Modeling and simulation of a parallel quadruped robot

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***Abstract*—This paper's focus is on quadruped robot design and kinematics. First, an overall idea is presented focusing on other existing solutions. Next, a custom brushless controller is introduced and a combination of a motor with custom cycloidal gearbox. The idea of actuating the robot's limbs by rods is presented. Forward and inverse kinematics is described as well as different ways of saving the energy in walking robots. In the end, the simulation of the dynamic model is presented in a V-rep program in order to test the position and Euler angles regarding the position of the quadruped's body.**

Keywords*—*quadruped robot, kinematic model, brushless, simulation

I. INTRODUCTION

Quadruped robots are walking machines able to move in areas frequently unavailable for wheeled vehicles. This feature is mostly desired by companies inspecting areas hazardous for humans or military.

Similarly to animals, they maintain good stability in rough terrain and overcome terrain obstacles [1]. Autonomous robots require advanced control including vision system, LIDARs and other systems basing on visual experiences. This makes the quadruped robots expensive and rarely used in practice, though they are still being discovered in order to get the best power efficiency, high power and longer work time. One of the most challenging tasks is programming the gait [2]. Walking is a very challenging task, especially when it comes to uneven terrain with obstacles on the path. Advanced machines are able to keep the dynamic stability which is considered to be the most efficient way of locomotion, though the most complex to adapt in a robot. Robots able to keep that stability sometimes are adapted to transfer the kinetic energy from segments of gait when the work is done on the system and charge batteries using that energy.

The other idea is to use parallel springs offloading the actuators during stance. All these techniques allow to longer the work time, however usually result in greater complexity of the robot. In this article, a simplified model of a paralleled leg configuration quadruped will be presented based on custom brushless dc motors controllers. Brushless motors are an excellent trade-off between available power and mass making them the right choice for walking robots. Basing on the 3D model forward and inverse kinematics [3] equations are derived using analytical approach [4]. In order to test the construction and approximate maximum load of the robot v-rep simulation is introduced [5]. In the simulation simplified rigid bodies are used for faster dynamic computations.

II. MOTORS AND CUSTOM BRUSHLESS CONTROLLERS

Quadruped robot presented in this article uses custom BLDC motors. This approach was chosen due to great parameters of these motors – high torque and relatively low mass compared to available power. Brushless motors with a gearbox seem to be used in all of the advanced constructions – Boston Dynamics' spot mini [6], Laikago from UNITREE [7] or MIT's cheetah [8].

There are a few approaches in the ways of connecting the motor to the limb. Motor's direct connection with the effector, called "direct drive" is used for instance in the Minitaur robot [9]. It's the most significant advantage is the agility, due to high angular velocities it can reach. Direct limb connection with the motor effects in the accurate proprioceptive technique of ground collision detection. This technique is based on torque measuring (and therefore the force acting on the effector) and is considered the most accurate when adapted in systems below 5:1 gearbox ratio.

Systems requiring high torques use higher ratio gearboxes. The proprioceptive method can sometimes mislead the controller as the force read on the motor may not come from the impact with the ground though robots with high ratio gearboxes can carry heavier loads which is inevitable in some fields of interest.

Considering all the pros and cons of constructions as mentioned earlier, it was decided to use a fusion of a 250W BLDC motor with a 22:1 cycloidal gear. The motor is 41mm in diameter and is an outrunner, meaning the rotor is on the outside of the coils. Outrunners are able to produce more torque than innruners, are much lighter and cheaper. Moreover, they usually have a lower profile (meaning the height) therefore they are easier to implement in this solution. A safe current limit of 2A was set in order not to overheat the motor. With this current and at stall the motor is able to produce about 1,4 kg/cm of torque.

Cycloidal gear was introduced (Fig.1.) as it can reach high ratios in a low-pitched case, is not self-locking, and is cheaper to build than planetary gear. The main disadvantage of this type of gearbox is higher friction due to several components rubbing against each other. Where it is possible, the gearbox is equipped with bearings minimizing the friction. The output of the gearbox is the outside ring with metal rods, which in most implementations is fixed. In this robot's case, the inside rods are connected with both motors' mountings and fixed to the torso. This configuration allows placing pulley rods directly on the output of the gearbox.

