# Dynamic Modeling and Control of the Hexapod Robot Using Matlab SimMechanics

**Conference Paper** · November 2018

DOI: 10.1115/IMECE2018-88226

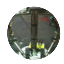


**4 authors:**

Sameh I. Beaber
Military Technical College


Abdelrahman Zaghloul
Military Technical College


Mohamed A. Kamel
Military Technical College

Wessam Mahmoud A M Hussein
McMaster University

**Proceedings of ASME 2018 International Mechanical Engineering Congress and Exposition**
**IMECE2018**
**Novemver 9-15, 2018, Pittsburgh, PA, USA**

**IMECE2018-88226**

# DYNAMIC MODELING AND CONTROL OF THE HEXAPOD ROBOT USING MATLAB SIMMECHANICS

**Sameh I. Beaber**
Department of Mechatronic Engineering
Military Technical College
Cairo, 11766, Egypt
Email: sibrahim@mtc.edu.eg

**Abdelrahaman S. Zaghloul***
Department of Mechanical Engineering
McMaster University
Hamilton, ON, L8S 4L7, Canada
Email: abdelrahman.a.zaghloul@ieee.org

**Mohamed A. Kamel**
Department of Mechanical Engineering
Military Technical College
Cairo, 11766, Egypt
Email: mohamed.atef.kamel@mtc.edu.eg

**Wessam M. Hussein**
Department of Mechatronic Engineering
Military Technical College
Cairo, 11766, Egypt
Email: wessam_hussein@mtc.edu.eg

## ABSTRACT

*This paper presents a detailed dynamic modeling of phantom ax12 six-legged robot using Matlab SimMechanics$^{TM}$. The direct and inverse kinematic analysis for each leg has been considered in order to develop an overall kinematic model of the robot. Trajectory of each leg is also considered for both swing and support phases when the robot walks with tripod gait in a straight path. Newton-Euler formulation has been utilized to determine the joints' torque. These results were verified using SimMechanics$^{TM}$. Also, feet force distributions of the hexpaod are estimated via SimMechanics$^{TM}$ using minimization of norm of feet forces, which is necessary for its control.*

## NOMENCLATURE

$\alpha$ roll angle of the robot
$\beta$ pitch angle of the robot
$\gamma$ yaw angle of the robot
$a_i$ the distance from $Z_i$ to $Z_{i+1}$ measured along $X_i$.
$\alpha_i$ the angle from $Z_i$ to $Z_{i+1}$ measured about $X_i$.
$d_i$ the distance from $X_{i-1}$ to $X_i$ measured along $Z_i$.
$\theta_i$ the angle from $X_{i-1}$ to $X_i$ measured about $Z_i$.
$Z_{(offset)}$ the body height.
$L_c$ coxa link length.
$L_F$ femur link length.
$L_T$ tibia link length.
$\theta_1$ coxa angle.
$\theta_2$ femur angle.
$\theta_3$ tibia angle.

## INTRODUCTION

In recent years, developments in mobile robots receive a great attention due to its importance in the real life that can be used in many application and many fields Mobile robots include wheeled, legged, and tracked. [1]. Legged walking robots become the main goal of many studies and research. The main role of legged robot is to make a machine that simulates some characteristics of biological organisms [2]. The attention of robotics researchers go towards legged robot, which use a mechanical limb for movements that make it better than tracked and wheeled vehicles on uneven and unstructured terrains [3]. Based on the number of legs for each robot, there are many types of legged robots

*Corresponding Author

such as: bipeds, tripods, quadrupeds, hexapods, and octopods.

However, the study of modeling and control of legged robots still an open research issue, and the development of models or prototypes for these studies is still very expensive and take long time. That fact leads to create a software models that allow the realization of these studies and help in their real-time implementation. Control and locomotion studies required these models to obtain the main features of biological organisms.

There are a lot of software tools helps to design, simulate, and test the behavior of mechanical systems in different conditions. These software programs make it easy to design the mechanical parts with a real-time view. Also, they make it possible to test the designed robot in three-dimensional space. Using these programs does not eliminate the need to design a working prototype of the mechanical systems, it decreases the error by making the required needed tests before building the prototype. Dynamic systems simulation uses software programs that can be used in many types of industries, with interest in robotics, due to the possibilities for modeling and simulation of many types of complex systems. There are many software tools that study the three-dimensional simulation of mechanical systems such as **(i)** Webot [4]; **(ii)** Simpack [5]; **(iii)** Adams Multibody Dynamic Simulation [6]; **(iv)** VisSim [7]; and **(v)** Matlab/SimMechanics$^{TM}$.

