Building a low-cost ROS-based quadruped SpotMicro robot

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***Abstract*—This research revolves around both an opensource robot design, the SpotMicro as well as Mirte, an open source educational robotics platform. The aim of this research is to design a SpotMicro robot which incorporates Mirte hard- and software with the lowest possible cost. To accomplish this, a theoretical model and simulations of the movements of the robot are made and then evaluated using a real life SpotMicro. The found results are used to determine which components result in the least costing SpotMicro robot with Mirte Hardware. It is determined that incorporating the least costing, working servomotors are the most efficient to decrease cost, since servomotors are not included in standard Mirte Hardware. In order to build the lowest costing SpotMicro Robot with Mirte Hardware the MG996R servomotor is advised.**
***Index Terms*—Robotics, Servomotors, Mirte, SpotMicro, Low-cost Robots**

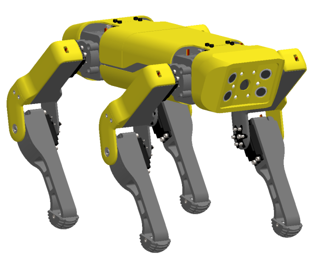

Fig. 1. SpotMicro

I. Introduction

According to 'How robots change the world' by Oxford Economics, Robots could take over 20 million jobs by 2030 [1]. It is no longer a question of if robotics will shape our future, but how much and in what way. This makes teaching young students about robotics all the more important. This research focuses on designing a low-cost educational DIY robot, to make robotics and even quadruped robots accessible for educational institutions.

Mirte was created with the idea that educational robots should be cheap, open source, focus on more than just software, have as few custom parts as possible and should be useful from primary/elementary school all the way to university [2]. The software is a python API for ROS, in order to control robots from Python and therefore also Blockly. This makes robot control accessible for beginner programmers. The Mirte hardware that is used in the Spotmicro robot consists of an OrangePi Zero and an STM32 Microcontroller.

SpotMicro is an opensource robot which takes design elements from the famous spot robot by Boston Dynamics. There are a number of existing designs for the SpotMicro, of which one is picked for this project. Therefore, the design challenge of this project is not in the physical design of the robot but in selecting components to make SpotMicro work with the Mirte hard- and software at the lowest possible price. The research question of this report is: 'What is the lowest possible cost for a SpotMicro Robot with Mirte Hardware?'.

This report will include a presentation of the approach, an explanation of the calculations and simulations that were done, an evaluation of these calculations and simulations with the help of a real life SpotMicro robot, a presentation of the final design and a conclusion.

II. Background

To get a better understanding of the SpotMicro robot at hand, it is vital to elaborate on the landscape of existing quadruped robots. This section will include this elaboration as well as the motivation for choosing SpotMicro.

A. Landscape of existing quadruped robots

An animal or machine that usually maintains a four-legged posture and moves using all four limbs is said to be a quadruped [3], thus a quadruped robot is a robot that moves in this way. Presumably the most recognized quadruped robot is the Spot robot by Boston Dynamics which can be seen in figure 2. This quadruped robot became famous for videos of it struggling while its creators tried to push it out of balance. The Spot robot by Boston Dynamics costs €65.000 [4].
The Open Dynamic Robot Initiative is another quadruped robot made in a collaboration between robotic groups and universities. The robot can be seen in figure 3.
The robot by the Open Dynamic Robot Initiative uses legged locomotion (wheels at contact points with the ground) for moving. This differs from SpotMicro which uses its legs for moving. The Open Dynamic Robot Initiative focuses on building "A low cost and low complexity actuator module using brushless motors that can be used to build different types

Fig. 2. Spot by Boston Dynamics

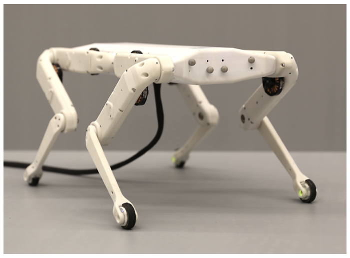

Fig. 3. The robot by the Open Dynamic Robot Initiative

of torque controlled robots with mostly 3D printed and off-the-shelves components". The Open Dynamic Robot Initiative has not presented a price for its robot [5].

A third example of a quadruped robot could be the MIT Mini Cheetah. The Mini Cheetah can be seen in figure 4. The Mini Cheetah is the first quadruped that is able to do a 360 degree backflip. The Cheetah was designed with the aim of a modular, cheap quadruped robot. The Mini Cheetah does not have an official price, but its designers aim to price it around €8.000 [6].

