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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 stickman should be able to walk down a shallow slope without any actuation and walk horizontally using an electromotor with control system. The global geometry of the stickman is determined by analyzing the stability. Then this geometry is slightly adjusted to produce a feasible design. The whole procedure is elaborated below.

The global geometry is defined by five parameters: Length, foot radius, horizontal and vertical position of the CoM and total weight of the legs. Based on feasibility and desires of the client two parameters are chosen and a guideline is set for a third. 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 and its Jacobian are determined to analyze the actual stability. The eigenvalues of the Jacobian should lie within the unit circle to ensure stability. The configuration with the smallest eigenvalues is chosen as the basis of the final design.

The electromotor and other controlling equipment can be chosen based on the overall geometry. The torque required is computed to determine a suitable motor. This is done using the same dynamic model as used above and manually to check the model. The motor is chosen based on a velocity-torque plot. This motor has a power of $60W$ which reaches a safety factor of 8 regarding the torque. The minimum gear ratio is determined by dividing the torque needed by the torque provided by the motor. This results in a gear ratio of 52:1. The client has a motor available with a gear ratio of 111:1. This combination is still sufficient regarding the torque and rotational speed.

Two sensors are chosen to measure the angle between the legs (on the axle) and the position of the motor (on the motor) respectively. Rotary encoders are chosen based on 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 at least with an accuracy of $0.1°$.

An amplifier, power supply unit (PSU) and a data acquisition system are needed to connect the stickman to a computer or laptop. These components are available for this project in the TU. The downside is that the amplifier and PSU are less powerful than the motor requires. This results in a maximum power of $27W$ and a safety factor on the torque of 3.7. This is acceptable according to the client. The data acquisition system of the TUe is used to connect the laptop and the sensors and motor. This unit converts digital and analog signals and is suitable for motion control up to $4\ kHz$.

At last, after all components are determined, the stickman is designed. The mass of the stickman is $6kg$ and the center of gravity lies $100mm$ below the axle. This is done by adding weights at calculated positions. Aluminum is used for almost all parts because it has a density which gives a lot of freedom in positioning the center of mass. Strength calculations are done to guarantee strength and stiffness. Ease of manufacturing is kept central during designing the stickman. The sensor is placed directly on the axle to acquire accurate data. Finally the whole stickman is build within the specified budget of €1500,-.

List of symbols

Variable	Quantity	Unit
a	Vertical distance to Center of Mass	m
B	Horizontal position of overall center of mass	m
b	Leg width	m
C	Vertical position of overall center of mass	m
d	Offset rotation axis with respect to center of mass	m
E	Young's modulus	Pa
F	Force	N
G	Shear modulus	Pa
I	Moment of inertia	kgm^2
J	Jacobian Matrix	$-$
j	Second moment of area	m^4
K	Column effective length factor	$-$
L	Leg length	m
m	Stickman mass	kg
P	Power	W
p	Maximum distance sprocket to outer leg	m
R	Foot radius	m
r	Axle radius	m
S	State vector of the stickman	$-$
S^*	Limit cycle	$-$
T	Torque	Nm
t	Leg thickness	m
γ	Slope angle	rad
δ	Displacement	m
λ	Eigen value	$-$
σ	Stress	Pa
ϕ	Angle leg	rad
$\dot{\phi}$	Rotational speed leg	$rads^{-1}$
$\ddot{\phi}$	Rotational acceleration leg	$rads^{-2}$
$\lvert \dots \rvert$	Absolute value	$-$
Subscript		
0	Initial condition	$-$
g	Gravity	$-$
i	Part number	$-$
k	Kinetic	$-$
n	Step number	$-$
np	Total number of parts	$-$
max	Maximum value	$-$
st	Stance leg	$-$
sw	Swing leg	$-$
$yield$	Yield condition	$-$

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Introduction

The human walking motion is the result of a combination of human motion control and the dynamics of the human legs. The lower body of a human consists of several elements connected by joints as shown in Figure I-1. The dynamics of such a system is very complex and has many degrees of freedom. Making a resemblance of the human lower body and its walking motion is the central objective in this report. The designed robot is a highly simplified version of the human lower body. It has one degree of freedom and sideways rocking is suppressed. This kind of robot is called a stickman (Figure I-2) and its motion will resemble walking with crutches. The goal is to create a stickman that can walk down a shallow slope without any actuation and walk horizontally using an electromotor with control system.

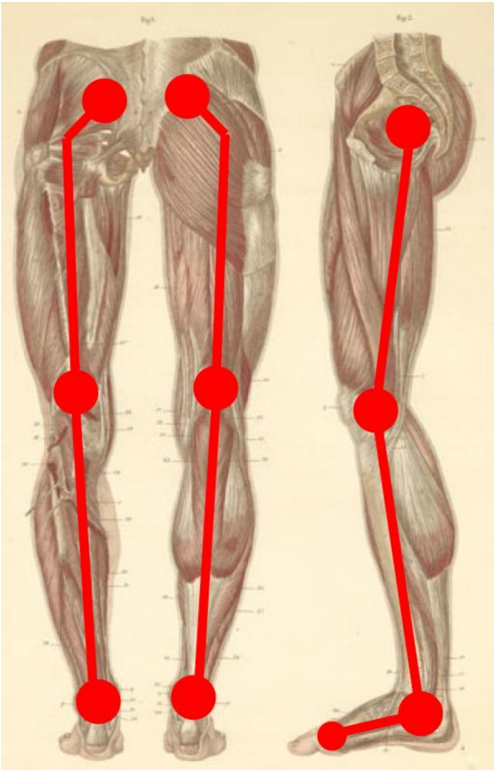


Figure I-1: The human legs with their joints

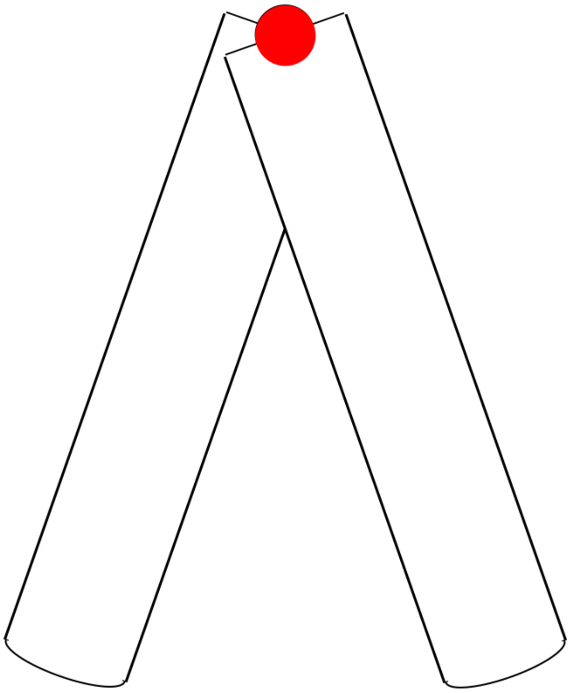


Figure I-2: A schematic view of a stickman

The design requirements and basic mass distribution of the stickman are discussed in Chapter 1. When the general idea of the stickman and its design criteria are clear the stability is tested and optimized as elaborated in Chapter 2. This analysis leads to the required parameters and their sensitivity, like the position of the mass center. Building a control system for the stickman is one of the goals. This means that the stickman has to be connected to a laptop. The electrical system and its components are discussed in Chapter 3. The final design of the stickman can be determined based on the stability analysis and electrical system. Chapter 4 describes the final geometry and all the components of the stickman. Finally, Chapter 5 describes the approach for the next step, meaning: assembly and testing of the system and the design of a robust controller.

Chapter 1

Preliminary design

In order to realize the stickman it should be clear what is expected from both designers and clients. The design of the stickman highly depends on the stability of the walking motion. Therefore, design criteria must be made. Restrictions for parameters are made based on feasibility and desires. A rough model is made of the stickman based on the determined criteria. This first model is made to clarify the positions of certain components and to determine the overall geometry. The exact dimensions are determined in Chapter 3.

1.1 Design criteria

The overall geometry of the stickman is based on five parameters. A schematic view of the stickman is shown in Figure 1-1. Table 1-1 gives the essential parameters.

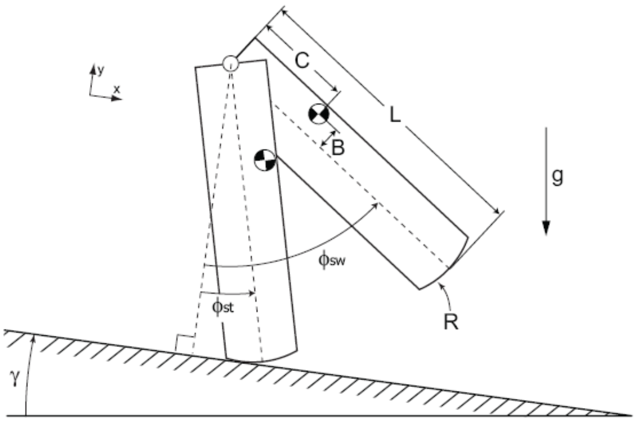


Figure 1-1: Schematic view of the stickman with parameters

Table 1-1: Essential parameters of the stickman

Parameter	Unit	Description
L	$[m]$	Length of the leg
R	$[m]$	Radius of the foot
B	$[m]$	Hor. position of center of mass (CoM)
C	$[m]$	Ver. position of CoM
m	$[kg]$	Total mass of the stickman

Two parameters are fixed, the length of the legs and the total mass of the stickman. These parameters are fixed to simplify the search for a stable configuration. The length of the legs is set to $0.4m$, for this value the material costs are low and the stickman is easy to transport and store. The total mass is chosen based on the size of the stickman and the used material. Aluminum will probably be used because it is a light weight material and easy to process. This results in a total mass of approximately $6.0kg$ based on the model shown in Figure 1-2 and Table 1-2. The client has provided a requirement for the horizontal position (B) and a guideline for the vertical position (C) of the center of mass (CoM). The value for B has to be zero, this means that the CoM is at the symmetry axis of the leg and the value for C should be as small as possible. These requirements imply that the CoM should be as high as possible, preferably in the hip-joint.

1.2 Visualization

To visualize the stickman and foresee construction problems a simple CAD figure is made (Figure 1-2). This figure is made based on the placement of the components. The center piece of the stickman is the axle which is the pivot point of the legs. The outer legs are clamped on the axle using bolts. To ensure there is no slip between the axle and the legs a locking pin is used. This method is used so parts can easily be replaced and repositioned.

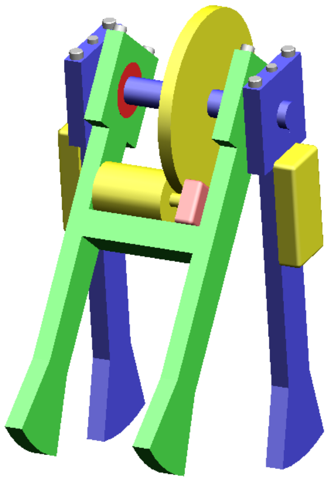


Figure 1-2: Preliminary design of the stickman

Table 1-2: Components of the stickman

Component	Total Mass $[g]$
Leg (4x)	3000
Axle	500
Bearing (2x)	100
Middle coupling	300
Electromotor	400
Mounting	200
Transmission	200
Other (screws)	300
Extra mass (outer leg)	1000
Total stickman:	6000

The inner legs are connected to the axle using ball bearings, so the inner legs can freely rotate. They are connected to each other by a connection piece to ensure rotational and lateral stiffness. Two separate center legs are chosen rather than one to increase lateral stability and to simplify mounting of the motor. Each leg is identical. The dimensions of the foot depend on the maximum swing angle.

1.3 Mass distribution and approximate mass

A proper mass distribution is essential for the motion of the stickman. There are two conditions on the leg systems to prevent a limping and maybe unstable motion:

- The two legs should have exactly the same mass
- The position of the center of mass should be the same for both legs

The whole stickman is separated into components to easily achieve the conditions stated above. The different components and their approximate masses are given in Table 1-2. The mass of the middle leg system consists of the mass of the legs, coupling of the legs, the electromotor and its mount, a sensor and potential transmission. The outer leg system consists only of the mass of the legs and the axle. Adjustable masses are added to balance the legs which may be replaced by batteries later on.

1.4 Conclusion

The geometry of the stickman is based on three parameters: length, mass and horizontal position of the center of mass to the axle. Respectively these are set at $0.4m$, $6.0kg$ and $0.0m$. The length of the legs ensures low material costs and easy use and transportation of the stickman. The mass is estimated based on the size and density. The horizontal position of the CoM is set by the client. A guideline is given by the client for the vertical position of the CoM as well, namely that it should be as close to the axle as possible.

Chapter 2

Stability analysis

In the previous chapter the stickman design criteria are set and a first design is made. In this chapter the stability of this design is analyzed and optimized. The walking motion of the stickman can be divided into two phases, the swing phase and the double support phase. The swing phase is defined as the time during a swing of a leg. The double support phase is defined as the time both legs touch the ground. These phases are described in a dynamic model which can be used to determine the angular positions and velocities of the legs. The model is based on the simplified form of the stickman as shown in Figure 1-1. The key parameters in the model are: mass, position of the CoM, length of the legs, magnitude of the foot radius and the ramp angle. This model is used to check the stability of walking of different configurations of the stickman. In this case stability implies that the stickman can walk without falling, so after each step it should have the same angle and angular velocity for each leg. The method to calculate stability is elaborated in this chapter.

2.1 Theoretical background

The state of the stickman during motion is described by the state vector S_n. This vector consists of angular positions and velocities of both legs of the stickman and can be determined with the dynamic model. The walking motion is stable if the angular positions and velocities reoccur after each step. This stable walking gait is called the limit cycle S^*. The Jacobian is computed to test the stability of a limit cycle. The Jacobian is the matrix of the partial derivatives of the step to step function. This matrix can be determined numerically and can be used to determine the state after one step as followed:

$$\Delta S_n = S_n - S^*$$

$$\Delta S_{n+1} \cong J \, \Delta S_n \qquad (2.1)$$

So with the initial state, the state after n steps can be computed as follows.

$$\Delta S_n \cong J^n \, \Delta S_0 \qquad (2.2)$$

The walking gait is stable if the state of the system converges to the limit cycle. So ΔS_n should converge to zero and this implies that J^n must converge to zero as well. To meet this demand the eigenvalues of λ have to lie within the unit circle in the complex plane. So the system is stable if the following statement holds.

$$|\lambda|_{max} < 1 \qquad (2.3)$$

Where $|\dots|_{max}$ is the maximum absolute value

2.2 Walking simulation

The dynamic model is a highly simplified representation of the actual stickman. This means that the following assumptions are made.

1. All the mass is located in the CoM. Hence; the inertia of each leg can be computed by:

$$I = mC^2 \qquad (2.4)$$

2. Energy loss caused by rolling resistance or elastic collision during the double support phase is neglected.
3. There is no friction or slack in the hip-joint.

Seven free parameters remain from the set requirements in Chapter 1. These parameters are shown in Table 2-1 along with their value and range of variation. The parameter values are varied during the simulation to check all configurations on stability. The stability criterion is based on the number of successful steps (n) defined as a step from which another step follows without a fall. A configuration is assumed stable if $n \geq 100$.

