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Trotting Gait Planning and Modeling of a Quadruped Robot

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Abstract — **Quadruped robots are generally more stable and agile than biped robots. In this paper, a model of a quadruped robot similar to Mini-Cheetah has been presented and investigated in terms of dynamic gait planning. First, the model has graphically been designed by SolidWorks which is composed of four legs with twelve rotational joints (three joints for each leg). Then, the robot has been dynamically modeled in ADAMS, by introducing appropriate constraints and contacts. An intuitive graphical kinematic analysis has been conducted and a proper dynamically stable gait for the robot locomotion, i.e. trotting gait, has been planned. To extend and parameterize the gait study, the robot has further been simulated by linking ADAMS and MATLAB. The results showed the feasibility and effectiveness of the approach for quadruped gait planning and simulation.**

Index Terms--**Quadruped robot, Gait planning, Trotting, Dynamic modeling, Simulation.**

I. INTRODUCTION

Although, wheeled and tracked robots are able to access roughly half of the earth's geographical surface, legged robots can move over most of the earth’s terrain. Among various multi-legged robot structures, the quadruped robot is optimal, because of the least complex mechanical design and better/good stability of configuration [1].

The Phoney Pony was known as the first real quadruped robot, built at the University of Southern California [2]. Since then, a large number of four-legged robots, such as BISAM, WARP1, KOLT, Tekken, HyQ, etc., have been developed throughout the world [3-7]. In 2008, early initiatives encouraged Boston Dynamics to develop the Big Dog, which could record the mobility and speed of a normal four-limbed animal. A big dog can move on very steep, uneven, rocky, wet surfaces, as well as on muddy and snowy surfaces, and can be used to carry objects. The Big Dog serves as an inspiration and as theendpoint of insight among the quadruped robots, which results from MIT Leg Lab's Quadruped Robot [8].

At the same time, another four-legged robot called Little Dog was built [9]. Mini-Cheetah belongs to the category of Little Dog robots. This robot is a small and agile four-legged robot that can run and turn completely. This robot has powerful stimuli, allowing researchers to perform experiments and test new controllers without fear of breaking the robot [10].

Gait means a specific pattern of leg joint positions performed in a certain sequence. Four-legged robots have two different types of gait. Static gait (e.g., crawl, wave) occurs when the vertical projection of the center of gravity always remains inside the polygon formed by the supports. Dynamic gait (e.g., trot, pace, gallop) means that the vertical projection of the center of gravity is not necessary to be inside the polygon created by the supporting legs for dynamic balance. The trot gait is a system of progress in which each pair of diagonal feet of robot is alternately lifted with synchronicity, thrust forward, and again placed on the ground [11]. Here, trotting gait is chosen for the straight locomotion of four-legged robot because of the following advantages [12]:

- The transverse legs have the same phase of movement. In theory, they hit the ground at the same time. Therefore, the symmetrical trot can implement the robot's symmetrical movement, while maintaining stability and reducing the complexity of attitude control.
- The gait of the trot is energy efficient and has a larger speed adaptation range.
- Even if the crossed support legs are turned upside down; using a quick touch of the ground, the other two crossed legs can also prevent the robot from tipping over.
- This gait can easily change from trot to crawl and vice versa. Also it has good adaptability to complex terrain.

Li et al. [13] presented a pattern generation strategy based on the composite cycloid method for the trotting gait in order to improve the stability of quadruped robot. Based on the forward kinematics (FK) and inverse kinematics (IK) equations of the quadruped robot, the trotting gait is constructed in terms of the foot trajectory of the swing legs and the posture of the support legs [14].

ADAMS/MATLAB co-simulation can make full use of the strengths of the two in the field of control and dynamics simulation, and it can carry out rapid iteration of robot structures and algorithms [15]. The motion planning and gait simulation of a bionic hexapod robot during walking, turning and stair climbing has presented in based on MATLAB/ADAMS co- simulation [16].

The purpose of this paper is to plan an efficient trot gait for a quadruped robot. There are a variety of ways to plan and implement the trot gait in order to move the quadruped robot. However, most of them are very complex and time consuming/inefficient. We present a straightforward and proper approach for trot gait planning at desired speed, while respecting the stability of the robot.