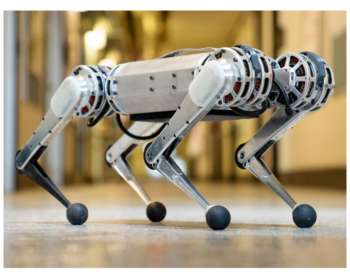

Fig. 4. Mini Cheetah by MIT

An example of a current educational robot which is similar to the SpotMicro is the Freenove Robot Dog Kit that can be seen in figure 5. The Freenove robot dog has a total cost of €170,- [7].

B. Motivation for choosing SpotMicro

The Mirte robotics platform that is used for SpotMicro has the aim to get scholars in the age between 15 and 19 years excited for robotics. Therefore the appearance and familiarity of the robot are important factors. SpotMicro combines a solid, modular design with the looks of a miniature version of Spot. This makes SpotMicro suited to try and build a low-cost

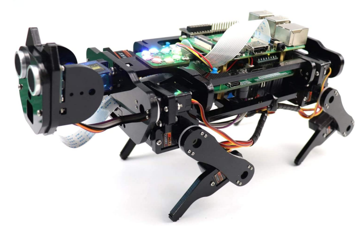

Fig. 5. Robot Dog by Freenove

quadruped robot. The SpotMicro design by Michael Kubina [8], which can be seen in figure 1, will be used in this research, because of the open access to the CAD files of this design, which simplifies customization if required.

III. Theory

In this section the research will be further defined and an overview of the constraints will be given.

This research aims to lower the costs of a quadruped SpotMicro through the implementation of the most economical components that still meet the requirements of a properly working robot.
The component selection is constrained by both the SpotMicro design and the choice for the Mirte robotic platform. The first constraint of choosing Mirte components is that some of the components are pre-selected. The second constraint of choosing Mirte components is that selectable components have to cooperate with the pre-selected components. The SpotMicro design is also a constraint since the space for components is limited, although this limitation can be decreased by customizing the design.

In order to start the component selection process, the aforementioned requirements have to be set. The establishing of these requirements involves calculations and simulations which will be covered in section IV.

IV. Methods

This section will cover an explanation of the methods that were used.

In order to predict the minimal required motor torque, multiple theoretical models will be made. The first model will be a motion study in Solidworks. Next, a dynamical kinematics model will be made with the use of python. From the findings of the theoretical models, a motor selection will be done and implemented in an actual robot. And lastly, in order to validate the models, a video analysis of the motion of the robot will be done with the use of Coach 7 and Python.

A. Motion study

The motion study will be done by modeling the form, material and movements of the parts of the robot. The model is going to be based on the parts that were made by Michael Kubina [8] and completed by modeling all the required hardware for a functional robot. All the parts are going to be coupled to the right materials, in order to provide them with the correct density. Before modeling the movements, the assumption will be made that the peak in required motor torque for basic functionality, will be in standing up. This is assumed because the mass of the robot travels the furthest distance against the direction of gravity while standing up, in comparison to walking or other movements. Therefore, two modes of standing up are going to be simulated and compared. The first being the stretching of all 4 legs at the same time, from now on called simultaneous rise, where the wrists shall rotate by 90 degrees and the elbows by 40 degrees as can be seen in figure 6 or here as a GIF. This movement is going to be made in 0.8 seconds.

Fig. 6. Simultaneous

The second method will make the robot rise by first stretching the rear legs completely before stretching the front legs, which will be called rear first rise from now on and can be seen in figure 7 or here as a GIF. The rear legs stretch in 0.8 seconds and after a delay of 0.2 seconds, the front legs stretch in 0.8 seconds.

Fig. 7. Rear First

The motion study will measure the torque that is provided to make these movements by the motors in the wrists and elbows of the robot. The motors of the shoulders are not going to measured, because the assumption is made that these deliver significantly less to the movement because of the fact that they do not rotate and have an negligibly small moment arm.

B. Dynamical kinematics model

This theoretical model will calculate the required torques based on two components: the force of gravity and the angular momentum of the servo motors. [9]
For this model it will be assumed that the robot has an equal weight distribution and is symmetrical over its longitudinal and transverse axis. Because of this assumption, modelling one robot leg is sufficient, as can be seen in figure 8. The three joints represent the three servo motors (1, 2, 3; wrist, elbow, shoulder, respectively). In this model each joint and link have a defined mass and thus gravity working upon them. The force F is a quarter of the force caused by the weight of the body of the robot. Since each motor has its own angular displacement, all motors have angular speed and angular acceleration. For this model these angular displacements, speeds and accelerations of the motors are simplified, they are assumed to be equal.