A function to determine the limit cycle is given in the dynamic model. With the initial state of the most stable configuration the function computes a limit cycle. The function compares the error between the initial state vector and the state vector after one step with a provided tolerance. A limit cycle is returned when the error is smaller than the tolerance.

The Jacobian and its eigenvalues are determined as well. The configurations are sorted in ascending order based on the maximum absolute eigenvalue ($|\lambda|_{max}$). This leads to the most stable configuration which is given in Table 2-2. This configuration has $|\lambda|_{max} = 0.66$ and a value of $0.10m$ for the variable C which is the vertical position of the CoM. The CoM should be as close to the axle as possible according to the requirements ($C \approx 0.0m$) and there is a stable configuration with $C = 0.05m$ but $|\lambda|_{max} = 0.87$. The stability of this configuration is much less certain and the CoM is $5cm$ closer to the axle. So the most stable configuration is chosen. All files used for calculations are given in Appendix A.2.

Table 2-1: Parameters with ranges of variation and constants

Parameter	**Minimal value**	**Maximum value**	**Step size**	**Unit**
C	0.05	0.20	0.05	$[m]$
R	0.2	0.4	0.1	$[m]$
γ	0.005	0.020	0.005	$[rad]$
ϕ_{st}	$-\frac{\pi}{4}$	$\frac{\pi}{4}$	$\frac{\pi}{10}$	$[rad]$
ϕ_{sw}	$-\frac{\pi}{4}$	$\frac{\pi}{4}$	$\frac{\pi}{10}$	$[rad]$
$\dot{\phi}_{st}$	-1.05	-0.85	0.05	$\left[\frac{rad}{s}\right]$
$\dot{\phi}_{sw}$	-0.90	-0.70	0.05	$\left[\frac{rad}{s}\right]$
Constant	**Value**			
L	0.40			$[m]$
m	6.00			$[kg]$
B	0.0			$[m]$

Table 2-2: The most stable configuration

Parameter	**Value**	**Unit**
C	0.1	$[m]$
R	0.2	$[m]$
γ	0.015	$[rad]$
ϕ_{st}	0.16	$[rad]$
ϕ_{sw}	-0.47	$[rad]$
$\dot{\phi}_{st}$	-1.05	$\left[\frac{rad}{s}\right]$
$\dot{\phi}_{sw}$	-0.90	$\left[\frac{rad}{s}\right]$

The eigenvalues of the most stable configuration are shown in Figure 2-1.The final simulation of the stickman with the optimal parameter values leads to a plot of the state vector. Figure 2-2 shows that the first five steps are not cyclic nevertheless the system converges clearly to the limit cycle. This figure is based on a simulation of 40 steps made by the stickman. Simulations for higher number of steps, up to a thousand, are done and show that the motion is stable during the complete simulation time. An elaboration on stability is given in Appendix A.3.

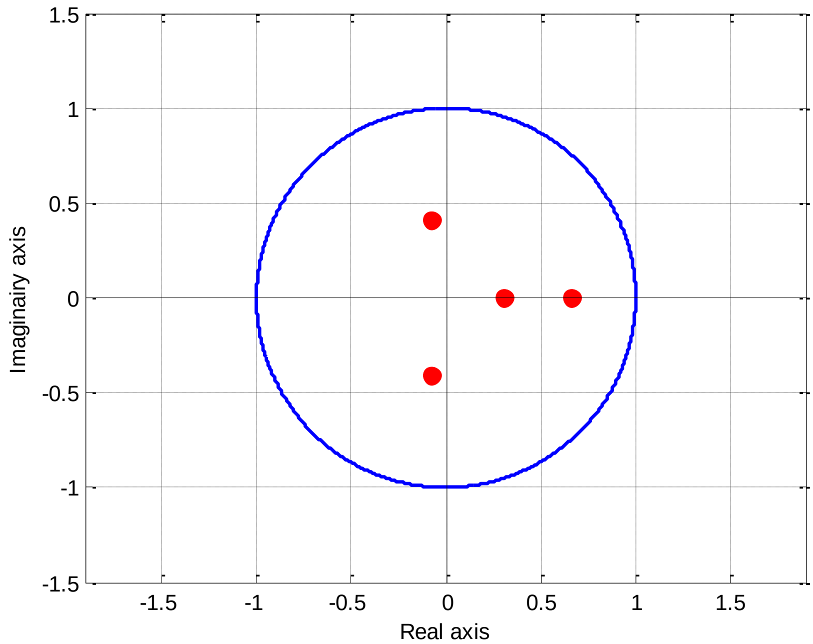


Figure 2-1: The eigenvalues of the most stable configuration plotted along with the unit circle

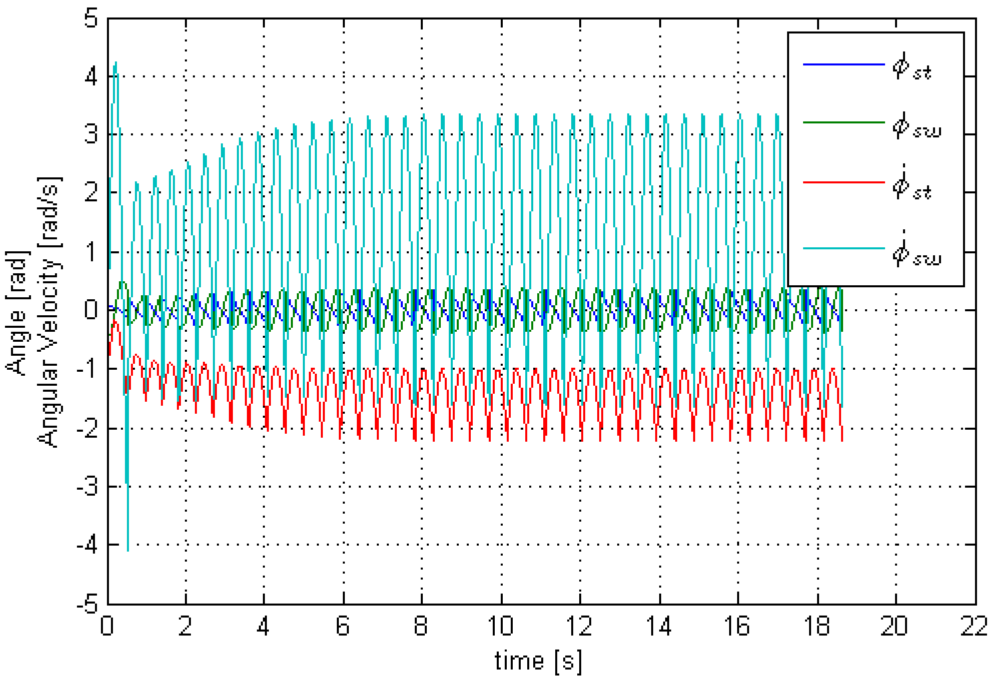


Figure 2-2: The state vector versus time during 40 steps

2.3 Parameter sensitivity

The results of the previous simulations give a stable walking motion. However, the exact parameters are hard to realize in practice because of manufacturing inaccuracies. Therefore, another set of simulations is done to show the influence of minor deviations in the parameter values found in the first set of simulations. These new simulations provide insight in the sensitivity to parameters inaccuracies. The possibility to walk a large number of steps and the maximum absolute eigenvalues $|\lambda|_{max}$ are observed during the simulation as done before.

Simulation ranges are determined regarding the accuracy that can be achieved during the production of the parts. This results in the simulation ranges with the corresponding step sizes as cited in Table 2-3.

Table 2-3: Parameters with ranges of variance and constants.

Parameter	Minimal value	Maximum value	Step size	Unit
C	0.08	0.12	0.02	$[m]$
R	0.19	0.21	0.01	$[m]$
γ	0.01	0.020	0.005	$[rad]$
L	0.38	0.42	0.02	$[m]$
m	5.950	6.050	0.05	$[kg]$
Constant	**Value**			
B	0.0			$[m]$
ϕ_{st}	0.16			$[rad]$
ϕ_{sw}	-0.47			$[rad]$
$\dot{\phi}_{st}$	-1.05			$\left[\frac{rad}{s}\right]$
$\dot{\phi}_{sw}$	-0.90			$\left[\frac{rad}{s}\right]$

These settings give a set of calculations with 243 results. From these results 200 combinations are able to walk 200 steps without falling. The $|\lambda|_{max}$ of these combinations is determined which shows that most of the combinations have $|\lambda|_{max} < 1$. Therefore, the limited accuracy during production of the several parts is not a big issue. Small variations still lead to a stable system. However, the convergence rate is smaller for less stable systems.

2.4 Conclusion

The system can be analyzed on the number of successful steps made by the stickman in simulation. All configurations are tested by varying three variables and the initial state. The combinations of parameters that lead to at least 100 steps are tested on stability. To do this the limit cycle is determined and its Jacobian. The eigen values of the Jacobian give information on the stability of the limit cycle. When all eigenvalues lie between -1 and 1 the motion is stable. The variables in Table 2-1 meet the defined goals and ensure stability.

Furthermore, an analysis is performed on the stability with small inaccuracies in the values of the determined parameters, due to production restrictions. This shows that these inaccuracies still give a stable walking stickman, but the convergence rate decreases.

Chapter 3

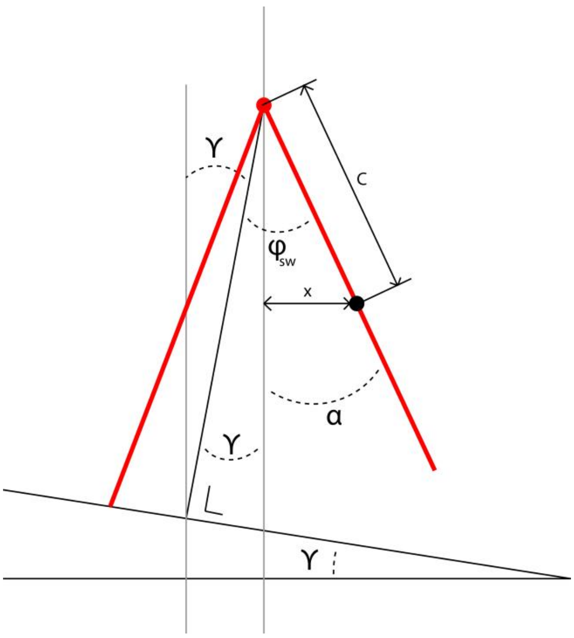
Motor and control

Now the values of the essential parameters are known the electromotor, amplifier, sensor, laptop and the connection between these parts can be determined. In this chapter the motor is chosen based on the calculated torque. Then the sensor, amplifier and connection are determined. Finally an overview of the whole interface is given.

3.1 Motor choice

The stickman can walk without actuation on a shallow slope. The gravitational force on the stickman induces a torque in the legs and kinetic energy in the swing leg. The electromotor should make it possible to walk on a horizontal surface. Therefore, the motor should be able to provide the torque and energy that is induced by gravity on a slope. The choice of the motor is highly depended on the amount of torque needed, so this is calculated first. After that the motor is chosen based on rotational velocity needed, gear ratio and set requirements. Torque can be calculated manually based on a simplified stickman or with the previously used dynamic model. Both methods are used to get a good view on the behavior.

The manual calculations ignore the double support phase so essentially they describe a pendulum. Based on Figure 3-1 the torque is manually computed. In this figure the CoM of the swing leg is shown as a black circle. The torque consists of three contributions, one induced by the gravity and two by the kinetic energy of the swing leg and stance leg. These contributions can be calculated by the following formulas:



$$T_g = m \cdot g \cdot C \cdot \sin(\phi_{sw} - \gamma) \qquad (3.1)$$

$$T_k = \ddot{\phi}_{sw} \cdot I \qquad (3.2)$$

Figure 3-1: Schematic view of the swing leg

The total torque needed is determined by subtracting T_g from T_k. Figure 3-2 is obtained by inserting the parameter values found in the previous chapter. The absolute rotational speed is plotted against the absolute torque. The inner rectangular surface represents the precise maximum power calculated. The surrounding rectangular surface represents the required power with a safety factor.

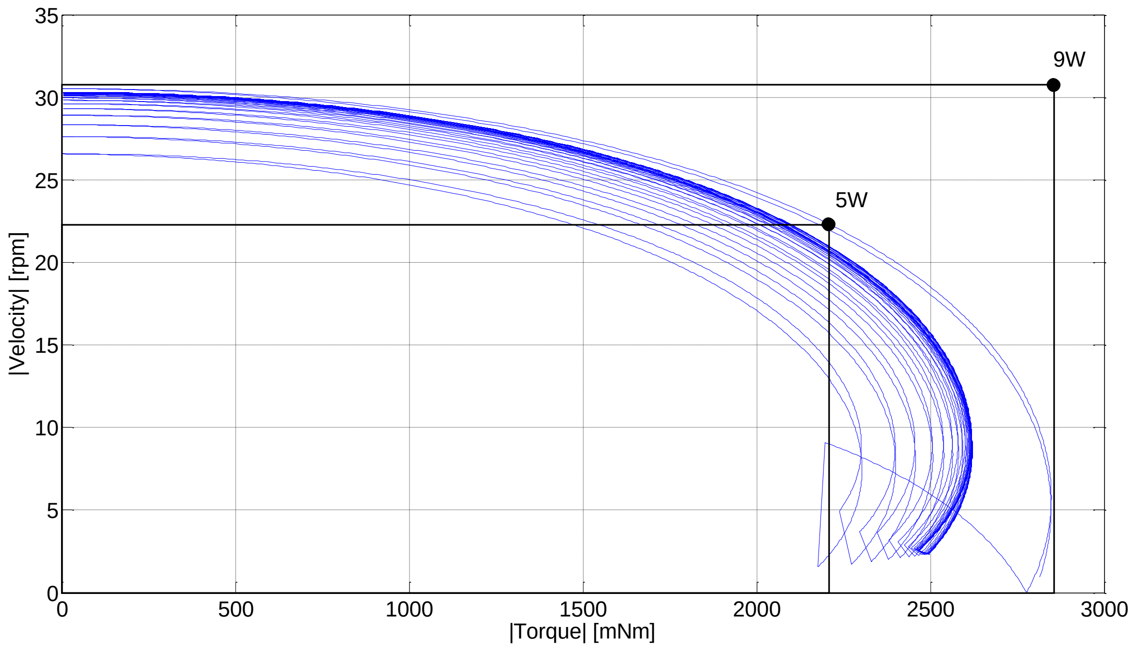


Figure 3-2: Rotational speed of the swing leg versus manually determined torque

The double support phase is included in the calculations with the dynamic model. The reduced force vector which consists of the two torque elements is determined by a simulation. The differences between this method and the previous one can be shown by plotting both in the same graph. Figure 3-3 shows the manual computed torque in red and the torque from the dynamic model in blue. Again the surrounding rectangle is drawn to determine the power required. From this figure can be concluded that the differences are significant, but the cause of the difference is unclear.