We consider a model of a quadruped robot similar to Mini-Cheetah for this goal/study. It is dynamically modeled and a proper stable gait for the robot locomotion, i.e. trotting gait, is planned by linking ADAMS and MATLAB. Using ADAMS, the predominant dynamic equations of the robot can be efficiently solved, while there is no need to cope with deriving the equations of motion directly. On the other hand, using the Simulink toolbox of MATLAB, one can parameterize or optimize the gait study of such a nonlinear dynamic system. Furthermore, the robot can move by specifying the stride length or number, as well as the locomotion velocity at the beginning of the gait.

Hence, the structure of the paper is as follows: the detail of quadruped model under study and its dynamic modeling is explained in Section II. In section III, we describe quadruped robot gait planning using graphical approach, as well as quadruped robot simulation using ADAMS and MATLAB-SIMULINK. Section IV is dedicated to the results and discussion and Section V concludes the paper.

II. QUADRUPED MODELLING

As a case study, a model of four-legged robots is considered and its 3D CAD model is prepared by SolidWorks in detail. The model is very similar to Mini-Cheetah robot as shown in Fig.1. The robot has twelve 1-DOF rotational joints such that each leg has three joints; i.e. Knee joint, hip joint and Abduction/Adduction (Ab/Ad) joint, which help the robot to rotate to the left or right. The four knee joints connect the thighs to the shanks. The four hip joints connect the thighs to the shoulders. The remain four Ab/Ad joints connect the shoulders to the main body and their rotations are perpendicular to the rotations of hip joints. Here, to simplify the study of model for co-simulation in ADAMS and MATLAB, we can consider that Ab/Ad joints are locked during straight walking gaits. Such a simplified model with fewer parts is shown in Fig. 2.

The CAD model is further imported into ADAMS. In order for the robot to go forward, we first, set a friction coefficient for the ground. Also, to construct a linkage between the robot's components, we first created the contact constraints and applied them to our model. We defined rotational joints and applied motion functions to them, enabling the robot to move.

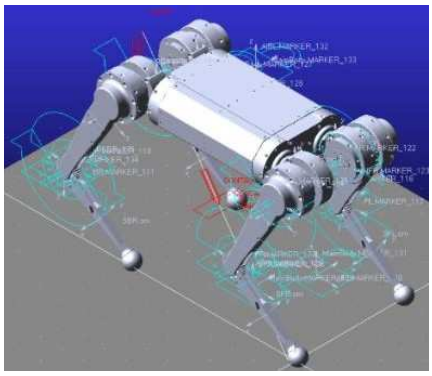

Fig. 1. Main quadruped robot designed in SolidWorks

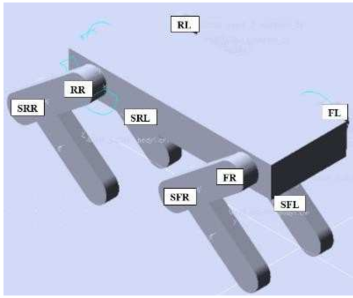

Fig. 2. Simplified model of the main quadruped robot

III. GAIT PLANNING

A gait is a cyclic motion pattern in which the feet interact with the ground to create mobility. The legs provide support for the robot's body, while ground contact forces propel it forward. The trot gait is a type of movement in which a robot's diagonal feet are elevated, propelled forward, and then lowered to the ground again. The trotting gait is utilized here to allow the robot to go straight ahead or backward while being steady.

A. *Gait planning using graphical method*

Taking into account the initial position of the robot's hip and knee joints, its body parts were moved at specified times, and thus the trotting gait was applied to the robot's movement. The robot’s main body dimension is 0.795m × 0.540m × 0.780m, and the initial joint angles, length of the robot’s legs have been indicated in the Fig. 3.

According to the values specified in Tables I and II, we can implement trotting gait in order to move the robot. These values produce two schematic diagrams for the movement of the hip and knee joints. By giving the initial angle to the joints and following the Schematic diagrams introduced in Fig. 5, 6. We can change the stride length.

It should be noted that joint 1,2,3,4 indicate the hips joints and joint 5,6,7,8 indicate the knees. Moreover, FL is related to the front left hip, FR is related to the front right hip, RL is related to the rear left hip, and RR is related to the rear right hip. The same combination is applied to SFL, SFR, SRL, SRR for knees.