SimMechanics$^{TM}$ is a three-dimensional modeling tool running in the Simulink environment. SimMechanics$^{TM}$ can simulate multi-body mechanical systems such as landing gear of planes, vehicle suspensions and robots [8]. It represent the bodies (links), motion constraints, joints, forces and torques by means of some blocks, which facilitate the real design of mechanical system dynamics. Lines connected the elements to each other to transmit signals from one block to another. Although the previously mentioned software tools can simulate the dynamic systems with almost similar capabilities to SimMechanics$^{TM}$, but the main advantage of SimMechanics$^{TM}$ is its ability to import the Cad models from the Cad software tools such as Inventor, Catia, and SolidWorks. This is an easy operation, and a fairly complete tool that can be interacted with many Simulink$^{TM}$ tools.

In this research, hexapod walking robot is considered. Hexapods with 3 degree-of-freedom (DOF) legs are widely used as they have a simple design with respect to its minimum DOF per each leg when walking on unstructured terrain and different obstacles. Hexapod structure like an insects with symmetrically distributed six legs along two sides [9]. Many researchers presented different methods to investigate the characteristics of legged robots by using SimMechanics$^{TM}$. In [10], the dynamic model of hexpod is investigated based on Lagrange method. Experimental results of leg control are provided. However, the calculation of each joint's torque are omitted. Silva et al. [2] developed a quadruped robot model in SimMechanics$^{TM}$, that work with different gaits considering the angular positions of the hip and knee joints as inputs to the model. However, the contact forces calculations are not presented. Sorin et al. [11] calculated the trajectory generation of each leg using the piecewise cubic spline interpolation method for both transfer and supports phases based on Matlab and SimMechanics$^{TM}$. However, the contact forces with the ground are not presented. Asif et al. [12] studied the simulation of a 6-DOF legged robot via SimMechanics$^{TM}$ to find robot's kinematics and joint motion profiles. But, the joint torques and feet forces are not considered. In [13], modeling and simulation of biped robot based on SimMechanics$^{TM}$ is presented. However, the contact with the ground plane is not considered. In [14], SimMechanics$^{TM}$ is used for three-dimensional simulation of a trotting quadruped robot. Two phases are considered; the first one created a controller to achieve the trotting gate. In the second one, the model was built considering the ground contact force, where the relationship between the robot and the ground is modeled as a linear spring-damper system. Ponticelli and Armada [15] exploited a dynamic simulation of biped robot to provide a platform for gait control and parameters measurements for biped walking, considering the ground contact between the ground and the robot feet. Woering [16], designed a hexapod simulator consists of two parts: the first part is a dynamic simulator for testing the effect of gravity and mass on the model, while the second part is a kinematic simulator.

Motivated by the aforementioned issues, this paper presents a complete kinematic and dynamic model of the hexapod robot using MATLAB/SimMechanics$^{TM}$ Toolbox. The robots forward and inverse kinematics are studied to calculate the angular positions of the coxa, femur, and tibia joints for each leg. Then, a trajectory for each leg is generated for both swing and support phase that allows the robot to walk with tripod gait in straight path and level terrain, as the tripod gait is very stable in such cases and easy to be controllable [17]. Moreover, a dynamic model is studied to calculate joints torques using Newton-Euler formulation considering the feet forces.

The main contribution of this research is: developing a complete dynamic model of the hexpod robot via SimMechanics$^{TM}$, considering both forward and inverse kinematics, the robot dynamics, and the contact forces between the robot legs and the ground.

The remainder of this paper is presented as follows. Section two, presents the structure, kinematic, and dynamic modeling of hexapod robot. In section three, the modeling of the robot via SimMechanics$^{TM}$ is presented. Section four Simulation results and discussion is illustrated in Section four. Finally, conclusions and future work are drawn in Section five.

## STRUCTURE AND MODELING OF HEXAPOD ROBOT

The robot considered in this work is the phantom ax-12 hexapod robot. This section presents the structure, kinematic, and dynamic model of this robot, as the modeling of the robot is very important step to control the robot motion planning.

### Hexapod robot Structure

As mentioned in Section One, hexapod robots like an insects with symmetrically distributed six legs along two sides, each side having three legs as shown in Fig. 1. Each leg consists of three links: coxa, femur and tibia, as shown in Fig. 2. This symmetrical design is fast and flexible in forward direction but less flexible in moving sidewards and turning. It is clear that the hexapod has eighteen joints, three for each leg.