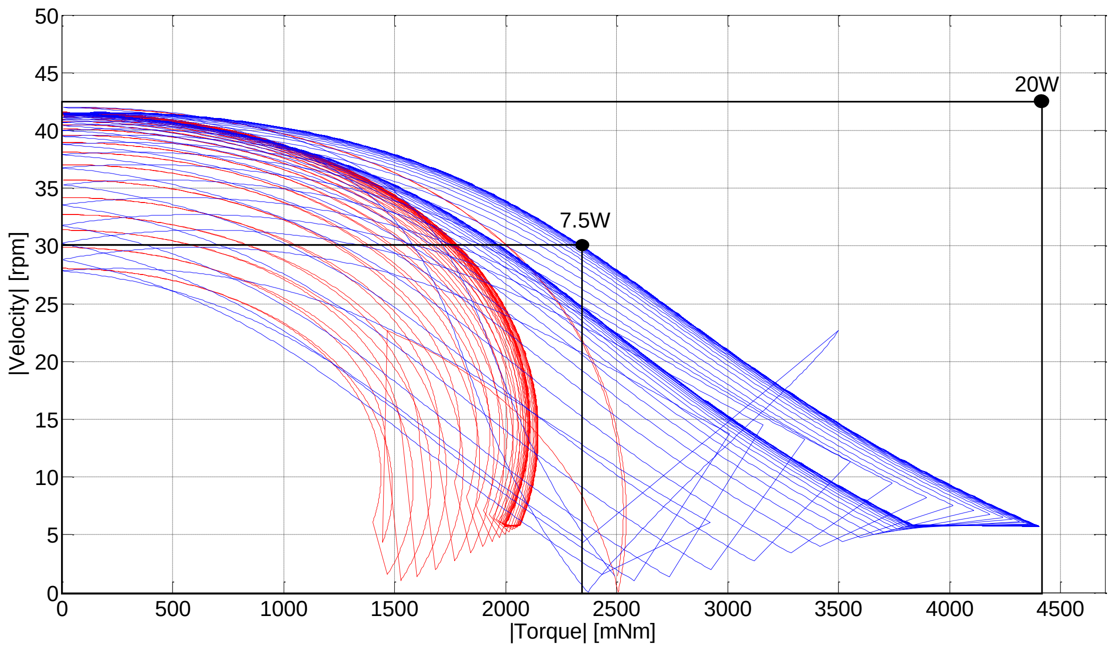


Figure 3-3: Rotational speed of the swing leg versus manually determined torque (red) and with the model determined torque (blue)

The maximum computed power is $7.5W$ as shown in Figure 3-3. A surrounding rectangle is chosen to compute the power because the computations are unsure. The requirement for the motor set by the client implies the following. “The final goal is controlling the movement of the stickman. To make sure this is actually possible the actuator must have enough power. So the safety factor on the torque has to be at least 3.” The safety factor on the torque is implemented with the following equation.

$$P = f \cdot T \cdot \dot{\phi} \tag{3.3}$$

The minimal required power becomes $60W$ by applying the safety factor to the surrounding rectangle. The resulting safety factor regarding the computed maximum power of $7.5W$ is 8, which is clearly sufficient.

The motor is chosen from a catalog based on the power and gear ratio. The “rotational speed versus torque” diagram for each motor is shown in the catalog. The motor typically runs at high rotational speeds and has low torque. For the stickman a low rotational speed and high torque is needed. Based on both speed-torque diagrams a suitable gear ratio can be determined by simply dividing the required torque by the motor torque. The chosen motor is a Maxon motor (RE 30) with a power of 60W. The exact type of motor is based on a standard voltage of $24V$ so it is easily integrated in an electrical system. This leads to a motor with a nominal torque of $85mNm$ and a gear ratio of at least 52:1. An identical motor with a gear ratio of 111:1 was supplied by the client for temporary use. The gear ratio ensures enough torque but decreases the rotational speed. Nevertheless, the requirement on the rotational speed is met. The finally chosen motor is listed in Table 3-1 and the pricing is listed in the next chapter.

Table 3-1: The specifications of the chosen encoders

Part	Specifications	Made by
Electromotor	Nominal speed: $8050rpm$ Nominal torque: $85mNm$ Nominal current: $3.44A$ Gear ratio: 111:1	Maxon
Encoder on motor	Accuracy: 9bit Incremental Multi turn	Maxon
Encoder on axle	Accuracy: 12bit Absolute Single turn	Scancon

3.2 Other equipment

The remaining components are sensors, an amplifier, power supply unit and a data acquisition system. Sensors are essential parts to control the movement of the stickman. There are many different types of sensors that can be used. The amplifier has to be compatible with the chosen motor. This implies that it has to deliver proper current and voltage. The power supply unit provides the whole system with power. The data acquisition system converts the analog signals of the sensors to digital signals which can be processed. It also converts the digital signal back to an analog signal to drive the motor.

The intension is to control a rotary movement at high accuracy so only rotary encoders are considered. Rotary encoders are absolute or incremental and single turn or multi turn. An absolute encoder knows its own position at all times. The incremental encoder only counts the number of pulses. This means that it has to be calibrated each time the system is started. A multi turn encoder records the amount of revolutions. Two encoders are chosen for the stickman. One that directly measures the angle between the legs (mounted at the axle) and one that measures the rotation of the motor. The main consideration for an encoder is its accuracy. The client required that the legs of the stickman can be positioned with an accuracy of at least $0.1°$ such that the angular speed can be reasonably approximated. This means that the encoder on the axle has to produce at least 3600 pulses per turn. The accuracy is usually described in bits, so a 12bit (4096 counts/turn) encoder is required. The legs will never rotate a whole circle with respect to each other so a single turn encoder is sufficient. The encoder on the motor can be less accurate due to the gear ratio between the motor rotation and the leg rotation. This encoder is incremental and ordered together with the motor. Making a robust controller is simplified by doing measurements as accurate as possible. However, the accuracy of encoders is usually directly connected to the budget. Also an absolute encoder is more expensive than an incremental encoder. So the accuracy of the measurement is based on budget. An absolute encoder on the axle is feasible within the requirements and budget. The used encoders and their specification are shown in Table 3-1. The price of the encoders is listed in the next chapter.

The control signal from the computer is a low voltage signal. This voltage has to be amplified by an amplifier which is powered by a power supply unit (PSU). The PSU converts the voltage of the electrical grid to the work voltage of the amplifier. An amplifier and PSU are available at the TU/e but this amplifier cannot provide the required power of $60W$. However, this option is cheaper and easier than ordering a new amplifier and PSU. So the system with the motor is tested. The amplifier provides a maximum current of $1.3A$ if a control voltage of $2.5V$ is send from the computer. This signal is sent to the motor and the rotational speed is determined with the encoder signal. Based on the current and the torque constant the torque is determined. The rotational speed is measured at $7778\,rpm = 814.4\,rad/s$ and the torque at $33.67mNm$. The maximum provided power is $27{,}4W$ and the safety factor is still 3.7. This is deemed acceptable.

The TU/e has data acquisition systems that are used to control robots. These systems are called TUeDacs and can be used freely. The TUeDacs is used to easily connect all the electrical components. The TUeDacs MicroGiant is suitable for up to $4\,kHz$ closed loop motion control and regular data acquisition. The final system is shown in Figure 3-4.

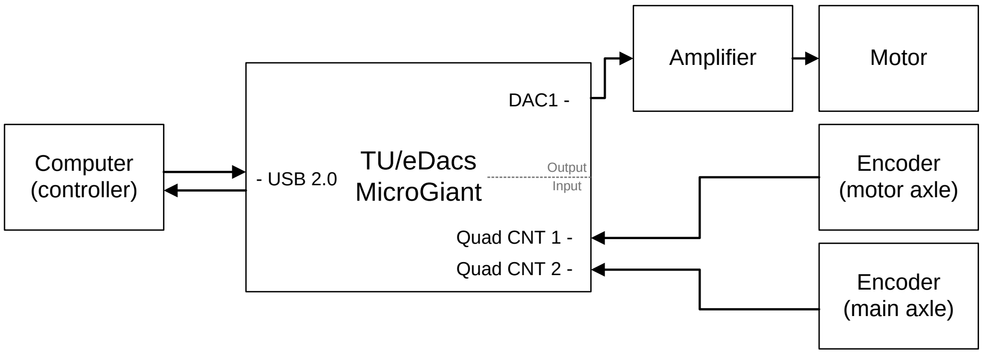


Figure 3-4: Overview of the whole interface

3.3 Conclusion

The required power of the electromotor is determined based on a manually computed torque and the torque computed in the dynamic model. The rotational velocity can be plotted against the torque to determine a suitable motor. The chosen motor has a maximum power of $60W$ with an overall safety factor of 8. The minimum gear ratio is determined by dividing the nominal torque by the motor torque. This results in a ratio of approximately 52:1. The adopted motor has a gear ratio of 111:1 which is sufficient on both torque and rotational speed.

Two sensors are used on the stickman, one on the motor and one on the axle. Both sensors are rotational encoders. The encoder on the axle is an absolute single turn encoder with an accuracy of 12bit. This accuracy is based on the requirement set by the client. The position of the legs should be known at an accuracy of $0.1°$. The encoder on the motor has a lower accuracy (9bit) and is an incremental multi turn encoder. The lower accuracy is not a problem because of the gear ratio. An amplifier and a power supply unit (PSU) are available on the TU/e. Using these components is a lot cheaper than ordering new ones. However, they are not entirely compatible so they are tested. The amplifier can deliver a power of $27.4W$. This is acceptable for the stickman because the safety factor is still 3.7.

Finally a data acquisition system, the TUeDacs, is used to connect all pieces. This unit converts digital and analog signals and is suitable for motion control up to $4\ kHz$. The final system is shown in Figure 3-4 and the motor and encoders are described in Table 3-1.

Chapter 4

Final design

The stickman shown in Chapter 1 is the basis of the final design of the stickman. Essential aspects are maintained such as two inner legs and two outer legs, motor mounted to the inner leg and bearings between the inner leg and the axle. The actual dimensions and geometry are adjusted according to the calculations from Chapter 2. The feasibility is taken into account in this chapter as well. Firstly, the geometry and dimensions are discussed. This leads to the stickman as it is built. Secondly, specific design aspects are elaborated such as placement of the actuator and the type of transmission. Finally, the design considerations of each component are discussed.

4.1 Geometry and dimensions

The final dimensions of the stickman are based on restrictions. The most basic restriction is the fact that both legs must have the same mass and the same position of the CoM. Further restrictions to the size and mass stated in Chapter 1 are: the length of the legs $L = 400mm$ and the total mass $m = 6kg$. Figure 4-1 shows the final design of the stickman divided into two legs, green is the inner leg and blue is the outer leg. Applying the calculated parameters from Chapter 2 the position of the CoM lies $100mm$ below the axle and the radius at the bottom of the foot is $200mm$. The calculations from Chapter 2 are based on a 2D model so the width of the stickman is free to choose. However, this width has an effect on the torsion of the axle. The error in the foot placement is the torsion magnified with the length of the leg. So it could influence the motion. Therefore the axle length is chosen based on the length of the motor to make sure it is as short as possible. The exact dimensions of the stickman are given in Table 4-1.

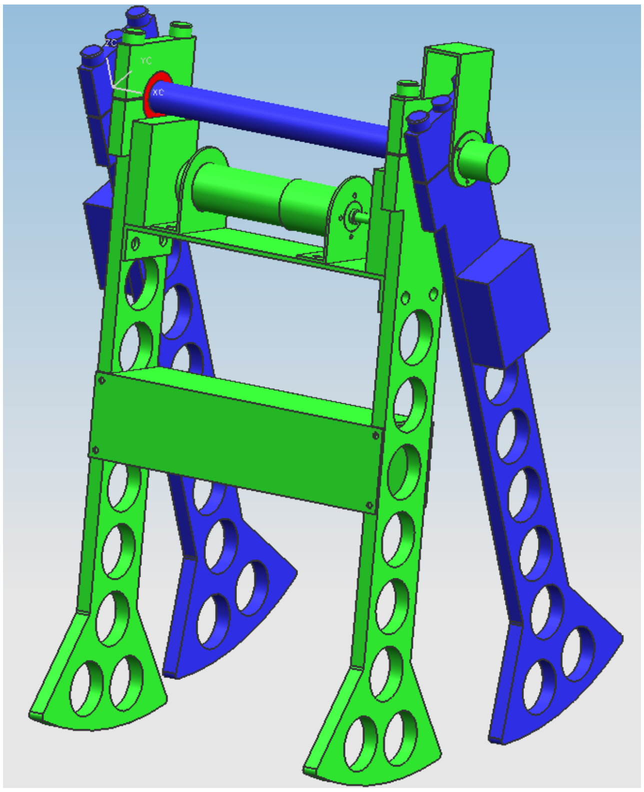


Figure 4-1: Final design of the stickman

Table 4-1: Dimensions of the stickman

Dimension	Value $[mm]$
Leg length	400
Foot radius	200
Distance between inner legs	200
Total axle length	270

4.2 Specific design aspects

The motor is placed horizontally between the legs such that it is easy to mount and the transmission is easily realized. The distance to the axle is crucial to get the CoM at the right height. A simple bridge with a thickness of $3mm$ is made between the two inner legs to mount the motor. To get the CoM at the desired position it would be more efficient to place the motor at the axle height. However, to make this kind of setup possible the axle should be divided into two halves which are less rigid than the whole axle and realizing the transmission is more complex as well. That is why this setup is not chosen.

Each of the four legs consists of two parts: a cap above the axle and the leg piece beneath the axle. The outer legs are clamped on the axle by bolting the cap on the leg piece. The hole in the cap is constructed slightly of center such that it really fixes the legs on the axle. Secondly a locking pin is inserted in the outer legs to make sure they cannot rotate relatively to each other or the axle. The inner legs are clamped on bearings that are fixed on the axle. This ensures that the inner legs can rotate freely. These inner legs are connected to each other by a square tube to make sure their motion is the same. The placing of this tube has a great influence on the position of the CoM. The mounting of the motor increases the stiffness of the inner legs as well. The stickman should be very rigid because the placement of the legs has to be precise. The position of the CoM of the four leg pieces is determined using a CAD drawing. It is important to know what this position is for each part of the stickman to make sure the CoM of the whole system lies at the right height.

The transmission between the motor and the axle is realized with a drive belt. The belt is very strain resistant so the connection is stiff. The belt is chosen over a transmission with gears so the distance between the motor and axle can be chosen more freely. This is very important because the CoM has to be at the exact specified position. The belt is also advised by a professional.

The encoder is placed at the end of the axle. Mounting the encoder between the inner legs around the axle would be easier to construct. However, encoders that fit around the axle of the stickman are hard to find and probably very expensive. The encoder is mounted on the axle which supports its weight. The axle is fixed on the outer legs so the hull of the encoder should be fixed to the inner leg. The rotation of the hull is fixed to the inner leg with a bridge over the outer leg.

In order to position the CoM, the weight of each part is determined. Each leg system is designed separately because it moves on its own. The inner leg is the most complex because it has a lot of parts. Al these parts have an influence on the total CoM. The contribution of each part is defined as the vertical distance in between the CoM of the part and the required CoM of the whole leg system multiplied by the mass of the part. The sum of all these contributions should become zero. Only the vertical position of the Com is relevant because the stickman is almost symmetrical in the x and z direction.

$$position\ CoM = \sum_{i=1}^{np} a_i \cdot m_i = 0 \qquad (4.1)$$

The actual stickman will probably slightly differ from the above stated situation. Variable weights can be added to each leg system to make sure the CoM lies at exactly the right position. The mass of each weight and its position is determined based on the real stickman.