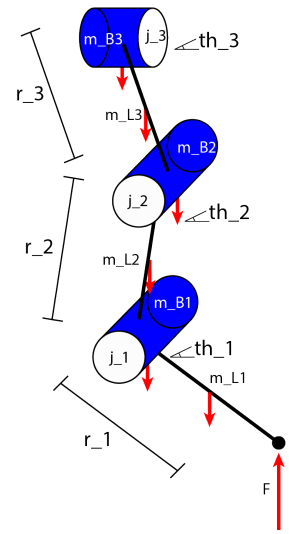

Fig. 8. Cans in series

1) Gravity: The torque T due to gravity will be calculated by equation 1, where r is the moment arm and F the force acting on it.
To calculate the torque requirements for each motor it is necessary to calculate all the joint and links it carries. The first motor carries one link and the force F that is exerted on it, the second carries two links, the first joint and the force F, the third carries three links, two joints and the force F. The torque calculation for the first motor is calculated by equation 2, where g is the gravitational constant $9.81 \frac{m}{s^2}$. Equation 2 is the sum of the moments due to gravity that act upon j_1, because these moments act on an angle the perpendicular distance to j_1 is first calculated.

$$T = r \cdot F \tag{1}$$

$$T_{1g} = cos(th_1) \cdot r_1 \cdot F + \frac{cos(th_1) \cdot r_1 \cdot m_{L1} \cdot g}{2} \tag{2}$$

2) Angular momentum: The torque due to the angular momentum is calculated by equation 3, where I is the moment of inertia of the rigid-body (e.g. joints, links) and α is the angular acceleration.
To calculate the torque requirements for each motor it is necessary to calculate the angular momentum for every rigid body the motor carries, section IV-B1 covers which motor carries what. The torque calculation due to angular acceleration for the first motor is calculated by equation 4.

$$T = I \cdot \alpha \tag{3}$$

$$T_{1a} = \alpha \cdot m_{tot} \cdot (cos(th_1) \cdot r_1)^2 + \frac{\alpha \cdot m_L 1 \cdot (cos(th_1) \cdot r_1)^2}{3} \tag{4}$$

The total torque T_tot requirement per motor is then given by 5, where T_g is the torque by gravity and T_a the torque due to angular momentum.

$$T_{tot} = T_g + T_a \tag{5}$$

The model will be used to simulate the movement of the robot leg, once the movement is simulated the model will calculate the required torque for each servomotor in that position.

Once the highest possible torque is calculated, this data together with the speed at which the robot stands up, retrieved from section IV-A, can be used to define the ideal motor required for the movement. A motor can easily be selected when torque is plotted against motor RPM (rotations per minutes).

C. Validation

After all theoretical models are made, a real robot will be built in order to examine the predictions of the models and their correctness. By building the robot, both the motion study as the dynamical kinematics model can be tested; whether or not their predictions were accurate, were the design choices good enough and do the components meet the actual requirements? Once the robot is working, it's movements will be analysed. This will be done in different ways: First, the robot will be programmed to make the simulated movements in real life. If the robot is capable to make these movements, a video analysis will be done; the time it takes to stand up, the actual angular acceleration of the motors, whether or not the method of standing up is ideal. This will provide a conclusive answer to what the required motor torque is and if these are the cheapest motors that are up for the task.

V. Results

In this section the results of the simulations and calculations are presented and explained, along with a presentation of the final design, overview of costs and validation of the results.

A. Results motion study

The Solidworks model of all the parts resulted in a robot with a mass of 2157 grams. From the motion study of the simultaneous rise, the highest witnessed peak in motor torque was 732 N·mm and was located at the motors of the front wrists as can be seen figure 9. The motor torque in the elbows during the simultaneous rise can be seen in figure 10.
During the motion study of the rear first rise, the highest witnessed peak in motor torque was 702 N·mm and located in the motors of the rear wrists and can be seen in figure 11. The motor torque in the elbows during the rear first rise can be seen in figure 12.