### Robot Frames

Developing the robot model requires a coordinate frames to be defined for all important parts. Therefore, coordinate systems have to be defined for all parts of the robot. Different coordinate frames are applied for the robot; the global frame, the robot body frame, and the leg frames.

The global frame is the one that all other frames are defined relative to it. It is a fixed frame of reference with a vertical z-axis. The robot body frame is attached to the center of the body with the z-axis pointing up. Leg Frames are attached to the legs parts. They are four frames. Frame zero, at the point where the leg is attached to the body. Frame one is the coxa frame, and coincides with frame zero. Frames two and three coincide with the femur and tibia links, respectively. Finally, frame four is at the end point of the leg and is parallel to frame three. Fig. 3 illustrates the leg frames.

**Robot Leg Parameters** The transformation between the leg frames can be described by the following parameters shown in Table 1, that follows the Denavit Hartenberg notation [19], where $a_i$ is the distance from $Z_i$ to $Z_{i+1}$ measured along $X_i$, $\alpha_i$ denotes the angle from $Z_i$ to $Z_{i+1}$ measured about $X_i$, $d_i$ is the distance from $X_{i-1}$ to $X_i$ measured along $Z_i$, and $\theta_i$ is the angle from $X_{i-1}$ to $X_i$ measured about $Z_i$.

**FIGURE 1**. PHANTOM AX-12 HEXAPOD ROBOT [18].

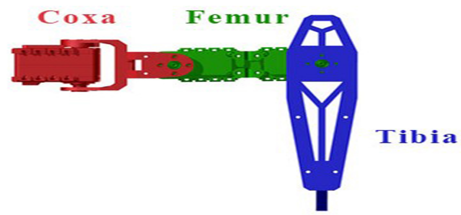



**FIGURE 2**. CONSTRUCTION OF THE HEXAPOD'S LEG.

### Forward and Inverse kinematics

The Kinematic model consists of a kinematic description of the robot with its legs, This makes it easy to find the joint's angles for each leg. The transformation matrix between robot's frames depends on set of forward kinematics equations comes from transforming coordinates from one link frame to another one.

In this case, the transformation matrix between one leg frame to another, can be written as follows:

$$T_i^{i-1} = \begin{bmatrix} c(\theta_i) & -s(\theta_i) & 0 & \alpha_{i-1} \\ s(\theta_i)c(\alpha_{i-1}) & c(\theta_i)c(\alpha_{i-1}) & -s(\alpha_{i-1}) & -s(\alpha_{i-1})d_i \\ s(\theta_i)s(\alpha_{i-1}) & c(\theta_i)s(\alpha_{i-1}) & c(\alpha_{i-1}) & c(\alpha_{i-1})d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where $c(x)$ and $s(x)$ denote $\cos(x)$ and $\sin(x)$, respectively.

Then, the transformation matrix from the $i^{th}$ leg frame, $i = [1, 2, \ldots, 6]$ to the body frame can be obtained as follows:

$$T_l^{body} = \begin{bmatrix} c(\gamma_k) & -s(\gamma_k) & 0 & x \\ s(\gamma_k) & c(\gamma_k) & 0 & y \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where $\gamma_k$ is the yaw angle of the $i^{\text{th}}$ leg, $i \in \{1, 2, \ldots, 6\}$ relative to the body frame.

Finally, the transformation matrix from the robot body frame

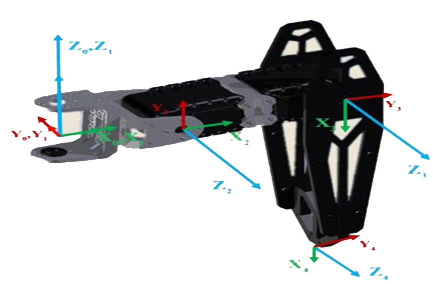


**FIGURE 3**. LEG FRAMES

**TABLE 1**. DENAVIT HARTENBERG OF ONE LEG

| Transformation | $\alpha_{i-1}$ | $a_{i-1}$ | $d_i$ | $\theta_i$ |
|---|---|---|---|---|
| $1 \rightarrow 0$ | 0 | 0 | 0 | $\theta_1$ |
| $2 \rightarrow 1$ | 90 | 52 | 0 | $\theta_2$ |
| $3 \rightarrow 2$ | 0 | 82 | 0 | $\theta_3$ |
| $4 \rightarrow 3$ | 0 | 140 | 0 | 0 |

to the global frame is defined as:

$$T_B^G = \begin{bmatrix} c(\alpha)c(\gamma)-s(\alpha)s(\beta)s(\gamma) & -c(\beta)s(\gamma) & c(\gamma)s(\alpha)+c(\alpha)s(\beta)s(\gamma) & X \\ c(\alpha)c(\gamma)+c(\gamma)s(\alpha)S(\beta) & c(\beta)c(\gamma) & s(\alpha)s(\gamma)-c(\alpha)c(\gamma)s(\beta) & Y \\ -c(\beta)s(\alpha) & s(\beta) & c(\alpha)c(\beta) & Z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where $\alpha$, $\beta$, and $\gamma$ are the roll, pitch, and yaw angles, respectively.