4.3 Parts, materials and center of mass

Different parts described above are listed for the inner leg system in Table 4-2 and for the outer leg system in Table 4-3. These tables give the important properties of each part such as material, mass and position of the CoM. The exact geometry is defined in the technical drawings of each part which can be found in Appendix A.5. Important parts like the axle, leg pieces and the motor mount are briefly elaborated.

The axle has a diameter of $20mm$, a length of $270mm$ and it is made of steel. This large diameter and the material steel are chosen to minimize the torsion in the axle. Torsion occurs due to the torque applied by the motor. The bottom of the two outer legs must have the same position which is ensured by a rigid axle. The axle is loaded in the vertical direction as well. The inner leg system supports the outer leg system during the swing phase or vice versa. Calculations on the loading of the axle are shown in Appendix A.4. The high weight of the axle has a positive effect on the CoM. The minimum length of the axle is determined based on the width of the actuator, a margin of $10mm$ between the legs and spacing for optional extra weight.

The leg pieces are made of $10mm$ thick aluminum. The strength is tested by calculating the required force to snap the legs described in Appendix A.4. The thickness of the leg pieces is constant, making them easy to fabricate. The weight of each leg piece is reduced and the CoM is repositioned by making holes. The foot is part of a circle which has its center point $200mm$ below the axle and has a radius of $200mm$. The maximum angle between the leg systems during motion determines the size of the foot.

The motor mount consists of a horizontal $3\ mm$ thick plate of aluminum between the inner legs. The motor is mounted to this plate using two brackets and the plate itself is bolted to the legs by four bolts. The brackets that hold the motor can be connected with two different sets of holes so two different types of electro motors can be mounted. This makes it possible to switch actuators.

Table 4-2: Information on all parts of the inner leg

Part	Material	Amount	Mass $[kg]$	CoM position$[mm]$
Inner leg	Aluminum	2	0.4357	-104.17
Inner cap	Aluminum	2	0.0507	120.17
Clamp screws	-	4	0.0220	119.00
Motor mount	Aluminum	1	0.0980	36.69
Motor mount plate 1	Aluminum	1	0.0170	53.54
Motor mount plate 2	Aluminum	1	0.0150	51.79
Motor + gearbox + sensor	-	1	0.4320	50.00
Sprocket	Steel	1	0.1200	50.00
Connection tube	Aluminum	1	0.2440	-100.00
Sensor mount	Aluminum	1	0.0280	142.60
Sensor	-	1	0.0750	100.00
Div screws	-	1	0.0400	-100.00
Additional mass	Steel	2	0.4171	58.19

Table 4-1: Information on all parts of the outer leg

Part	Material	Amount	Mass $[kg]$	CoM position$[mm]$
Axle	Steel	1	0.6600	100.00
Sprocket	Steel	1	0.0800	100.00
Outer leg	Aluminum	2	0.4716	-96.15
Outer cap	Aluminum	2	0.0560	118.80
Screws	Steel	6	0.1320	119.00
Additional mass	Steel	2	0.5364	-11.48

4.4 Budget

To prevent overrunning the budget, an assessment on the expected costs is made. The list is created by defining of and searching for the parts needed and asking inquiries about delivery times, shipping costs, product costs and suppliers. An overview of the products and their costs is stated in Table 4-4. A more detailed overview is shown in Appendix A.6.

Table 4-4: Overview of the parts and their expected costs.

Part	Supplier	Number	Subtotal	Delivery time
Material and fabrication		1	€ 750.00	2 weeks
Cables	gamma	3	€ 21.00	
Encoder (main axle)	Fortop	1	€ 434.35	4 weeks
Materials for slope and table		1	€ 80.00	
Motor	Maxonmotors	1	€ 0.00	8 weeks
Gear head	Maxonmotors	1	€ 0.00	
Encoder (motor axle)	Maxonmotors	1	€ 0.00	
TUeDacs		1	€ 0.00	
Amplifier		1	€ 0.00	
Total		**11**	**€ 1,285.35**	

The encoder is the most expensive part. This also has the longest delivery time so it is crucial to order this in an early phase of the project. The TUeDacs and amplifier are borrowed and directly available at the TU/e. A motor with gear head and encoder is also available for use. This enables the purchase of a very accurate encoder.

4.5 Conclusion

The stickman is designed so that the mass is exactly $6kg$ and the center of gravity is $100mm$ under the axle. This is done by adding weights at calculated positions. All parts are made of aluminum, except the axle and the additional masses, these are made of steel. Aluminum is used because it has a low weight which gives a lot of freedom in positioning the CoM. Strength calculations are done to secure strength and stiffness. Ease of manufacturing is kept central during designing the stickman. The sensor is placed directly on the axle to acquire as accurate data as possible. At last a budget is made which meets the demands of the limit of € 1500,-.

Chapter 5

Plan phase 3 and 4

Since the end of phase one and two is coming up soon, it is good to take a look forward to phase three and four and make plans to have an overview of the things left to do and the given deadlines. The planning is made as detailed as possible.

week nr.	week	Phase		To do
45	11	Phase 3/4	Test phase	Report - Contents - Structure - Time schedule Measurements on stickman parameters - Mass separate parts - Exact dimensions - Mass moment of inertia of the legs Building of slope - Interaction Simulink and stickman Buying motor
46	12			Studying stickman's behavior - Transfer function and sensitivity
47	13		Design/production phase	Building a controller
48	14			Improvement of the controller - PD - PIDS
49	15			Further improvements on the controller
50	16			Buffer
51	17		Test phase	
52	18			
1	19			Finish the report
2	20			Prepare presentation
3	21			Report hand-in
4	22			Final presentation (28-01-2011, 9:00-12:00, WH-3A08)

Examinations	Holidays

Conclusion

The goal of this project is to create a stickman that can walk down a shallow slope without any actuation and walk horizontally using an electromotor with control system. The stickman is designed using a verified dynamic model and it is made regarding the specifications as stated in Table C-1. Ease of manufacturing is kept central during the design phase. Aluminum is used for almost all parts because it has a low weight which gives a lot of freedom in positioning the center of mass. The strength of the main parts is calculated to assure stiffness. The final stickman is made and the budget stays within the stated limit of €1500,-.

The parameters from Table C-1 are determined based on the stability of the walking gait of the stickman. The stability criterion holds that the stickman should be able to walk 200 steps or more in simulation. Next to the stability the sensitivity of each parameter is tested. The position of the center of mass is the most crucial parameter which follows from this test. The stickman remains stable when it is not perfectly constructed and weights that can be repositioned are included in the design to increase stability robustness.

The actuation of the stickman is determined by the electrical system which has four main components. The choice of an electromotor is based on a calculation of the torque needed and a motor of $60W$ is the result. A safety factor of 8 is reached using this motor. According to the client the position of the legs should be at least measured with an accuracy of $0.1°$. This accuracy requirement is met with a 12bit rotational encoder which directly measures the angle between the legs. A second encoder measures the position of the motor to simplify the synthesis of a robust controller. This encoder has an accuracy of 9bit. Finally, the TU/e provided an amplifier embedded in a power supply unit and a data acquisition system to convert digital and analog systems. These components are chosen because they are simple to use in a control system and it is cheaper than ordering each component. However, the decision for the PSU and amplifier are not made based on the system described above. The combination of the amplifier and the motor has a maximum power of $27W$ which is significantly lower than the determined power. This is not a big problem, since a safety factor is chosen for the motor. The safety factor still reaches 3.7 with the components provided by the TUe.

Table C-1: Stickman specifications

Parameter	**Value**	**Unit**
Overall length	400	$[mm]$
Vertical distance center of gravity to axle	100	$[mm]$
Horizontal distance center of gravity to vertical symmetry axis	0	$[mm]$
Foot radius	200	$[mm]$
Weight per leg	3.0	$[kg]$
Angle of the slope	0.015	$[rad]$

Bibliography

[1] Garcia, *The simplest walking model, stability, complexity and scaling*, Cornell University, Department of Theoretical and Applied Mechanics, 1998

[2] Hobbelen, *Limit cycle walking*, TU Delft, 2008

[3] McGeer*, Passive dynamic walking*, Simon Fraser University, 1988

[4] Wisse, *Essensials of dynamic walking*, TU Delft, 2004

[5] van Zutven, *Modeling, identification and stability of humanoid robots*, TU Eindhoven, Department of Mechanical Engeneering, 2009

[6] McGeer, *Passive dynamic walking*, Intern. J. Robot. Res., Vol. 9, No. 2, pp. 62–82, 1990.

Appendices

A.1. Patent Research

The search methods and results

General search

The first exploration of the patent database is done with a general search for this particular subject. The search is done to investigate the amount of patents regarding this subject and the diversity of the patents. The following keywords are used:

- Biped
- Control

The first keyword results in 515 when searching in titles and abstracts. This design is specifically a controlled biped so the second keyword is added, this results in 252 patents. On both searches the astrix is added to search for more possibilities such as bipedal and controlled.

Search for Authors of documents related to our topic

In order to find relevant patents also searches are performed for persons who could own these patents. Such persons are by example authors of papers about passive walking bipeds and controlled bipeds. There are a lot of papers used as background information to construct this biped. Authors of these papers could own one or more patents. By example a paper of Ted McGeer, he was the first person who mathematically described a passive walking biped. The used search criterion was inventor. If there were too many results an additional search criterion is used. A list of results per inventor is below. Surprisingly all of these people do not have patents which are relevant for this design.

Table A.1-1: List of inventors related to stickman designs

Inventor	Results	Relevant results
Ted McGeer	0	0
Mariano Garcia	190	0 (biped* , control*)
Ryan W. Sinnet	3	0
Aaron D. Ames	0	0
Mark Spong	5	0
P.W.M. van Zutven	7	0
Daan Hobbelen	3	0
Martijn Wisse	0	0

Search for ECLA-codes

It is useful to find an ECLA-code related to this design. To find such a code, the following searches are performed:

- Biped
- Two* feet* robot*
- Human* robot*

- Humanoid* robot*

When looking at the results and especially for recurring codes, the following codes appear to be codes that are strongly related to our topic:

B62D57/032: Vehicles characterized by having other propulsion or other ground- engaging means than wheels or endless track, alone or in addition to wheels or endless track; with ground-engaging propulsion means, e.g. walking members; with alternately or sequentially lifted supporting base and legs; with alternately or sequentially lifted feet or skid (B62D57/024 takes precedence)

B62D57/024: Vehicles characterized by having other propulsion or other ground- engaging means than wheels or endless track, alone or in addition to wheels or endless track; with ground-engaging propulsion means, e.g. walking members; specially adapted for moving on inclined or vertical surfaces

Other codes appear to be related to this design:
A61H3/00: Appliances for aiding disabled persons to walk about

A61H3/00H: [N: Using suspension devices for supporting the body in an upright walking or standing position, e.g. harnesses]

There are lots of results searching with these codes, but none of them concerns this particular design. This is obvious when analyzing the results for searches with additional keywords like robot*, biped*, control*, slope* and combinations.

New searches are performed with in the ECLA-code field B62D57/032 and some additional terms in the field for “Keywords in Title or Abstract”. These additional terms are:
- Biped*
- Control*

This combination gives 90 results. Among these results, there is one that exactly describes the way of control that we are probably going to use and what would make our design “special”:

1 System for controlling locomotion of legged walking robot. verwijder

Uitvinder: OZAWA NOBUAKI [JP] ; TAKENAKA TORU [JP]
Aanvrager: HONDA MOTOR CO LTD [JP]
EC: B62D57/032
IPC: *B25J13/00; B25J5/00; B62D57/032;* (+8)
Informatie over publicatie: EP0488692 (A2) - 1992-06-03
EP0488692 (A3) - 1993-02-24
EP0488692 (B1) - 1997-03-05
Priority Date: 1990-11-30

The claims described in this patent, **EP 0488692 (A2),** are the following:

1. A system for controlling locomotion of a legged walking robot having a body link and a plurality of linkages each connected to the body link by a first drive joint and each including at least one second drive joint connecting an upper link and a lower link thereof, comprising: a servo motor for driving the joint; First means for outputting a command value of speed to drive the servo motor in response to a change rate of a target angle; and second means for calculating a deviation between the target angle and a real angle for carrying out feedback

compensation of the command value in response to the deviation and a gain to be multiplied thereto.

2. A system according to claim 1, wherein the target angle is predetermined in series with respect to time and said first means determines the command value based on a change between a target angle at time t and a target angle at time t+1.
3. A system according to claim 1 or 2, wherein the robot is a biped walking robot.

Conclusions

Since this patent describes the feedback-controlled control for a two-legged humanoid robot. It is not possible to qualify for a patent. Although there is a minor difference in the composition of the legs, this will probably be not enough to register a new patent. Furthermore, this patent is registered in 1992, which means that it is legal at this time, but only in a few countries, since it is only registered in Germany, France and the United Kingdom. Besides, there are a lot of publications on this topic, which makes it impossible for us to register a patent too. The design of this particular biped is based on Ted McGeers' stickman from the article "Passive dynamic walking"[6].