Control board (Fig.2) lies above each motor's rotor and consists of an STM32f405RGT6 32-bit microcontroller (1),

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three N-channel double MOSFETs (2), MOSFET driver (3), a built-in encoder (4), CAN controller (5) and LDO converter (6). The algorithm implemented on the microcontroller is SVPWM. Used in the BLDC controller has several advantages – better DC bus utilization than simple sine PWM control, lower total harmonic distortion and higher torque available. It allows controlling the currents in both q and d axis. Motors presented in this paper are permanent magnet so the d component is set to 0 in order to use all the current to produce torque. Current controller is fed with the position of the rotor which is obtained from the on-board absolute encoder (4). Another source of feedback is three phase currents. Considering the 5 mOhm resistors on the low side of each double MOSFET are then connected to internal DRV8323's operational amplifiers with selectable gain. Using Park and Clarke transformations, it is possible to get the measured values of current in both q and d axis and adequately change the set values of each component in order to get the expected values [10].

Two additional ADC channels of the microcontroller are used to check if the motor or control board is not overheating. An external 1K thermistor is placed between the windings which results in fast changes of the temperature when the motor is stalled and thus fast cut-off when the windings reach a certain predefined temperature. Another built-in thermistor is inside the STM32 microcontroller and is used for observing the PCB temperature.

An external encoder (7) is a solution used for each revolute joint in order to read the absolute position. Then the position is fed to the PID regulator that tries to keep the setpoint position basing on the actual one. The only exception is the femur motor as it is impossible to place axial encoder on the joint axis. In that case, the angle of the joint has to be derived from the rotor's rotation angle.

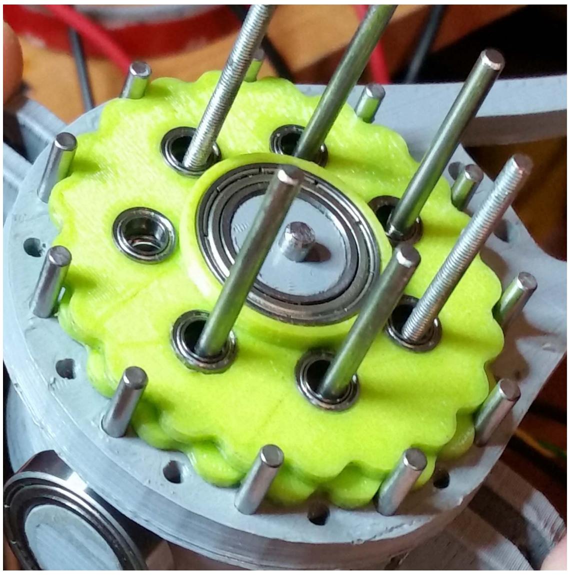

Fig. 1. The inside of the cycloidal gear

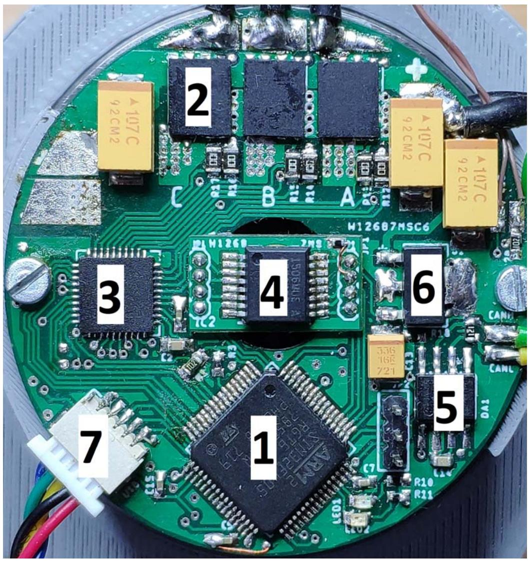

Fig. 2. The custom controller PCB layout

The regulator has two loops, one for adjusting the velocity, the other to keep the desired position. This approach allows controlling the velocity of reaching the desired point. Additionally, the two motors placed in the leg are not entirely independent – while rotating, the motor responsible for moving the femur, changes the angle of the tibia in reference to the femur slightly. However, this is not a concern if a position regulator is implemented