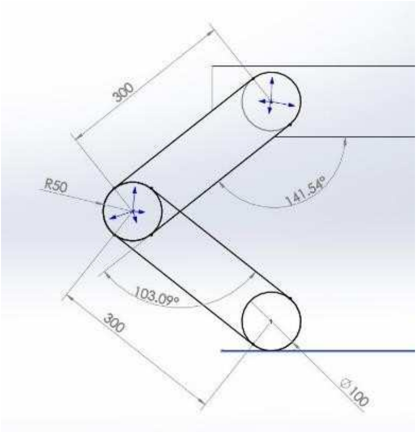

Fig. 3. Graphical display of hips and knees in their initial position (degree, mm)

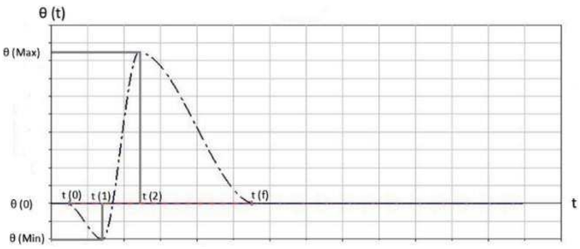

Fig. 4. Schematic of the time trajectory for moving the knee joints

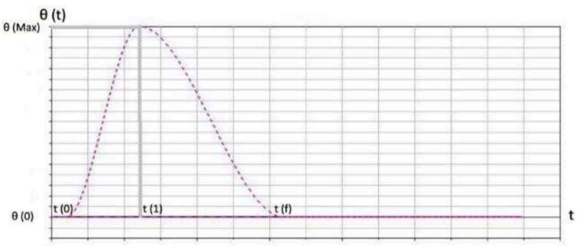

Fig. 5. Schematic of the time trajectory for moving the hip joints

TABLE I. HIP'S JOINT POSITION CORRESPONDING TO TIME INTERVAL (DEGREE)

Time intervals	FL-Foot 1	FR- Foot 2	RL- Foot 3	RR- Foot 4
	Joint 1	*Joint 2*	*Joint 3*	*Joint 4*
Initial joint angle	141.54	141.54	141.54	141.54
$0.1 \leq t < 0.6$	141.54	96.54	96.54	141.54
$0.6 \leq t < 1.6$	141.54	141.54	141.54	141.54
$1.6 \leq t < 2.1$	96.54	141.54	141.54	96.54
$2.1 \leq t < 3.1$	141.54	141.54	141.54	141.54

TABLE II. KNEE'S JOINT POSITION CORRESPONDING TO TIME INTERVAL (DEGREE)

Time intervals	FL- Foot 1	FR- Foot 2	RL- Foot 3	RR- Foot 4
	Joint 5	*Joint 6*	*Joint 7*	*Joint 8*
Initial joint angle	103.09	103.09	103.09	103.09
$0.1 \leq t < 0.35$	103.09	108.09	108.09	103.09
$0.35 \leq t < 0.6$	103.09	81.94	81.94	103.09
$0.6 \leq t < 1.4$	103.09	103.09	103.09	103.09
$1.4 \leq t < 1.6$	103.09	103.09	103.09	103.09
$1.6 \leq t < 1.85$	108.09	103.09	103.09	108.09
$1.85 \leq t < 2.1$	81.94	103.09	103.09	81.94
$2.1 \leq t < 2.9$	103.09	103.09	103.09	103.09

B. *Implementation of Gait in ADAMS*

The specified motion function has been assigned to each joint in ADAMS. In this way, the robot was able to move in the environment of ADAMS by using the following step functions:

• Front left and rear right knees - SFL, SRR
STEP (time, 1.6, 0, 1.85, 5d) + STEP (time, 1.85, 0, 2.1, -26.15d) + STEP (time, 2.1, 0, 2.9, 21.15d)
• Front right and rear left knees - SFR, SRL
STEP (time, 0.1, 0, 0.35, -5d) + STEP (time, 0.35, 0, 0.6, 26.15d) + STEP (time, 0.6, 0, 1.4, -21.15d)
• Front left and rear right hips - FL, RR
STEP (time, 1.6, 0, 2.1, -45d) + STEP (time, 2.1, 0, 3.1, 45d)
• Front right and rear left hips –FR, RL
STEP (time, 0.1, 0, 0.6, 45d) + STEP (time, 0.6, 0, 1.6, -45d)

A snapshot of robot movement in ADAMS due to gait planning above is illustrated in Fig. 6.