A.2. Matlab scripts

Finding stable configurations

```
clear all
clc

%% Constants
l = 0.4;              % Leg length
b = 5e-2;             % Leg width
m = 3;                % Leg mass
Iz = (1/12)*m*(l^2+b^2); % Inertia

nr_steps = 100;
t0 = 0;
A = [];               % Initial Matrix A

%% Variables
cmin = 0;
cmax = 0.2;
cstep = 0.1;
Cs = cmin:cstep:cmax;

gammin = 0.005;
gammax = 0.02;
gamstep = 0.005;
Gammas = gammin:gamstep:gammax;

rmin = 0.2;
rmax = 0.4;
rstep = 0.1;
Rs = rmin:rstep:rmax;

phistmin = -pi/4;
phistmax = pi/4;
phiststep = pi/10;
phists = phistmin:phiststep:phistmax;

phiswmin = -pi/4;
phiswmax = pi/4;
phiswstep = pi/10;
phisws = phiswmin:phiswstep:phiswmax;

wstmin = -1.05;
wstmax = -0.85;
wststep = 0.05;
wsts = wstmin:wststep:wstmax;

wswmin = -0.9;
wswmax = -0.7;
wswstep = 0.05;
wsws = wswmin:wswstep:wswmax;

par.L = l;                % (fixed)Leg length [m]
par.m = m;                % (fixed)Leg mass [kg]
par.B = 0;                % (fixed)Horizontal position center of mass [m]
par.g = 9.81;             % (fixed)Gravity constant [m/s^2]
```

```
%% Simulation and Save all the simulation results to matrix A
k = 1;

for c = Cs
    par.C = c;              %        Vertical position center of mass [m]
    par.I = Iz + m*c^2;     %        Leg inertia [kgm^2]

for r = Rs
    par.R = r;              %        Foot radius [m]

for gam = Gammas
    par.gamma = gam;        %        Slope [rad]

for phist = phists
for phisw = phisws
for wst = wsts
for wsw = wsws
        s0 = [phist phisw wst wsw]';
        [s_end, t_end, data, n] = Walk(s0, t0, par, nr_steps);
        A = [A; c r gam par.I s0' n];
        k = k+1
end
end
end
end
end
end
end

% Save the simulations with 100 steps to matrix B and find lc an
eigenvalues and save these to matrix D

B = [];
stappen = 100;

[mm,nn] = size(A);

for h = 1:mm
    if(A(h,9)> stappen)
        B = [ B; A(h,:) ];
    end
end

B = sortrows(B,[-9]);
save B.mat B

par.L = 0.4;              % Leg length [m]
par.m = 3.0;              % Leg mass [kg]
par.B = 0;              % Horizontal position center of mass [m]
par.g = 9.81;           % Gravity constant [m/s^2]

[mm,nn] = size(B);

D = zeros(mm, 19);


t0 = 0;                                  % t0 is the initial time
options = optimset('TolFun',1e-11);      % set tolerance
```

```
for h = 1:mm

    par.C = B(h,1);
    par.R = B(h,2);
    par.gamma = B(h,3);
    par.I = B(h,4);
    s0 = [B(h,5) B(h,6) B(h,7) B(h,8)]';

    % find the limit cycle and save it for further use
    lc = fminsearch(@(s0)sum((Step(s0,t0,par)-s0).^2),s0,options);


    % check the resulting error
    error = sum((Step(lc,0,par)-lc).^2);


    for i = 1:4
        %create a perturbation on the signal
        pt = [0 0 0 0]';
        pt(i) = 10^-4;

        s0 = lc+pt; % a perturbation is added to the limit cycle

        % perform a step and save the system parameters in s1
        [s_end, t_end, data] = Step(s0,0,par);
        s1 = s_end;
        % a column of the jacobian is calculated by subtracting the
        % limit cycle from s1 and dividing it by the perturbation
        s = (s1-lc)/(10^-4);

        J(:,i)=s; % a column is added to the Jacobian
    end
    checkJ=isnan(J);
    notan=any(any(checkJ));

        if(notan==1)
        J = diag(1e4*[1 1 1 1],0);
        maxeig = max(abs(eig(J)));
        else
        maxeig = max(abs(eig(J)))
        end
    D(h,:) = [B(h,:) lc' error eig(J)' maxeig];
    h
end
save D.mat D

% save stable configurations to Satbiel.mat
Stabiel=[];
z=1;

for h = 1:1400
    if(D(h,19)<=1)
    Stabiel(z,:) = D(h,:);
    z = z+1;
    end
end

% find configuration with smallest maximum absolute eigenvalues
```

```
[min_difference, rownr] = min(abs(Stabiel(:,19)) -
min(abs(Stabiel(:,19))));


% configuration with smallest maximum absolute eigenvalues
Stabiel(rownr,:)
```

M-file for checking sensitivity

```
clear all
clc
robuust = [];
load best

par.B = 0;              % Horizontal position center of mass [m]
par.g = 9.81;           % Gravity constant [m/s^2]

h=1;
t0 = 0;                                 % t0 is the initial time
s0 = best(1,5:8);
for C = 0.08:0.02:0.12
    par.C = C;
    for R = 0.19:0.01:0.21
        par.R = R;
        for gamma = 0.01:0.005:0.02
            par.gamma = gamma;
                for L = 0.38:0.02:0.42
                    par.L = L;
                    for m = 2.975:0.025:3.025
                        par.m = m;
                        h
                        par.I=m*(par.C)^2;

t0 = 0; % t0 is the initial time
nr_steps =200; % nr_steps
% do a simulation
[s_end, t_end, data, n] = Walk(s0, t0, par, nr_steps);
% plot(data.t,data.s,'linewidth',2)
% xlabel('time [s]')
% legend('\phi_s_t','\phi_s_w','\phidot_s_t','\phidot_s_w')

robuust=[robuust; C R gamma par.I L m n];
h=h+1;
                    end
                end
            end
        end
    end

save robuust.mat robuust


stappen = 200;

[mm,nn] = size(robuust);
robuust_eig = zeros(mm,nn+1);

for h = 1:mm
    if(robuust(h,7)== stappen)
    h
    par.C = robuust(h,1);
    par.R = robuust(h,2);
    par.gamma = robuust(h,3);
    par.I = robuust(h,4);
    par.L = robuust(h,5);
```

```
    par.m = robuust(h,6);


    s0 = [best(1,5) best(1,6) best(1,7) best(1,8)]';
    lc = best(1,10:13)';



    for i = 1:4
        %create a perturbation on the signal
        pt = [0 0 0 0]';
        pt(i) = 10^-4;

        s0 = lc+pt; % a perturbation is added to the limit cycle

        % perform a step and save the system parameters in s1
        [s_end, t_end, data] = Step(s0,0,par);
        s1 = s_end;
        % a column of the jacobian is calculated by subtracting the
        % limit cycle from s1 and dividing it by the perturbation
        s = (s1-lc)/(10^-4);

        J(:,i)=s; % a column is added to the Jacobian
    end
    checkJ=isnan(J);
    notan=any(any(checkJ));

        if(notan==1)
        J = diag(1e4*[1 1 1 1],0);
        maxeig = max(abs(eig(J)));
        else
        maxeig = max(abs(eig(J)))
        end
        robuust_eig(h,:) = [robuust(h,:) maxeig ];

    end
end
save robuust_eig.mat robuust_eig
```

Modified script to calculate new limit cycles and eigenvalues

```
stappen = 200;
load robuust
load best
[mm,nn] = size(robuust);
robuust_eig = zeros(mm,nn+1);
options = optimset('TolFun',1e-11);      % set tolerance

for h = 1:mm
    if(robuust(h,7)== stappen)
    h
    par.C = robuust(h,1);
    par.R = robuust(h,2);
    par.gamma = robuust(h,3);
    par.I = robuust(h,4);
    par.L = robuust(h,5);
    par.m = robuust(h,6);
    par.B = 0;
    par.g = 9.81;

    s0 = [best(1,5) best(1,6) best(1,7) best(1,8)]';
     % find the limit cycle and save it for further use
    lc = fminsearch(@(s0)sum((Step(s0,0,par)-s0).^2),s0,options);



    for i = 1:4
        %create a perturbation on the signal
        pt = [0 0 0 0]';
        pt(i) = 10^-4;

        s0 = lc+pt; % a perturbation is added to the limit cycle

        % perform a step and save the system parameters in s1
        [s_end, t_end, data] = Step(s0,0,par);
        s1 = s_end;
        % a column of the jacobian is calculated by subtracting the
        % limit cycle from s1 and dividing it by the perturbation
        s = (s1-lc)/(10^-4);

        J(:,i)=s; % a column is added to the Jacobian
    end
    checkJ=isnan(J);
    notan=any(any(checkJ));

        if(notan==1)
        J = diag(1e4*[1 1 1 1],0);
        maxeig = max(abs(eig(J)));
        else
        maxeig = max(abs(eig(J)))
        end
        robuust_eig(h,:) = [robuust(h,:) maxeig ];

    end
end
save robuust_eig.mat robuust_eig
```

A.3. Stability result graph

Figure A.3-1 shows the kinetic energy as well as the potential energy and the total energy of the stickman during a walk of 50 steps. During each step, the total energy in the system stays equal. This implies that the system has to be stable since no energy losses occur in this phase. Since friction is not covered by the dynamic model used, the total amount of energy in the system converges to a constant value once the stickman is walking in a limit cycle.

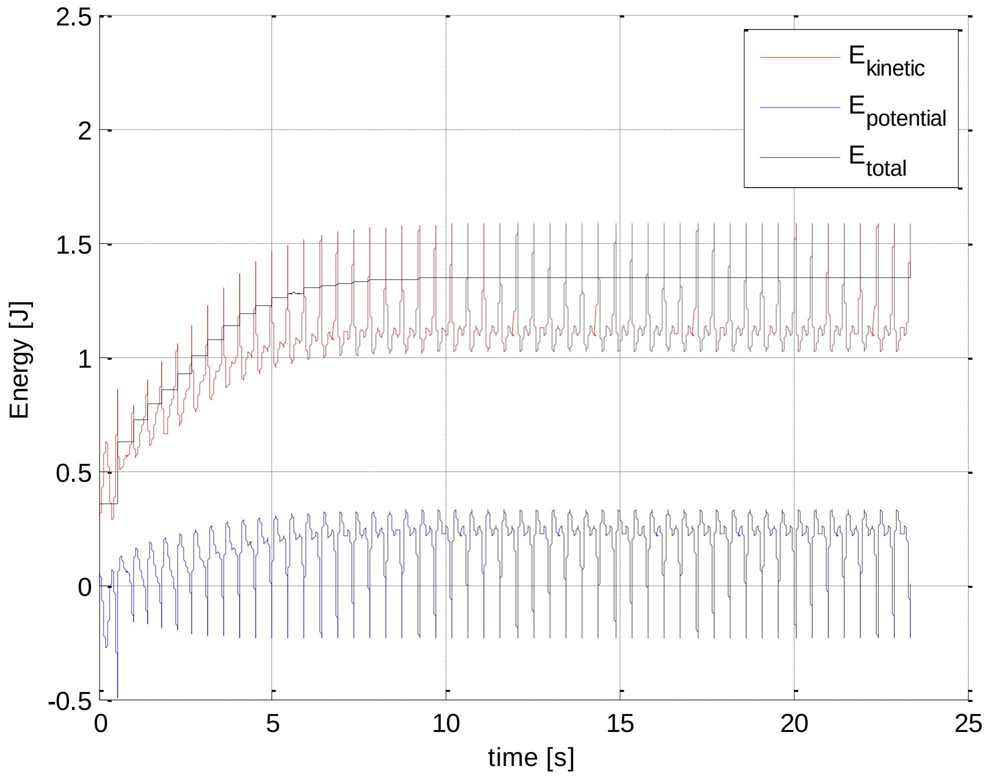


Figure A.3-1: Internal energy of the stickman during 50 steps

A.4. Strength of the final design

Because of the forces that are acting on the axle and the legs, mechanical calculations can assure that the construction will be stiff enough and will not deform too much.

Bending of the axle:

First, a calculation on the bending of the axle is made. When the outer legs are the supporting legs, the two inner legs apply a force at the center of the axle. This is shown in figure A.4-1.

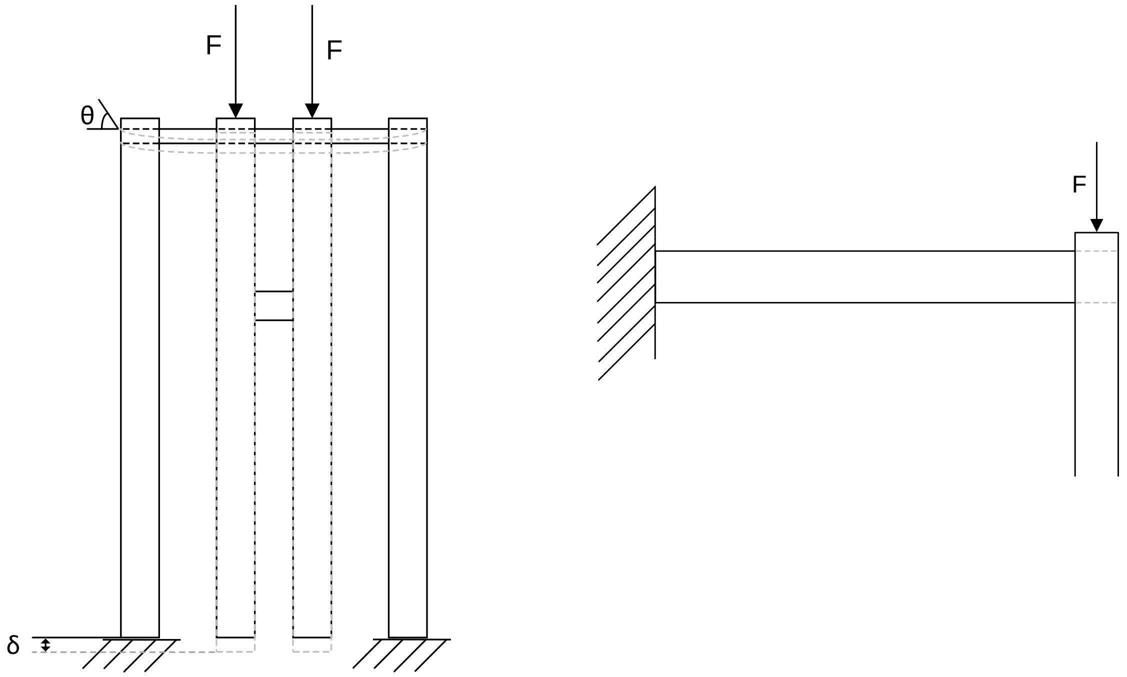


Figure A.4-1: Bending of the axle due to forces on the inner legs. Left: Full picture. Right: Simplified case.

Due to this force, bending occurs which will lead to a vertical displacement with the largest magnitude at the center. Stresses have to stay below yield stress and displacement has to be minimized. The maximum stress is calculated by the following formula:

$$\delta = \frac{-F \cdot L^3}{3 \cdot E \cdot j}$$

$$j = \frac{\pi r^4}{4}$$

With the following values for all the parameters, the deflection is determined.

$$r = 0.01$$

$$L = 0.02$$

$$E = 69 \cdot 10^9$$

$$F = 1.5 \cdot 9.81 = 14.715$$

$$\delta = 7.24 \cdot 10^{-8}$$

There are more conditions which will cause a deformation of the construction. Two of them are bending and buckling of the leg on the moment that it hits the ground.

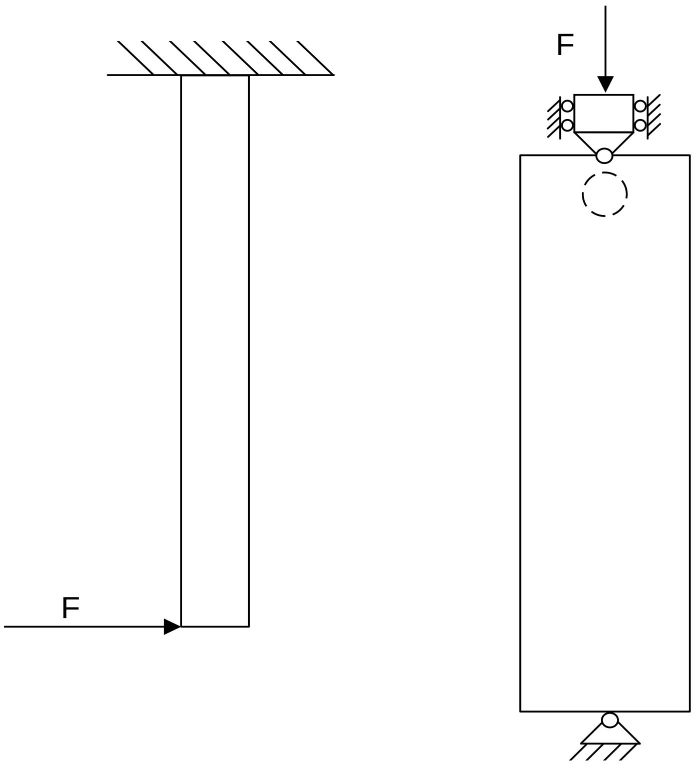


Figure A.4-2: Left: Bending of the leg due to an impact that is not completely perpendicular. Right: Buckling of the leg due to the impact when it hits the ground.