III. KINEMATIC MODEL OF THE QUADRUPED

Majority of legged constructions base on spider-like legs configurations. Static stability is improved in such systems as these robots usually have more than four legs and can manipulate the center of gravity more flexible. However, it effects in lower velocities these robots can achieve, due to higher mass (higher inertia) and more limbs to control. At stance, the actuators tend to consume lots of energy as they have to maintain a particular position counteracting the forces of gravity.

This article's focus is on the parallel leg configuration robot. This type of structure is more mammal-like and usually more complicated to control as the stability is harder to maintain with only four legs. The advanced technique is to maintain dynamic stability, which means the robot, at some point in time, is not stable statically but the position is held by the forces acting on the structure. If stopped at this exact moment the robot will lose its stability. Dynamic stability can be observed in humans and animals trot, as it is the fastest way of locomotion and the most power efficient.

Advanced robots such as MIT's Cheetah uses the kinetic energy from the segments of gait when the work is done on the system to transform it back to the energy in the batteries. It bases on converting the current inducted in the motors and directing its flow back to the battery. Although to perform such process the actuators must not be self-locking, and specialized electronic circuits are needed.

Parallel springs which offload the actuators are also used to lower the energy consumption. Added to the system, they decrease the power demand of the motors, decrease the power consumption during a static stand or in some segments of gait when work is done on the system.

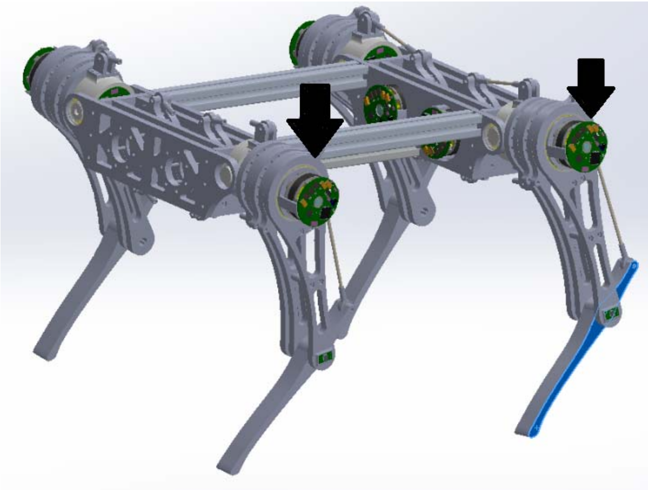

Fig. 3. Quadruped 3D model in SolidWorks

The chosen structure consists of four parallelly placed legs (Fig.3). Each leg of the quadruped is actuated with three independent actuators thus having three degrees of freedom. Two of them are placed in the leg, while the third one is mounted in the torso. One of them rotates the femur directly, and the other rotates the tibia by pushing and pulling a rod. Two additional rods are used to transfer the torque from the motor located in the torso to the hip. By placing two motors in the highest point of the leg It was possible to minimize the influence of inertia when rotating the hip. This is necessary in order to make rapid movements for instance when an external disturbance is introduced, and stability has to be maintained.

Two types of kinematic analysis of the quadruped are introduced: forward and inverse. Forward kinematics allows computing the end effector coordinates given the angles form each of the revolute joints. The inverse, on the other hand, is a process of finding the joint's variables with the known position of the end effector. To get to the desired position in space the robot has to know the angles of each revolute joint. Inverse kinematics is usually harder to compute due to nonlinear equations - for some positions in space may be unsolvable.