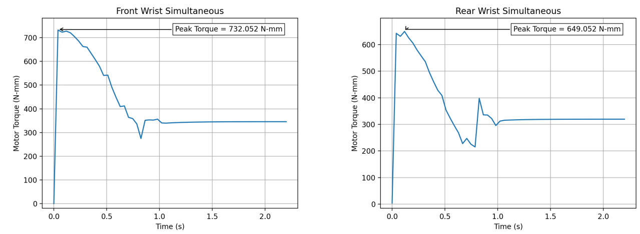

Fig. 9. Simultaneous rise wrists

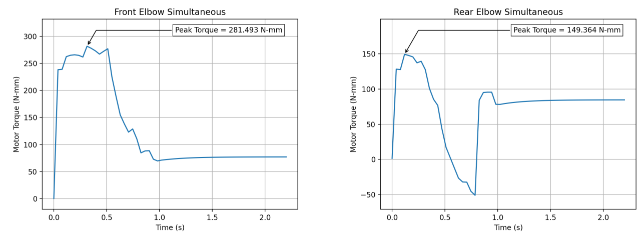

Fig. 10. Simultaneous rise elbows

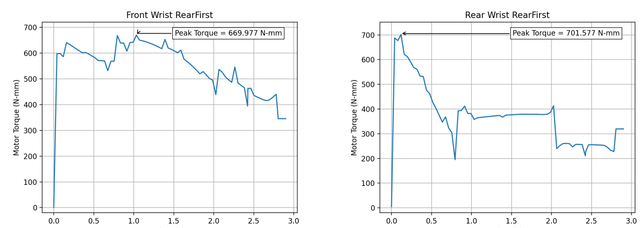

Fig. 11. Rear first rise wrists

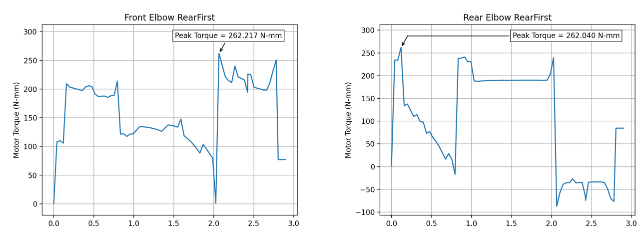

Fig. 12. Rear first rise elbows

TABLE I
PEAK TORQUE MEASURED

Mode of standing up	Measured Torque [N·mm]	Location
Simultaneous rise	732	Front wrists
Rear first rise	702	Rear wrists

From this motion study, it becomes clear that standing up with rear legs first is superior to simultaneously with all four legs. It also predicts that the minimal amount of torque that is required for the motors to make the robot stand up will be 702 N·mm. This can be seen in table I.

B. Results dynamical simulations

The model discussed in section IV-B, simulates the movement of the servomotors, it outputs the velocity and acceleration of the servomotors at their respective position and thus gives an insight in the requirements the motors are subject to. The servomotors in the design of this robot have an operating range, described in table II, it should be noted that j_3 does not have a range. j_3 is the shoulder of the robot leg, and for the simple gait movements that are analysed in this paper, the shoulder of the robot leg does not change position and thus has no range. The output of the model with this given range can be seen in figure 13.

TABLE II
MOTOR ANGLES

motor	angle (rad)
j_1	π - 1.92
j_2	0 - 1.22
j_3	$\pi/2$

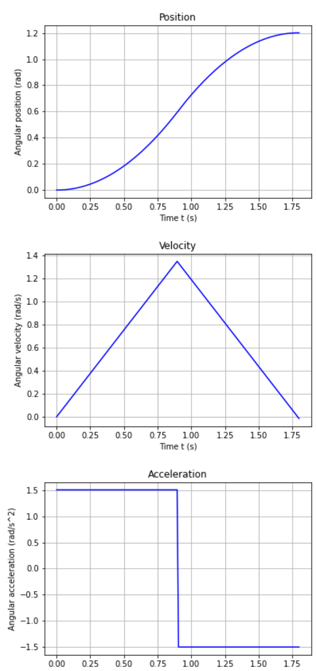

Fig. 13. Angular position, velocity and acceleration of servomotors

The forces acting in these servomotors can be seen in figure 14, where j_1, j_2, j_3, are servomotors one, two and three respectively. The absolute maximum torque the robot leg could achieve would be when stretched completely and every angle with respect to a horizontal line in figure 8 would be maximized, however this is not a realistic position for the robot leg since the motor angles have constraints and only have to operate in a range seen in table II. With these constraints the maximum absolute torque required by one of all the three servomotors is 265 N·mm for j_1 at 1.92 rad, this is when the wrist is stretched.

