check whether the plates are not crooked. If this is the case, solve this by putting weights on the sides of the plates or clamping the plates on the table. When putting weights on the make sure these do not interfere with the Stickman when walking.

3) Adjust the table height on one side so that the desired slope-angle is obtained. For calculating the height raise on one side simple goniometry is used, see formula (1.1).

$$height = \sin\alpha \cdot length\ of\ the\ table \tag{1.1}$$

Here α is the slope-angle. If using multiple tables (as in our case) make sure there is a good transition between the tables.

4) If necessary, reposition the walking blocks. Tape them to the wooden plate, so they can be removed if necessary. The distance between the first four sets of blocks should be $8\ cm$, after this the distance between two blocks should be $6\ cm$ (this was according to us the best set-up).

The walking surface is now prepared.

<u>Connecting absolute encoder</u>
It is not possible to write this part yet.

Actuated walking

In order to walk active you will need to prepare both the stickman and the walking surface. The preparation of the walking surface is exactly the same as with the passive walking, see section 1.1.3 for this. However the Stickman should be prepared different and additional preparations should be made which will be described here.

<u>You will need the following components for actuated walking:</u>

- Stickman
- Tables with a total length of 3 meters
- Material for raising the table
- The two wooden plates with blocks attached
- Clamps and/or weights
- An amplifier with an output of $3.2A$ over $24V$
- 1x TU/e DACs
- Laptop with Linux and Simulink
- USB stick
- Cables for connecting

<u>Follow the next steps in order to set up the stickman for active walking:</u>

1) Make sure the walking surface is prepared. If this is not done, follow instructions of Chapter 1.1.3.

2) Make sure the belt connects the motor axle and main axle. If the belt is not in place it can be put in place by first unbolting the motor (4 screws), then placing the belt between the motor axle and main axle. Note that an additional mass is taped under the motor bridge. Remove this weight in order to unbolt the motor. Make sure the tension in the belt is not too much when bolting the motor back in place. Also make sure to reattach the additional mass under the motor bridge because else the weight distribution will be wrong.

3) Make sure the weight distribution of the Stickman is okay. The whole Stickman should be around $6\ kg$ and the center of mass should be $10\ cm$ under the main axle. If the Stickman is original state it will be sufficient to check whether the additional masses on the outer legs are placed on the correct place (the center of these weights should be 10 cm under the main axle).

4) For active passively grip tape should be taped under the foot of the Stickman. Or else the Stickman will not have enough grip for walking.

5) Connect the Stickman to the TUe/DACs and the TUe/DACs to the laptop. This should be done as seen in Figure 1.1. If connected right there should go three wires from the TUe/DACs to the Stickman. One via the amplifier (in our case 3 amplifiers of $1.3A$ because these were available) to the motor of the Stickman. Make sure that the blue wire is connected to the + side of the motor and the white wire is connected to the – side of the motor. Else the signal of the motor-encoder will be in opposite direction which will cause an unstable behavior. The second cable is directly from the TUe/DACs to the motor-encoder. The third cable is from the TUe/DACs via the converter to the main axle absolute encoder. The TUe/DACs is connected to the computer via USB.

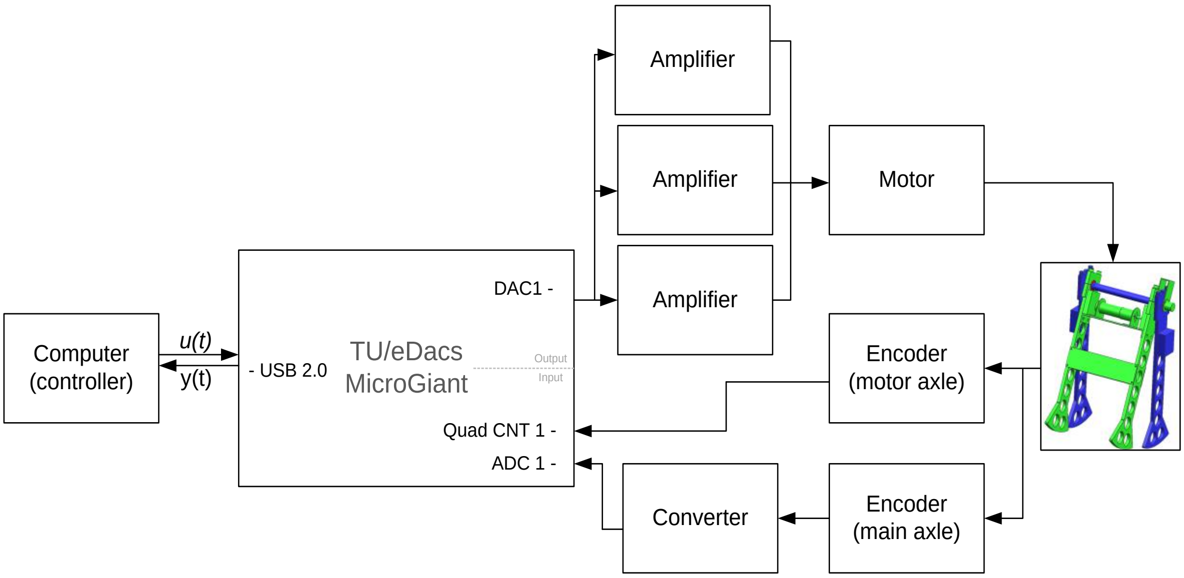

Figure 1.1. *Connection scheme of the Stickman*

6) Tape cables so they are easy guidable and not interfere with the legs if the Stickman is walking.

The Stickman is now ready for active walking.

2. Building a controller

In this section it is described

First insert the DVD or USB stick in the computer, and then start the computer. Press F9 while the startup screen shows. Then choose the option s

For actuated walking without the absolute encoder you will need to create two Simulink programs. First a controller needs to be made, and second a Simulink program needs to be made which puts the Stickman back into position.

Controller

Start tdblocklib in matlab. This because the drivers for the TU/e DACS settings are ok in this sceme

- (block scheme used by us)
- Openloop

3. Walking

Here passive and actuated walking will be discussed. If you have set up all components and, in case of active walking, made a suitable controller please proceed. Otherwise go back to either section 'Set-up' or 'Building a controller'.

Passive walking

Actuated walking

Running the simulation

Save your file, not necessary, but to make sure
Build, using control b
Start Console.
Enter ./ (the name of the Simulink file) -w
Connect to target
Start real time sim

Processing results

The files are saved under the name of the simulink file.mat

4. Errors

While experimenting errors nearly always will show up. Here a description and possible solution will be given of the errors which occurred while we were experimenting.

Overall errors

Passive walking

This is not yet possible because the absolute encoder does not work yet

Actuated walking

When Matlab does not respond → kill

5. Terminology

Some words could be unclear to the reader, therefore a short explanation of these words is given.

Word	Explanation
Stickman	A two-legged walking robot with only one degree of freedom (the angle between the two legs).
Passive walking	The walking of the Stickman on a small slope without using actuation. The gravity force is used for overcoming friction.
Actuated walking	The walking of the Stickman by using a motor and a controller.
Simulink	Functionality in Matlab which will be used for creating a controller.