Bending of the legs:

$$t = 10\ mm$$

$$L = 400mm$$

$$j = \frac{1}{12} \cdot b \cdot t^3 = \frac{1}{12} \cdot 0.05 \cdot 0.01^3$$

$$\sigma_{max} = \frac{F \cdot L \cdot t}{2 \cdot j} = \frac{F \cdot 0.4 \cdot 0.01}{\frac{1}{6} \cdot 0.05 \cdot 0.01^3} = 350\ MPa = \sigma_{yield}$$

$$F_{max} = 729.2\ N$$

The maximum force allowed to prevent plastic deformation is $729.2\ N$. This force will never be reached, because it will only be a small part of the gravity force, which is $30\ N$.

Buckling of the legs:

$$F = \frac{\pi^2 \cdot E \cdot j}{(K \cdot L)^2}$$

$$E = 69 \cdot 10^9$$

$$L = 0.4$$

$$j = \frac{1}{12} \cdot b \cdot t^3 = \frac{1}{12} \cdot 0.05 \cdot 0.01^3$$

$$for\ K = 1 \qquad F = 17708.7\ N$$

When buckling will appear, the force applied has to be at least $17.7\ kN$. This means that the construction will never buckle on the impact when it hits the ground, since the applied force is only about $30\ N$.

Torsion in the axle:

Since the stiffness of the axle and the legs is restricted, deformation occurs as a result of the applied torque in the motor.

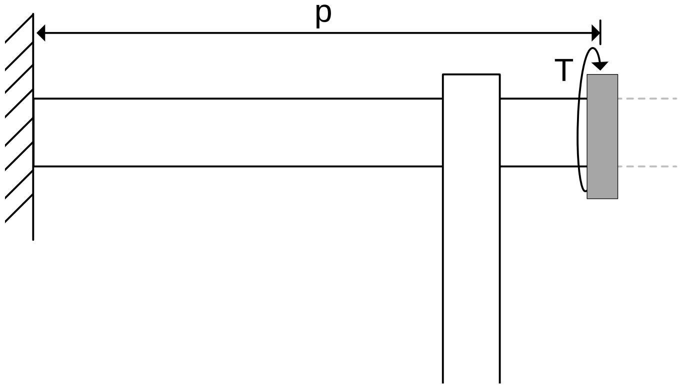


Figure A.3-3: Torsion in the axle due to the applied motor torque.

$$\delta = \frac{L \cdot p \cdot T}{j \cdot G}$$

$$j = \frac{\pi \cdot r^4}{32} = \frac{\pi \cdot 0.01^4}{32}$$

$$G = 79.3 \cdot 10^9$$

$$L = 0.4$$

$$p = 177.45 \cdot 10^{-3}$$

$$T_{max} = 4.5$$

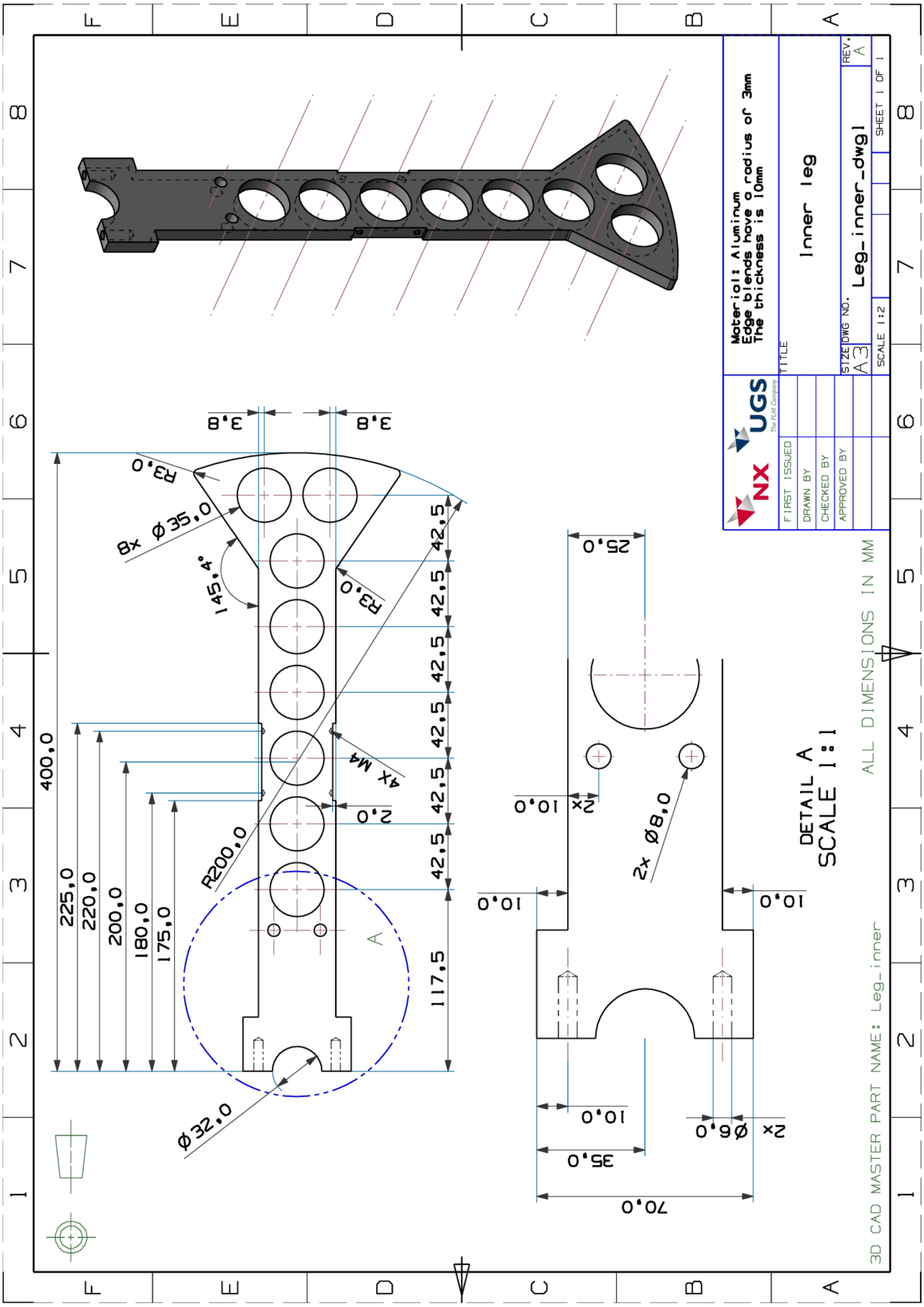
$$\delta = 4.1 \cdot 10^{-3}$$

The displacement at the foot will be very small, so the construction can perform in the way it is designed without too many unexpected deformations. Furthermore, the control system can take care of neutralization of this phenomenon.

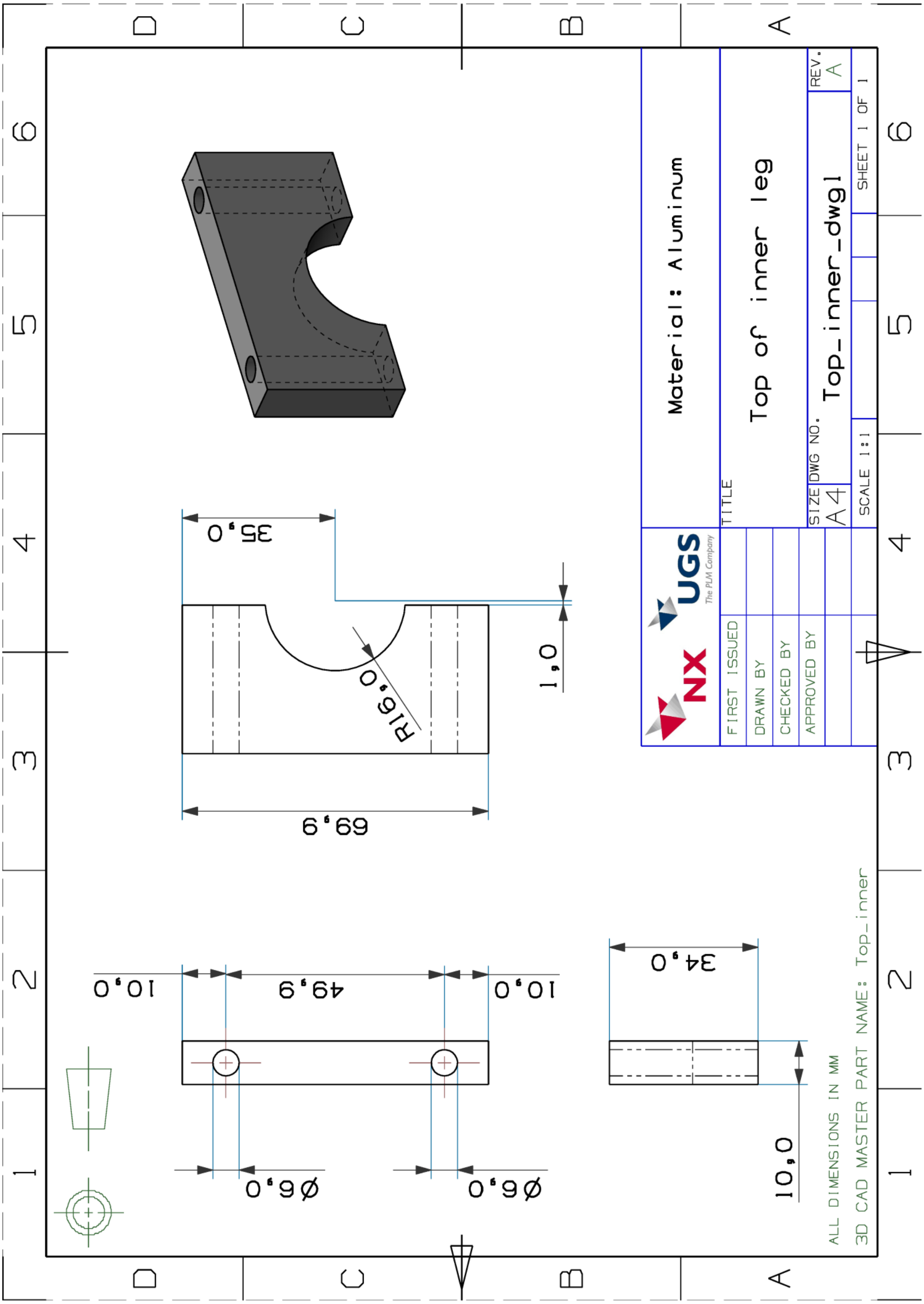
A.5. Technical drawings of the final design

All dimensions of each part of the stickman can be found in the technical drawings enclosed in this appendix.