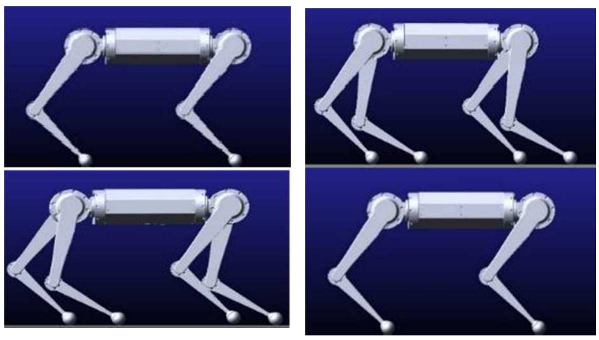

Fig. 6. Steps to move forward of the main model by using functions in ADAMS

C. *Gait planning by linking ADAMS to MATLAB*

As seen, the challenge of using ADAMS to simulate a four-legged robot locomotion is that we must define a series of particular functions for the robot movement. As a result, when we want the robot to move for more than one step or different step length, functions have to be written repeatedly, which is not time efficient. For example, applying the initial joint angles of Fig. 3. The robot moves a particular distance of 163.5 mm in each stride.

However, we can link the simplified model in ADAMS to MATLAB-SIMULINK. Then, parametrically defining the desired functions, the robot will be able to move forward or backward as we wish. Indeed, using MATLAB, it is possible for robot to be determined how far or how fast it can move. The Simulink model linked to ADAMS is depicted in Fig. 7. To accomplish so, we'll need to provide some variables in the left-hand side of the Fig. 7. And measures in the right-hand side, which provides us with the data on speed, toque, velocity, and etc. Also, a snapshot of robot steps due to the gait simulation above is illustrated in Fig. 8.

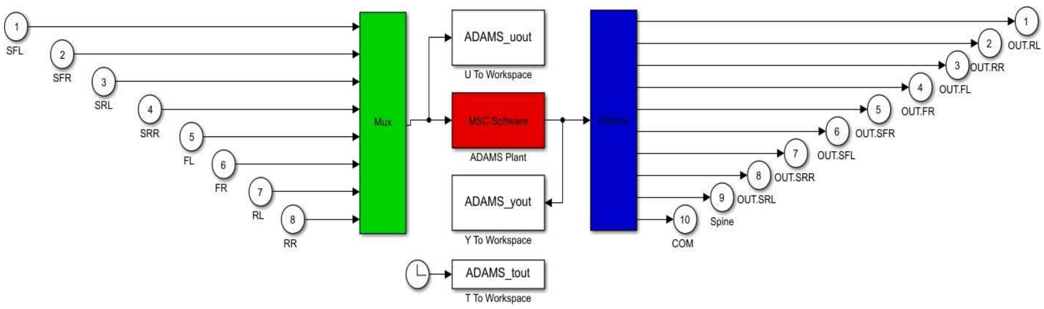

Fig. 7. Steps to move forwards of the simplified model by using Matlab Simulink

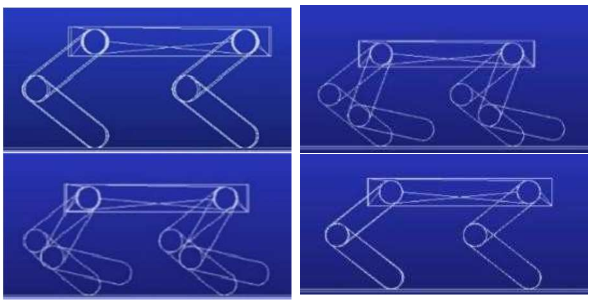

Fig. 8. Steps to move forward the simplified model by using Matlab-Simulink

IV. RESULTS AND DISCUSSION

Using the proper input of joint angles according to the planned gait, the trotting gait for the robot is simulated. By using the postprocessor in ADAMS, the change in knee angle of the Front Right (FR) leg during trotting gait of model is illustrated in Fig. 9. Also, the velocity of knee joint of FR leg is shown in Fig. 10. According to the structure of the quadruped robot and the friction coefficients of the ground, Fig. 11. Also shows the amount of contact force between the robot's foot and ground. Here, we assumed the amount of static and dynamic coefficients, 0.3 and 0.1 respectively. Fig. 11. Shows the contact forces in the time interval of a step.