Forward kinematics equations were obtained using elementary transformation matrices. A path form hip joint to the tip of the leg was described using matrix transformations of rotations and translations.

$$A_0^1 = \begin{bmatrix} cos\theta_1 & -sin\theta_1 & 0 & L_1 \cdot cos\theta_1 \\ sin\theta_1 & cos\theta_1 & 0 & -L_1 \cdot sin\theta_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$A_1^2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

$$A_2^3 = \begin{bmatrix} cos\theta_2 & -sin\theta_2 & 0 & L_2 \cdot cos\theta_2 \\ sin\theta_2 & cos\theta_2 & 0 & -L_2 \cdot sin\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$A_3^4 = \begin{bmatrix} cos\theta_3 & -sin\theta_3 & 0 & L_3 \cdot cos\theta_3 \\ sin\theta_3 & cos\theta_3 & 0 & L_3 \cdot sin\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$A_0^4 = A_0^1 \cdot A_1^2 \cdot A_2^3 \cdot A_3^4 \quad (5)$$

Fig.4. shows the assumed coordinate systems of each joint as well as the angles and lengths of each segment. Equations (1), (2), (3), (4) respectively consist of one or more operations which are then multiplied. By multiplying each transform matrix with the next one, a matrix from (5) is derived which describes the transformation from the hip to the leg's tip.

When the whole robot is being described there has to be a first transform from the center of the robot's body to the first coordinate system of each leg. When implemented it allows controlling the center of body position and orientation without worrying about each leg separately.

After substituting known joint angles to the forward kinematics equations, they give the coordinates of leg tip in the general coordinate system. Inverse transformations were derived by solving an equation system in which joint angles are the desired variables (6)-(12).

$$\theta_1 = -2atan2\left(dy + \sqrt{(dx^2 + dy^2 - L_1{}^2)}, dx + L_1\right) \quad (6)$$

$$\theta_2 = -2atan2\left(2 * dz * L_2 + \sqrt{B - s * C}, s\right) \quad (7)$$

$$\theta_3 = acos\left(\frac{-L_2 - D}{L_3}\right) \quad (8)$$

where

$$B = 4 * dz^2 * L_2{}^2 \quad (9)$$

$$C = \left(dy^2 + 2 * dy * L_2 + dz^2 + L_2{}^2 - L_3{}^2\right) \quad (10)$$

$$D = dz * \sin\theta_2 + cos\theta_2(dy * cos\theta_1 + dx * sin\theta_1) \quad (11)$$

$$s = dy^2 - 2 * dy * L_2 + dz^2 + L_2{}^2 - L_3{}^2 \quad (12)$$

Inversing the matrices was a way of finding the equations using an analytical approach. A path from the tip of leg to a given joint was described with inverse transformations and compared with the same path form the first joint (hip). Doing so for each joint resulted in several equations. Using Matlab software each angle's equation was derived.

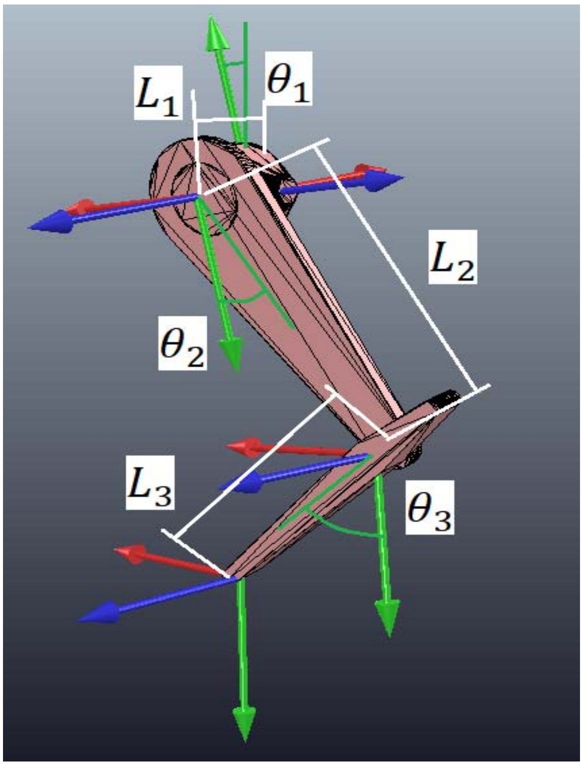

Fig. 4. Coordinate systems of a single leg

IV. V-REP SIMULATION RESULTS

V-rep is a simulation program which was used to test the robot regarding maximum positions in each axis it can reach as well as testing the ROS node. The simulation can also be helpful when it comes to testing the torques of each motor. Each part of the quadruped was imported from the Solid Works program and then substituted with less complicated compute-friendly equivalent made of fewer triangles, though still similar to the original part. Afterward, maximum torques were set for each motor (approximately 3 Nm) and approximated masses of each element.