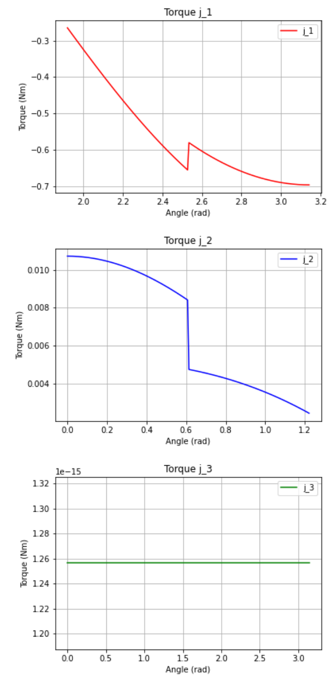

Fig. 14. Torque requirements for j_1, j_2 and j_3

Now that the highest possible torque is defined, the speed at which the motor stands up can be used to define the maximum RPM. In figure 13 it can be seen that the maximum angular velocity ω_{max} and thus the maximum RPM is achieved halfway through the movement at 0.9 s. The RPM can be calculated using equation 6 - 9. The maximum RPM the servomotors are subjected to is 12.96 RPM.

$$\omega_{max} = \frac{\text{total angle}}{0.5 \cdot \text{total time movement}} \tag{6}$$

$$\omega_{max} = \frac{1.22}{0.5 \cdot 1.8} = 1.356 \; \frac{rad}{s} \tag{7}$$

$$\text{RPM} = \frac{60 \cdot \omega_{max}}{2 \cdot \pi} \tag{8}$$

$$\text{RPM} = \frac{60 \cdot 1.356}{2 \cdot \pi} = 12.96 \tag{9}$$

Figure 15 plots these motor requirement: highest torque requirement, also known as stall torque and maximum RPM. Now, adequate motors can be selected. Figure 15 also plots motor characteristics of different motors. The figure only shows relevant motors, more were considered but did not fulfil the requirements. In the plot three motors can be seen, the DS3218 which outperforms the rest, the MG996R which is closer to our requirements and the CS-239MG which seems to suit the requirements ideally. The motor characteristics are plotted with their highest and lowest operating voltage to see how this influences performance. The lower voltage limit of the CS-239MG motor was not plotted because this did not meet the requirements.

The aim of this research is to optimize the cost of the robot, not to find the motor that suits the requirements best. In this case the traits do not have linear proportional relationship; the CS-239MG is much more expensive than the MG996R and the DS3218, thus leaving the latter two as viable options. The costs can be found in table III.

TABLE III
PRICES AND STALL TORQUES OF SERVOMOTORS

Type	Price	Stall Torque [N·mm]
DS3218	€9.55 [10]	1961
MG996R	€0.95 [11]	1275
CS-239MG	€8.16 [12]	460

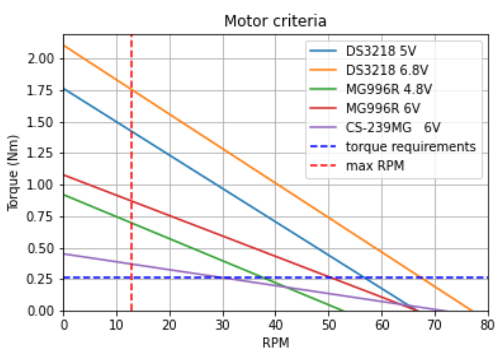

Fig. 15. Motor characteristics

C. Final Design

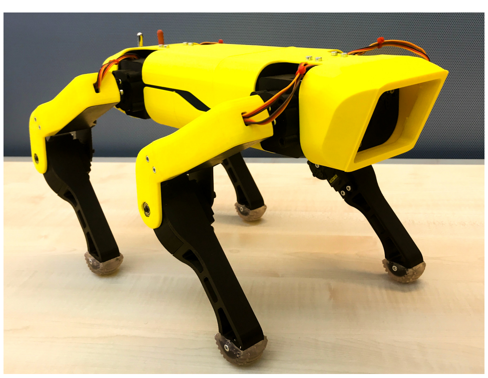

Fig. 16. Final design

Both the DS3218 and MG996R are suitable motors for the robot. The choice was made two build two robots with different motors to compare performances. The stall torque of both of these servomotors can be seen in table III. The MG996R servomotor operates in a range from 4.8 V to 7.2 V [11] and is also the least expensive servomotor within the validated possible servomotors.
Aside from the motors, the robots shared most of the other hardware. A lithium polymer battery, an OrangePi Zero, an STM32 Microcontroller, a 5 V step down converter and a screw terminal to divide the current to all the servo motors. A custom circuit board mounting plate was designed to house all these parts, as can be seen in figure 17.