As we can see, with investigation the data that we achieved from post processor we can observe that the amount of contact force is wisdom according to both the mass of the robot and these coefficients. Also, the contact force and velocity angle fluctuate little, which means that the posture of the robot is stable. From the Fig. 8. It can be seen that the main displacement occurs in the desired direction and the robot has passed the stepped terrain, Which verifies the feasibility of the foot trajectory planning on the stepped ground in the trot gait

As we expected, when the foot is in swing cycle, no force enters at the contact point. However, during the period when the foot is placed on the ground and the end of the step cycle, the force is continuously applied to the foot, except the time interval between 1.25 and 1.6. it occurs because of the open-loop control system of the robot that causes the loss of foot contact with the ground. Also, according to the information of this graph, the design of the robot's foot, especially the tip of the foot, can be optimized so it can prevent defects that may occur in the future, even it is possible to design the actuators of the robot optimally. It is noteworthy that we can increase the efficiency of the robot locomotion using a greater amount of friction coefficients without slipping. It is obvious that depending on the robot terrain condition, i.e. muddy, rocky, smooth and etc., the contact forces are different. The detail study of contact forces which can be used as the inputs for the robot control system are beyond the scope of this work. Applying appropriate force sensors, it is possible for the robot to walk easily in various terrain and in any direction without losing its balance.

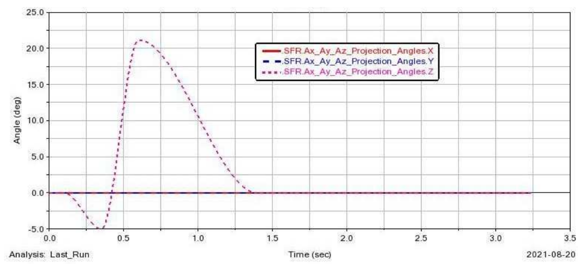

Fig. 9. Knee angle of the Front Right (FR) leg

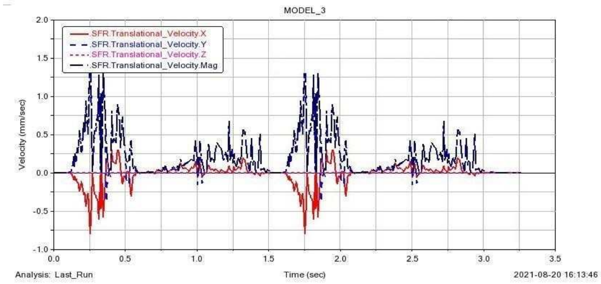

Fig. 10. Transitional velocity of Front Right (FR) leg

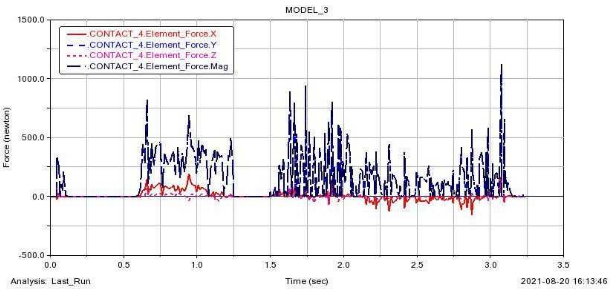

Fig. 11. Contact force of Front Right (FR) leg

V. CONCLUSION

In this paper, a four-legged robot, similar to mini-cheetah, was modeled and investigated in regard to stable gait planning. The planned trajectory presents good results when adopted the trot gait, especially for a velocity of VF = 0.05 ms−1. The appropriate model was designed in SolidWorks and imported to ADAMS. We planned a dynamic gait of trotting to move the robot forward or backward. To simulate this gait, ADAMS and MATLAB, were used. The robot could walk on a flat surface along a straight path with firmly stable gaits according to the amount of period specified in the input.

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For future work, a quadruped robot prototype can be built to experiment the result of this study. This robot may have more degrees of freedom, for example, by placing another actuator on the robot shoulder. It is also recommended to investigate the use of prismatic joints in the leg, which measures the pressure of the toes when they hit the ground and can send better feedback to the controller. A lot of robot prototypes are developed, but at present, there are still many problems in legged robot, such as walking, unable to finish complex movement, and Poor terrain adaptability. There is still a lot of space for growth in this field.

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