The simulation outcome was that the torso of the robot should be below 3kg in order to get smooth motions. A high force machine is considered to be able to lift 2 to 3 times the robot's body weight. This condition matches human's legs power while running. As for now the quadruped presented in the article is only a prototype and is not expected to run in the way mammals do.

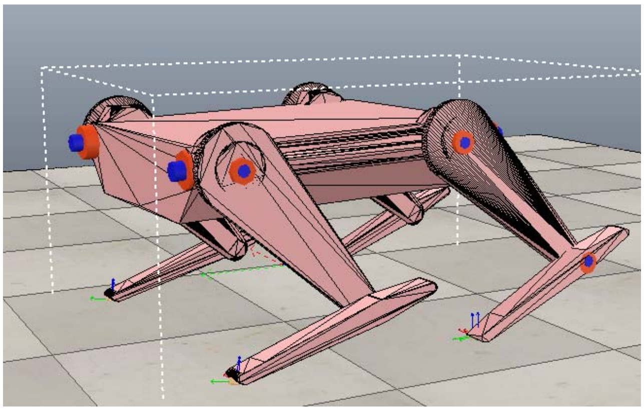

Fig. 5. Quadruped simplified model in the V-rep program

Fig. 5. is a picture from the simulation environment and shows the robot under its own load in the lowest point it can achieve.

After constructing the virtual model of the quadruped, all the joints were enabled as inverse kinematic entities. Doing so allowed to control the pose of the robot in 3-dimensional space only by setting three angles and three translations in each axis. By changing these values – position and orientation it was possible to get different poses. It is essential especially when the stability has to be maintained, but the terrain is not flat. In that case, the robot has to adjust the pose in order to keep the center of gravity in the area of static stability (polygon made by connecting the fulcrum points). Using the IMU sensor [11], it is possible to create a regulator taking care about stability in the background while gait is performed.

V. CONCLUSIONS

Quadruped robots are complex machines that are hard to control and develop without simulation and testing. The physical equivalent of the robot presented in this article is not finished yet. It was only tested with a single leg. This, however, is a big step in order to complete the real model and make it stable and able to walk.

BLDC controllers made especially for the purpose of actuators were the right choice as they significantly lowered the costs. Moreover, these controllers can be adapted to different conditions whenever needed – external controller, CAN bus or SPI bus connectors were provided during the design process. Control algorithm allows to use all the available torque and thus reach the highest efficiency.

The biggest disadvantage is the LDO converter which has to dissipate the power coming from a relatively high voltage drop on the regulator. It results in an increased temperature of the PCB and thus higher power consumption. In the future there will be a dc-dc converter lowering the voltage to 5V for CAN bus controller and the LDO will be only used to make 3.3V for the STM32. A version of the controller with a reverse motion of the motor charging up the batteries is also considered in the next design.

Cycloidal gear introduced in the robot also allowed to lower the cost and perform the first physical model tests. The real test for the gears is usually testing under load while testing the gait. For now, these gears proved to be adequate but for sure require a further test on the aspect of durability. The most concerning parts are the gear rotors which may lose their dimensions due to the friction against steel rods on the gear output.

Kinematic model of the leg can now be applied to the whole body, and other legs simply by translating and rotating the reference coordinate systems. The plan is to apply the kinematics on the real model without controlling the model from the simulation. All the angles are planned to be computed on an onboard microcomputer and then each angular position will be sent to a certain joint actuator through CAN bus.

Simulation performed using V-rep program showed that the robot is capable of maintaining stability and the actuators are strong enough to hold the body in different positions. This stage helped to make sure that the components used in the physical design are adequate for the dynamic forces occurring while simple movements are performed. Next stage will be the testing of the ROS node in order to be able to use all the software support regarding visual positioning or path planning in further development.

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