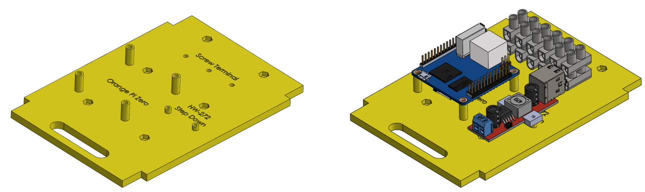

Fig. 17. Circuit board mounting plate

All the parts were 3D printed with PLA and connected to each other with galvanized steel nuts and bolts. The total mass of the robot was measured at 2180 grams, which is 1.07% off from the SolidWorks model.

D. Costs

It can be concluded from the results that the least expensive servomotor, the MG996R Hi-Speed still delivers a sufficiently high torque for the SpotMicro to work. With this determination, an overview of the costs can be made. An overview of all individual costs as well as the total cost of the robot can be seen in table IV. The total cost of the SpotMicro robot is €134.88. The same robot with the DS3218 servomotors would cost €238.08, an increase of 77%.

TABLE IV
COSTS OVERVIEW

Component	Unit Price	Quantity	Price
MG996R servomotor	€0.95	12	€11.40
Orange Pi Zero	€18.30	1	€18.30
STM32 Microcontroller	€3.28	1	€3.28
Micro SD Card	€1.52	1	€1.52
PLA for 3D print design	€18.00 (€/kg)	1 kg	€18.00
Terminal blocks	€0.75	2	€1.50
USB step down converter	€0.79	1	€0.79
LiPo battery pack	€28.50	1	€28.50
XT60 cable	€6.60	1	€6.60
Pack of jumper cables	€1.79	1	€1.79
$4mm^2$ Electrical cable	€0.86 (€/m)	0.30 m	€0.26
Toggle switch	€2.13	2	€4.26
M3 nuts	€1.35 (250 pcs)	1	€1.35
M2 nuts	€1.35 (250 pcs)	1	€1.35
M3x8 bolts	€2.05 (50 pcs)	2	€4.10
M3x20 bolts	€2.95 (50 pcs)	2	€5.90
M2x8 bolts	€2.75 (50 pcs)	2	€5.50
Ball bearing	€2.65	8	€20.48
Total			€134.88

E. Validation

In this section, the real world performance of the robot is quantified in order to compare it to the theoretical models.

1) Video analysis: A video analysis of the motion of the robot was made to validate the theoretical models and to find a conclusive answer to what the real torque is that is required to stand up. The validation is performed on the robot built with the MG996R servo motors.

Coach 7 was used to map out the x and y coordinates of the foot tip, wrist and elbow of the rear and front leg of the robot, a snapshot of this process can be seen in figure 18. These coordinates are then imported in a python script that map out the real angular position, velocity and acceleration of the servomotors. These real coordinates are then used to simulate the movement based on the real movements of the robot, which can be seen in figure 19 or in GIF format here. It should be noted that because it is still assumed that the robot is symmetric over its longitudinal axis, a profile of the robot is taken. In the calculations the rear of the robot will be referred to as the "left side" and the front as the "right side".

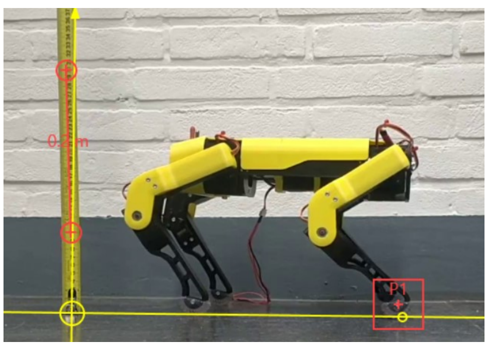

Fig. 18. Coach 7 video analysis

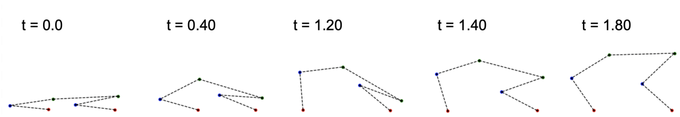

Fig. 19. Data points Coach7 simulated in Python

After simulating the movement, position, velocity and acceleration of the servomotors can be determined, this can be seen in figure 20 - 22. The position being derived from the coordinates, the velocity is the derivative of the position and the acceleration is the derivative of the velocity. Once the acceleration is known, the position, acceleration and total time of the movement can be used as inputs for the dynamical kinematic model described in IV-B. This simulation outputs the realistic torques at every angle, this can be seen in figure 23. The maximum output is now 2.47 $N \cdot m$.