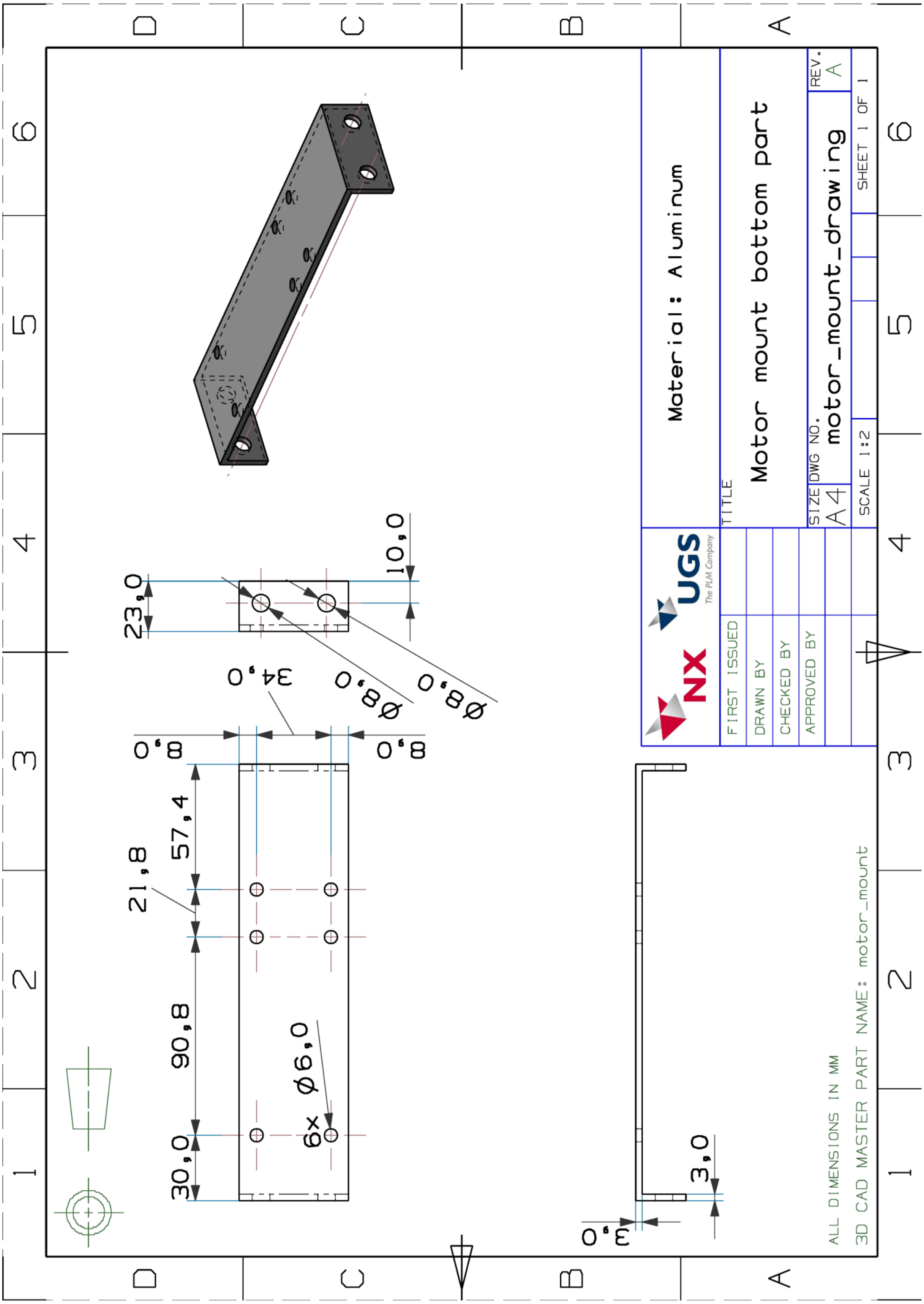
Inner leg



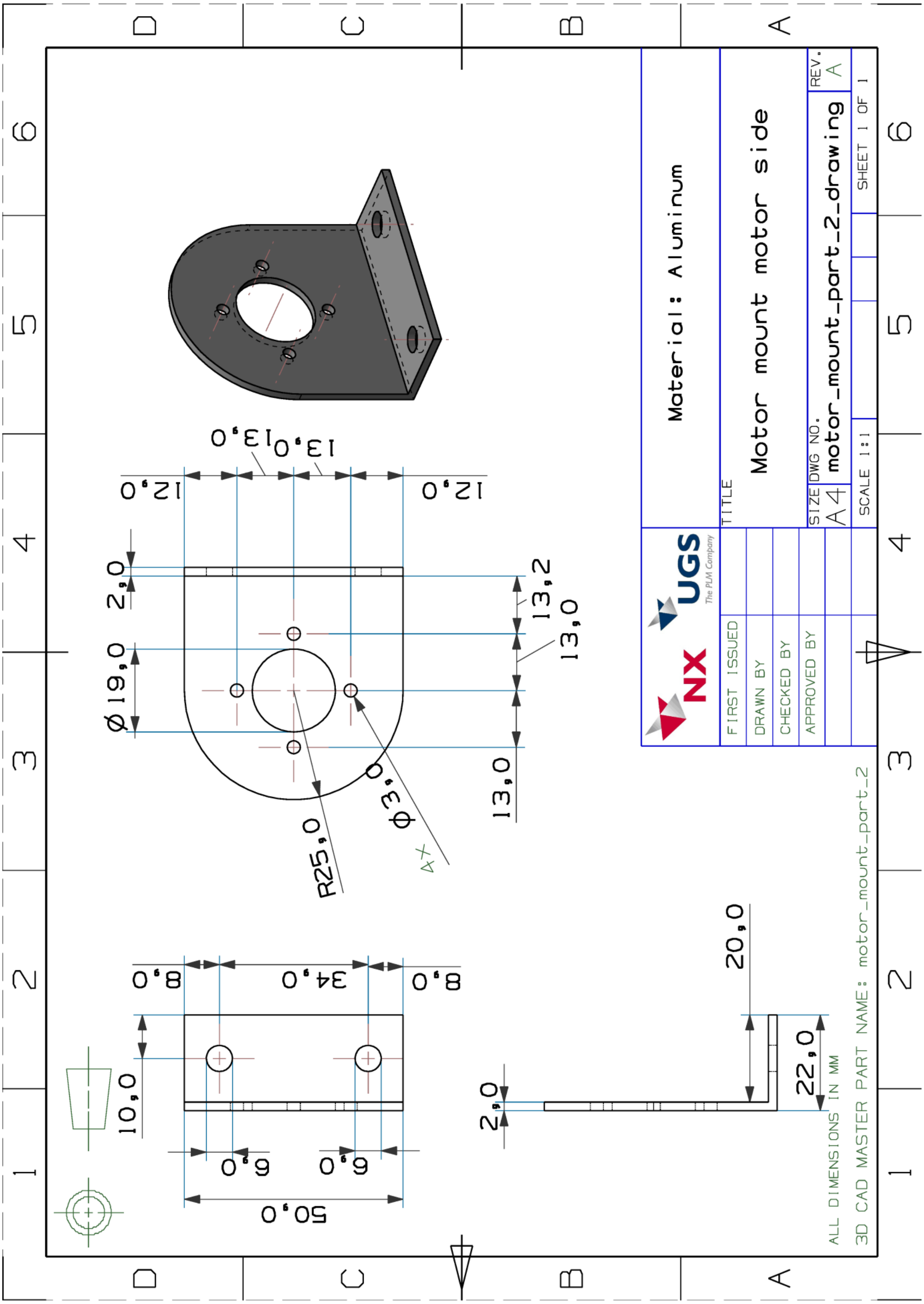
Inner cap


Material: Aluminum
TITLE
Top of inner leg
SIZE
A4
DWG NO.
Top_inner_dwg1
REV.
A
SCALE 1:1
SHEET 1 OF 1
FIRST ISSUED
DRAWN BY
CHECKED BY
APPROVED BY
ALL DIMENSIONS IN MM
3D CAD MASTER PART NAME: Top_inner
35,0
1,0
R16,0
69,9
10,0
49,9
10,0
34,0
Ø6,0
Ø6,0
10,0

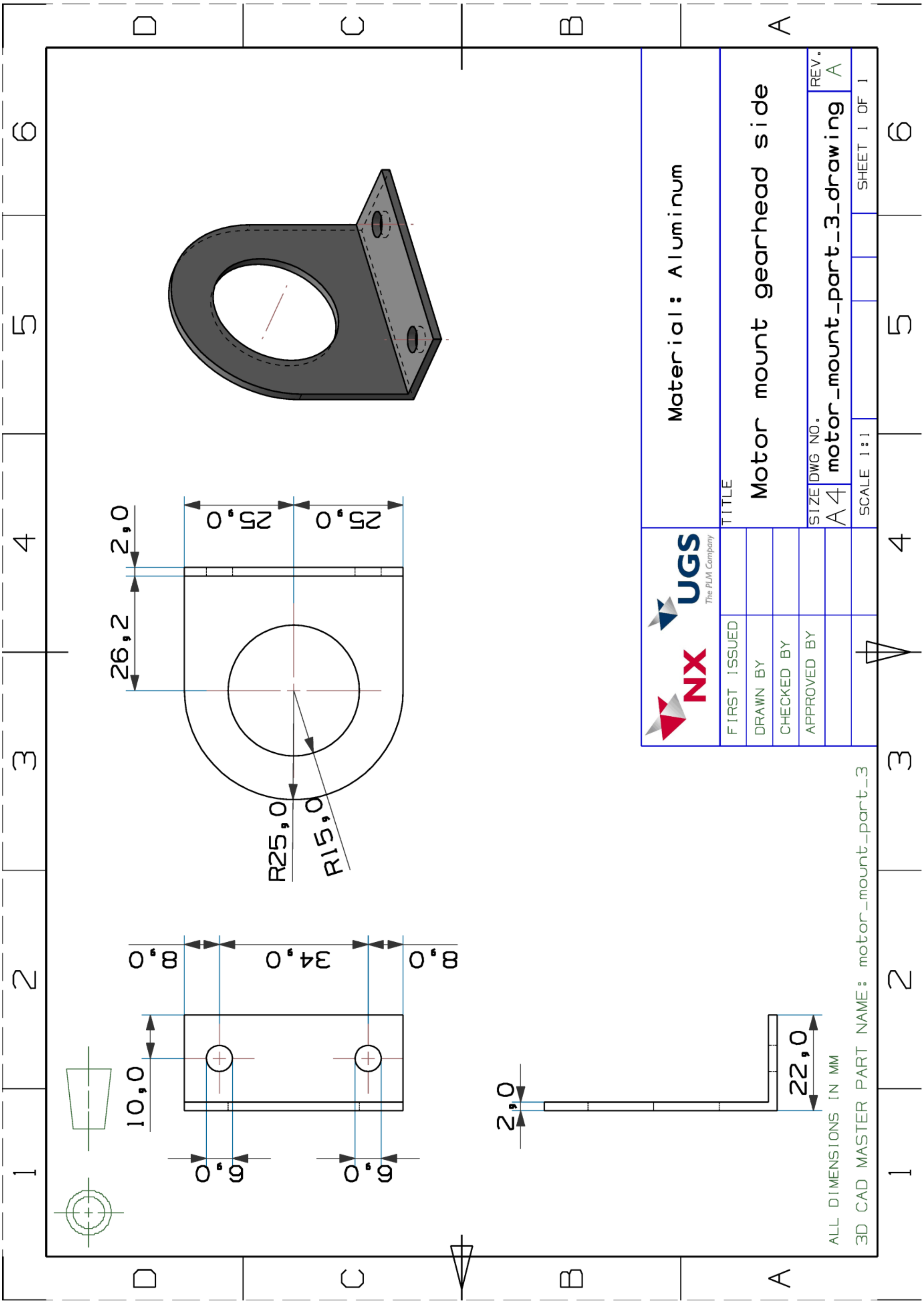
Motor mount


Material: Aluminum
TITLE
Motor mount bottom part
SIZE A4
DWG NO. motor_mount_drawing
REV. A
SCALE 1:2
SHEET 1 OF 1
FIRST ISSUED
DRAWN BY
CHECKED BY
APPROVED BY
NX
UGS
The PLM Company
ALL DIMENSIONS IN MM
3D CAD MASTER PART NAME: motor_mount
23,0
10,0
34,0
Ø8,0
Ø8,0
8,0
8,0
57,4
21,8
90,8
30,0
6x Ø6,0
3,0
3,0

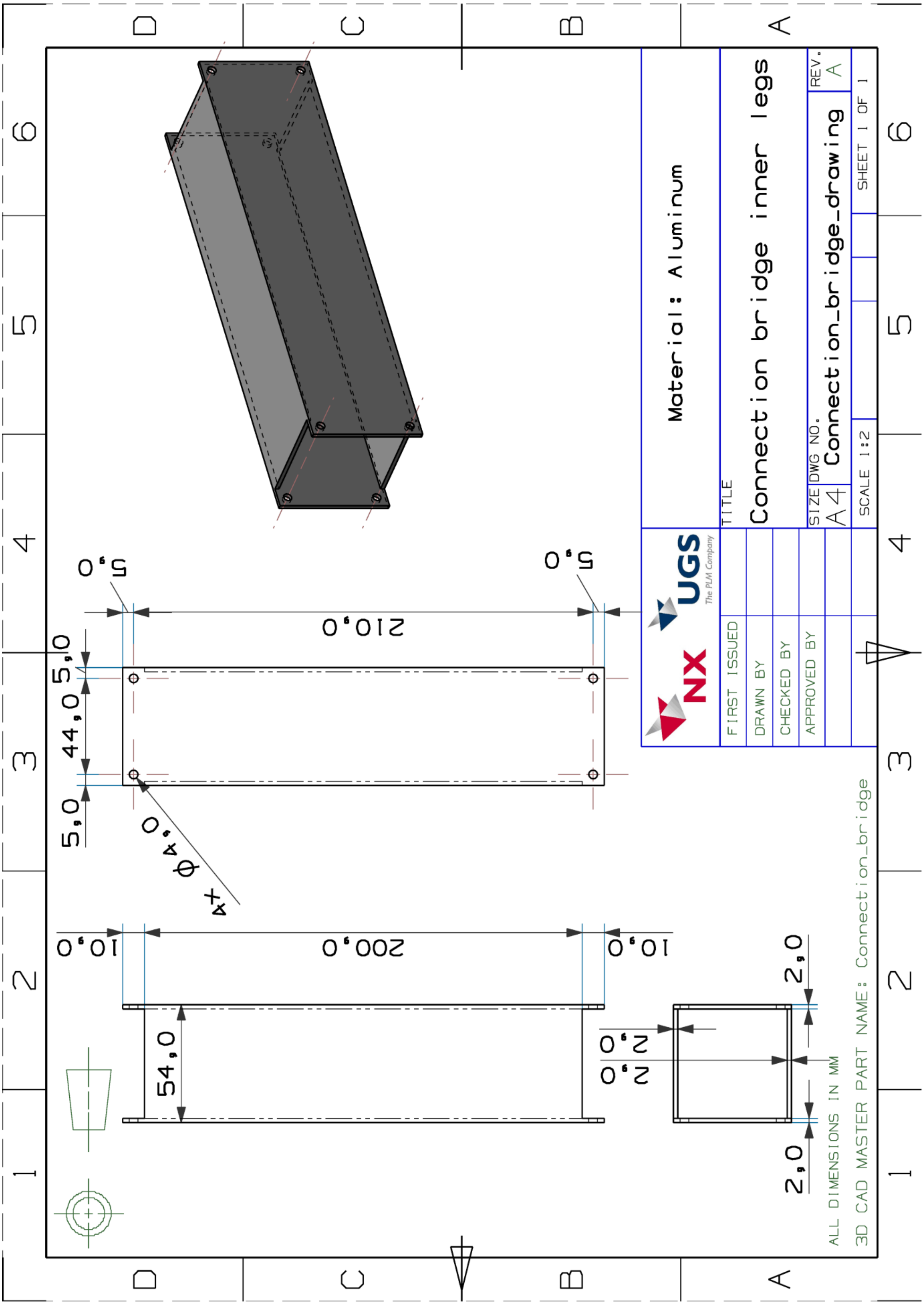
Motor mount plate 1



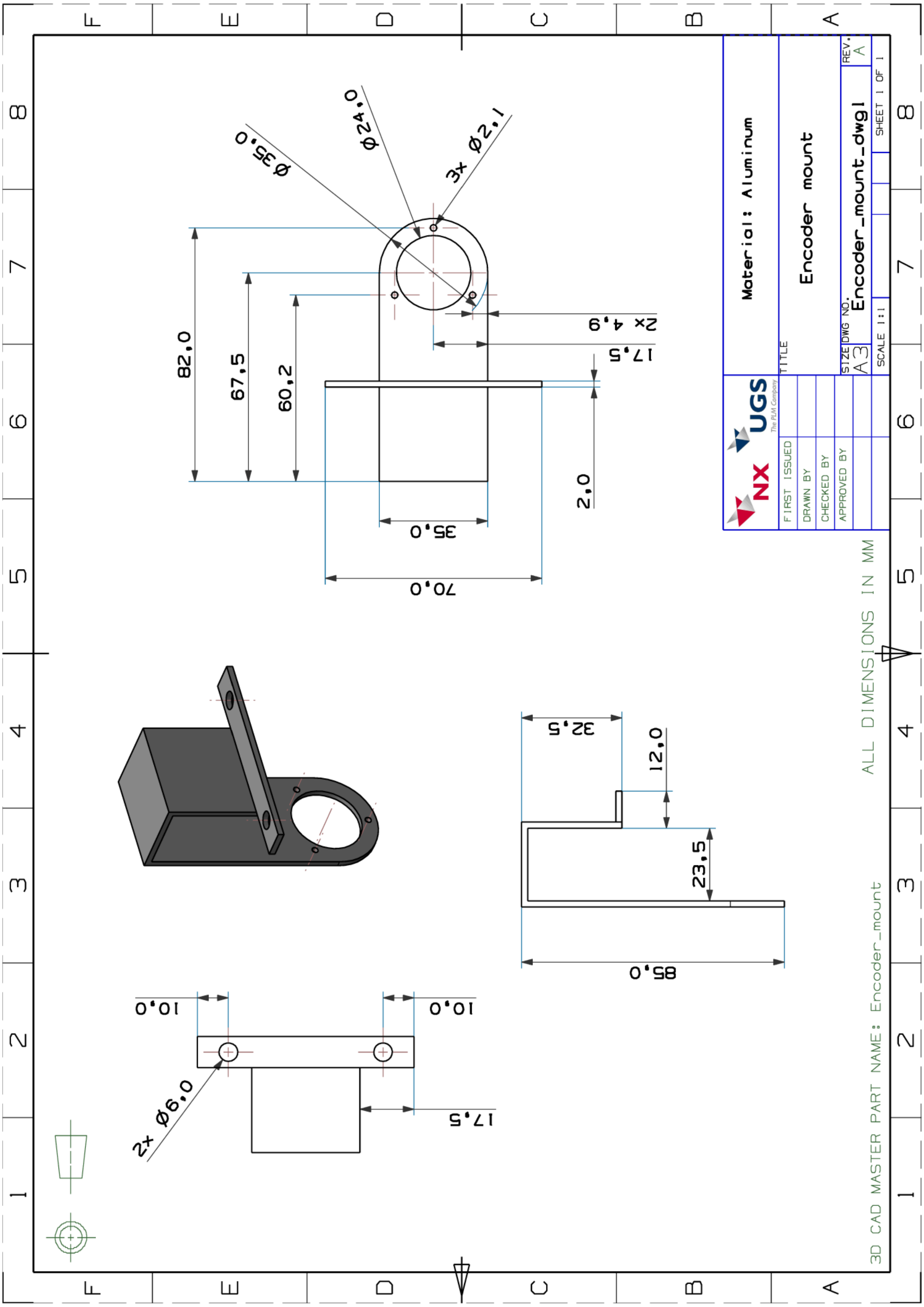
Motor mount plate 2



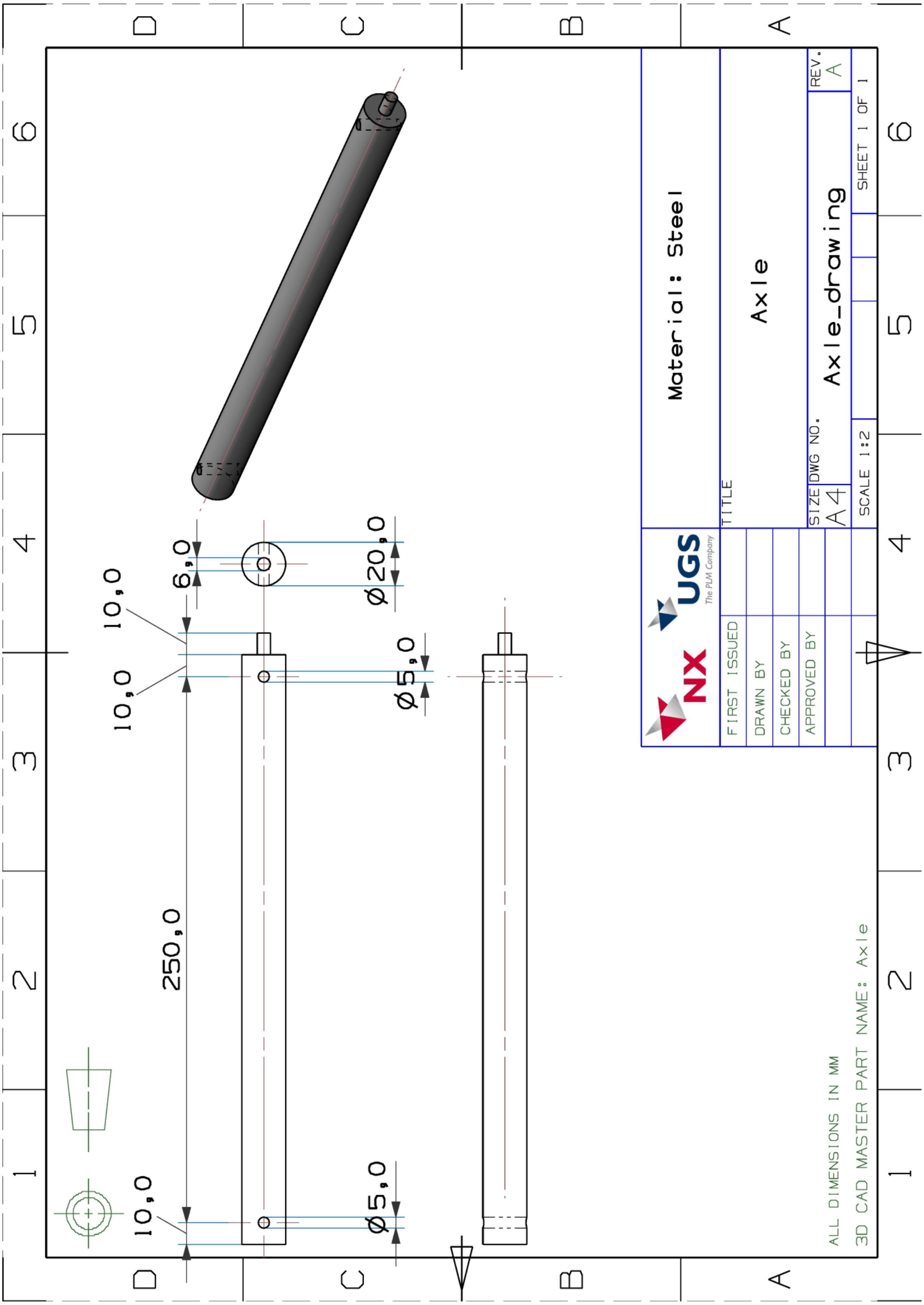
Connection tube



Sensor mount

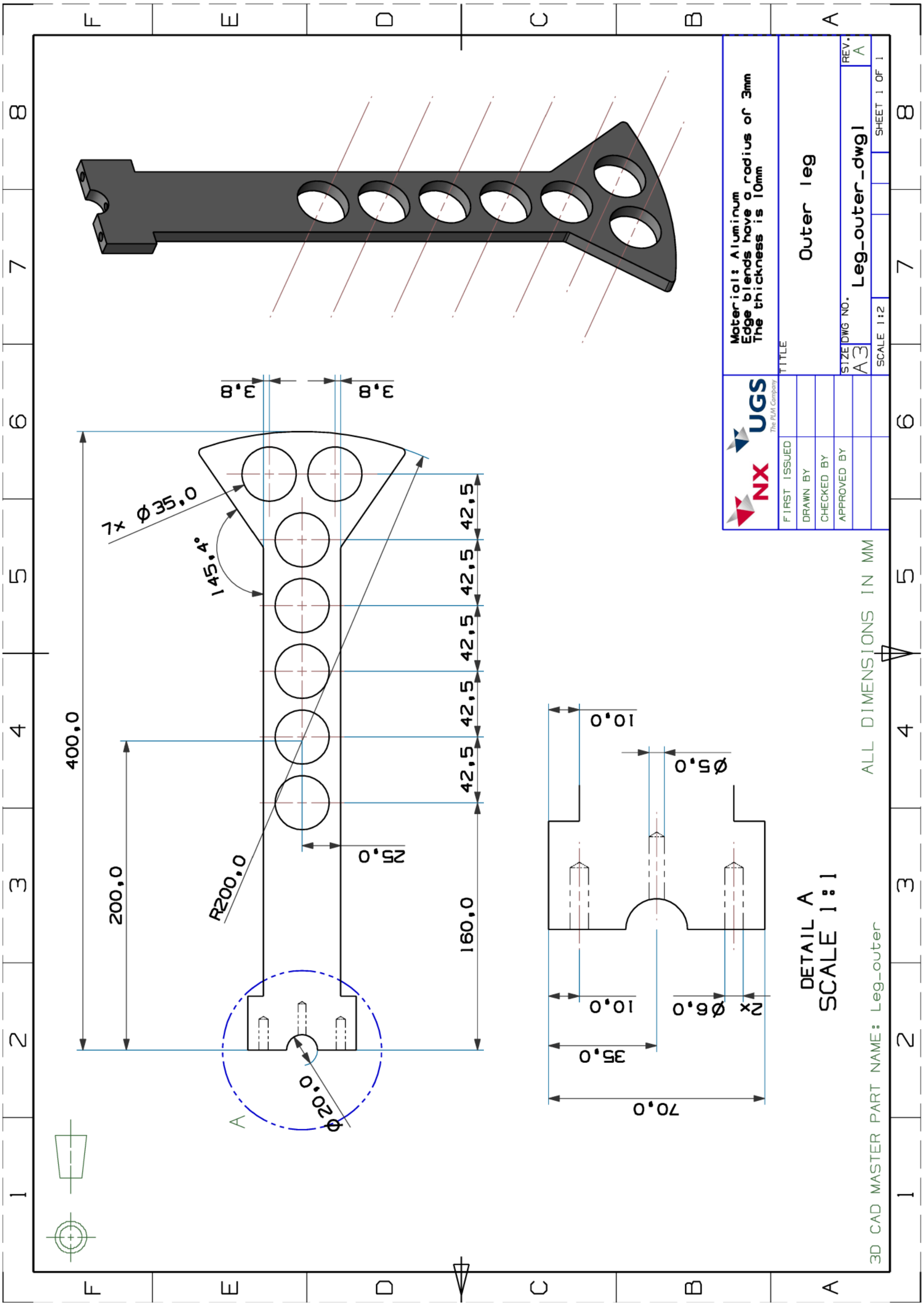


Axle



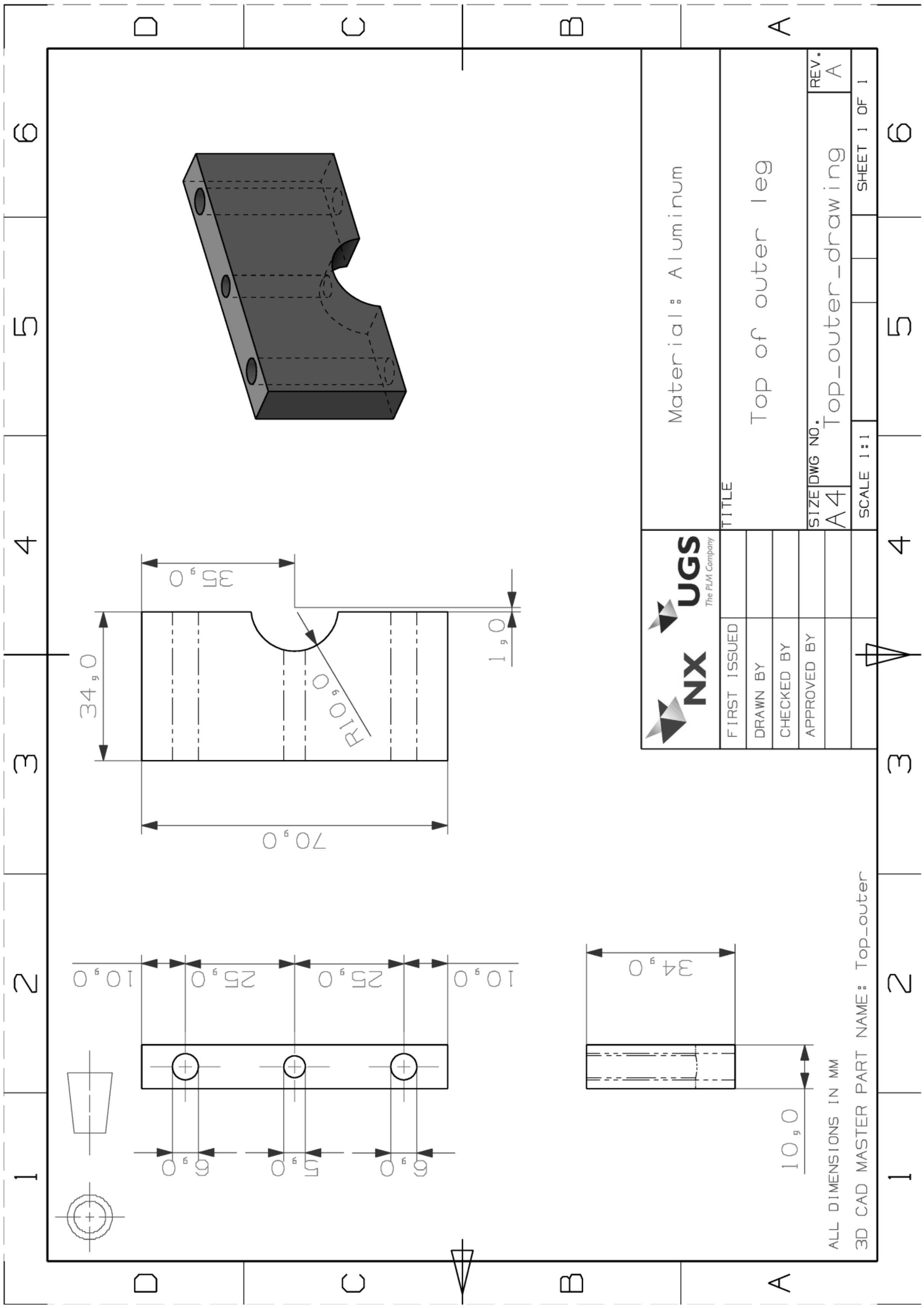
10,0
10,0
6,0
Ø20,0
Ø5,0
250,0
10,0
Ø5,0
Material: Steel
TITLE
Axle
FIRST ISSUED
DRAWN BY
CHECKED BY
APPROVED BY
SIZE
A4
DWG NO.
Axle_drawing
REV.
A
SCALE 1:2
SHEET 1 OF 1
ALL DIMENSIONS IN MM
3D CAD MASTER PART NAME: Axle

Outer leg



Material: Aluminum
Edge blends have a radius of 3mm
The thickness is 10mm
TITLE
Outer leg
FIRST ISSUED
DRAWN BY
CHECKED BY
APPROVED BY
SIZE A3
DWG NO. Leg_outer_dwg1
REV. A
SCALE 1:2
SHEET 1 OF 1
ALL DIMENSIONS IN MM
3D CAD MASTER PART NAME: Leg_outer
DETAIL A
SCALE 1:1
7x Ø35,0
145,4°
R200,0
400,0
200,0
160,0
42,5
25,0
3,8
Ø20,0
10,0
Ø5,0
Ø6,0
2x
35,0
70,0

Outer cap


Material: Aluminum
TITLE
Top of outer leg
SIZE
A4
DWG NO.
Top_outer_drawing
REV.
A
SCALE 1:1
SHEET 1 OF 1
FIRST ISSUED
DRAWN BY
CHECKED BY
APPROVED BY
ALL DIMENSIONS IN MM
3D CAD MASTER PART NAME: Top_outer
35,0
34,0
1,0
R10,0
70,0
10,0
25,0
25,0
10,0
34,0
6,0
5,0
6,0
10,0

A.6. Detailed budget

Part	Type	Manufacturer	Supplier	Article number	Number	Price per piece (excl.)	Price per piece (incl.)	Shipping costs	Subtotal	Delivery time
Material and fabrication					1		€ 750.00		€ 750.00	2 weeks
Cables	few different colors		gamma		3		€ 7.00		€ 21.00	
Encoder (main axle)	SCH24AB-shaft 12 bit (fast mode)	Scancon	Fortop	SCH24AB-shaft	1	€ 365.00	€ 434.35		€ 434.35	4 weeks
Materials for slope and table					1		€ 80.00		€ 80.00	
Motor	RE 30 (60W) 24V	Maxon	Maxonmotors	310007	1		€ 0.00		€ 0.00	8 weeks
Gearhead	Planetary GP32C	Maxon	Maxonmotors	166944	1		€ 0.00		€ 0.00	
Encoder (motor axle)	Encoder HEDS 5540, 500 CPT, 3 Channels	Maxon	Maxonmotors	110515	1		€ 0.00		€ 0.00	
TueDacs					1		€ 0.00		€ 0.00	
Amplifier					1		€ 0.00		€ 0.00	
Total					**11**	**€ 365.00**	**€ 1,191.35**	**€ 0.00**	**€ 1,285.35**	