First of all, it should be noted that the magnitude of these results are not in line with the theoretical dynamical kinematic model and not in line with the motion study. There are a couple of reasons causing this discrepancy. As can be seen in figure 23, the beginning and end of the simulation have a lot of noise, this is caused by the inaccurate translation of the video analysis to the coordinates. These errors from the inaccurate positions are increased when derived to velocity and acceleration. This can be seen in figure 22 where a certain angular acceleration of the servomotors would be 100 $\frac{rad}{s^2}$. Due to this inaccurate acceleration the maximum torque is also inaccurate, a torque of 2.47 $N{\cdot}m$ is not realistic since the MG996R have maximum stall torque of $\pm$ 1 $N \cdot m$.

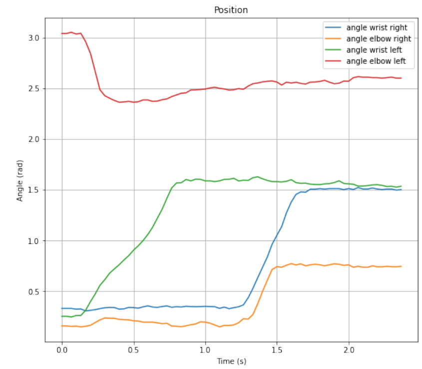

Fig. 20. Position

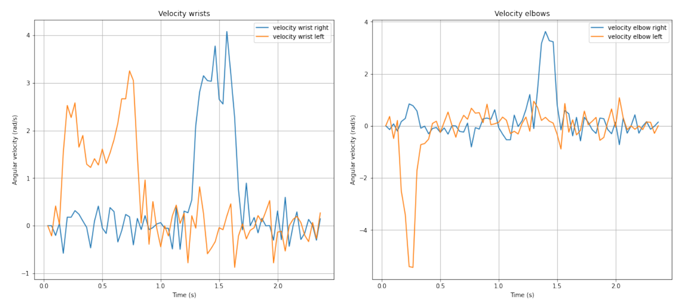

Fig. 21. Velocity wrists and elbows

However, the course of torque with respect to the position in figure 23 does match the course of figure 14, these are graphs that both describe the torque with respect to the position of the servomotor of j_1. Also, it should be noted that the peak values of figure 21 are realistic, the negative values represent

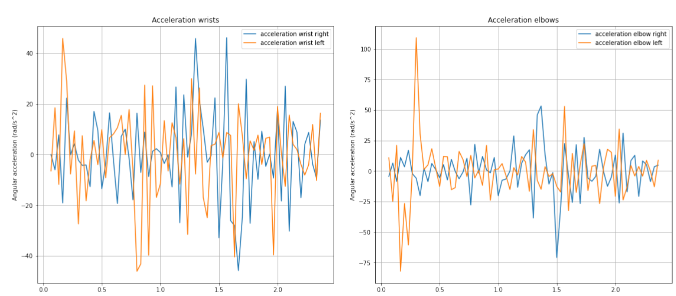

Fig. 22. Acceleration wrists and elbows

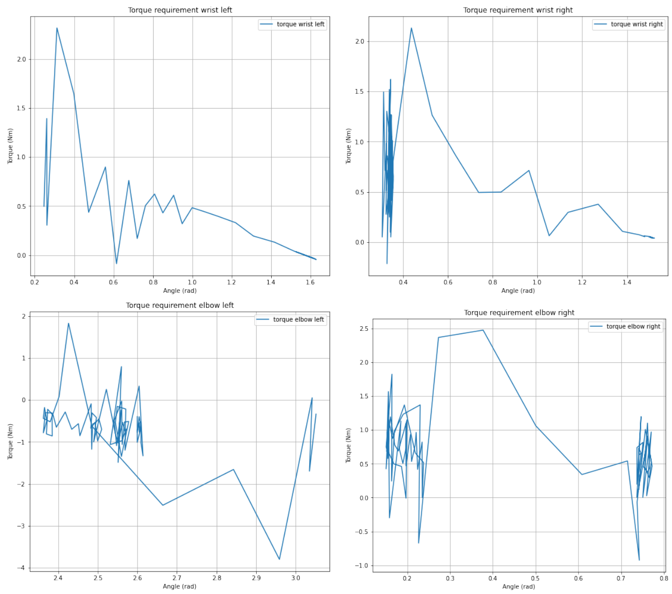

Fig. 23. Torque requirements wrists and elbows

a movement in the opposite direction.

2) Discrepancies motion study and dynamical kinematic model validation: The motion study gives a maximal torque 702 $N \cdot mm$ and the dynamical kinematic model gives a maximal torque of 265 $N \cdot mm$. This difference can be explained because both systems use other assumptions and take into account different variables.

The motion study done by Solidworks takes into account the friction between legs and the ground, the dynamical kinematic model does not.

The motion study done by Solidworks takes into account that the center of mass constantly changes and thus the robot is not symmetrical over its longitudinal and transverse axis, the dynamical kinematic model does not take into account this moving center of gravity.

The motion study done by Solidworks allocates a different density for every material, the dynamical kinematic model does not.

VI. Discussion

In this section a discussion of the research will be presented.

This research has right to exist as robotics is an increasingly vital part of our future, with that comes an increased demand for educative tools on the subject of robotics, like educational robots. The Freenove Robot Dog Kit that can be seen in figure 5 has a total cost of €170.-, including a separate battery and Raspberry Pi, on top of this, the Freenove Robot Dog is build using custom made, laser cut body parts. The SpotMicro with Mirte hard- and software is less expensive at €134.88 and only has body parts that can be made with a 3D printer.

Another benefit of the SpotMicro is that its design is appealing. The SpotMicro has a lot of similarities with the Spot by Boston Dynamics, which can be seen in figure 2 in section II. Therefore, the SpotMicro robot benefits from the publicity of the Spot by Boston Dynamics.

This research proves that designing a low-cost quadruped robot that captures the imagination is possible. These findings contribute to the possibilities for implementing robotics in education.

A. Limitations of research

The generalizability of this research is limited by multiple factors. The first and simplest factor are the external resources needed for this robotic project. External resources like computers, tools but also the difference in availability and price of components reduces the generalizability. Furthermore, the generalizability is limited by the set goals. The robot in this research has to stand-up. If a robot is to be designed that has to be able to accomplish more than these set goals, the findings in this research may not be applicable.

VII. Conclusion

The results of the research indicate that it is possible to design and build a low-cost quadruped Spot Micro robot. The lowest possible cost for a quadruped SpotMicro robot which incorporates Mirte hard- and software is €134.88. With this price, the robot is cheaper than readily available counterparts.

A. Advice for future research

Future research could benefit from an analysis of the center of mass of the robot. In the theoretical python model it is assumed that the robot is symmetrical and has its center of mass in the middle of its midsection. Since the results of the theoretical model are compared to a real life robot this is acceptable, but a future research could improve its theoretical model by implementing the exact center of mass. A future research could also implement a complex multi body model which increases the accuracy over using a simple multi body model.

Another point that could be tackled in future research could be to re-evaluate some the assumptions that were made in regards to the movements of the robot. It is entirely possible that some types of moments, that were not simulated nor tested during this study, could result in a requirement of more torque delivered by the motors. This also implies that there also might be methods of standing up that could require less torque than the ones that were tested in this paper. Furthermore, in line with the statement that the generalizability is limited by the set goals, there could be a re-evaluation of the requirements of movements of the robot. Less expensive motors might also suffice, in case the robot would start from a position where for example the legs are stretched, prior to it's placement on a surface.

The problems encountered in the validation of the theoretical models could be remedied by using a camera with a better resolution, using better "following points" such that the tracking software can better track the given points and less post-processing should be done by hand and most important:

repeating the experiment multiple times, the plots from section V-E are made after a single run.

It would be interesting to measure the complete voltage and currents of the finished motor to then backwards calculate the total required power and thus the total required torque for the motor. This would be the most accurate analysis of calculating required power and therefore torque of a given motor selection.

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For all the code, animations and further reading visit our GitHub: https://github.com/DennizGoren/SpotMicro