On the other hand, inverse kinematics is determined to find the angles of the three links, as the leg can be described by its links and rotational joints. Solving inverse kinematics required the following constrains:

1. The fact that all the robot joints allow to rotate about one axis;
2. Femur and tibia joints rotate on parallel axis; and
3. Each joint can rotate its link.

After transforming the coordinates of the leg end point from the global frame to the leg one as shown in Fig. 4, the coxa joint angle $\theta_1$ can be calculated as follows:

$$\theta_1 = tan^{-1}\frac{Y_4}{X_4} \tag{3}$$

To find the femur and tibia angles, the triangle with vertices in the origins of the coxa, femur and tibia frames is established

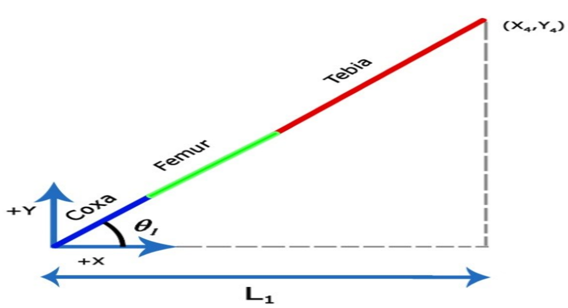



**FIGURE 4**. COXA JOINT ANGLE [17]

as shown in Fig. 5. Then, the femur and tibia angles can be calculated as follows:

$$L = \sqrt{Z^2_{(offset)} + (L_1 - L_c)^2} \tag{4}$$

where: $Z_{(offset)}$ is the body height, $L_c$ is the coxa link length; $L_F$, is the femur link length, and $L_T$ is the tibia link length. Get the femur angle above horizon $q_1$:

$$q_1 = \tan^{-1}\frac{Z_{offset}}{(L_1 - L_C)} \tag{5}$$

Then, apply the low of cosines in the triangle ABC to find the angle $q_2$:

$$q_2 = \cos^{-1}\frac{\sqrt{L_F^2 + L^2 - L_T^2}}{2 \times L_F \times L} \tag{6}$$

Therefore, the femur angle $\theta_2$ can be obtained as

$$\theta_2 = q_1 + q_2 \tag{7}$$

Get the tibia angle from femur $\phi$

$$\phi = \cos^{-1}\frac{\sqrt{L_F^2 + L_T^2 - L^2}}{2 \times L_F \times L_T} \tag{8}$$

Then, the tibia angle $\theta_3$ can be obtained as follows:

$$\theta_3 = \phi - 180 \tag{9}$$

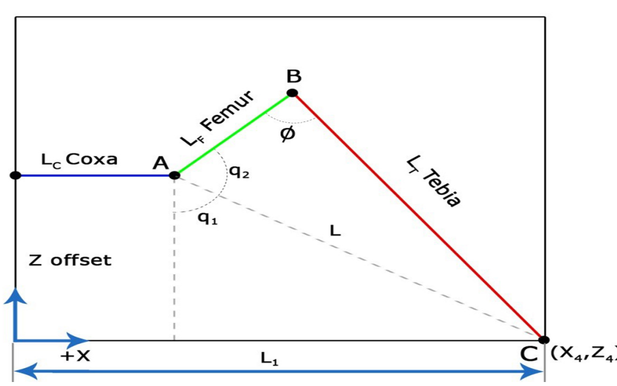



**FIGURE 5**. TRIANGLE SPANNED BY FEMUR AND TIBIA LINKS [17]

## Trajectory Generation

After developing the forward and inverse kinematics, the trajectory of each leg can be calculated. Trajectory means: a time history of position, velocity and acceleration of each joint. Step length, step height, step time, and sample, are the inputs that determine the number of points in the trajectory, in order to generate the trajectory for both transfer and support phase in a tripod gate for the robot leg. Fig. 6 illustrates the trajectory generation process.

## Dynamic model

Dynamics is the science of motion that describes how and why motion happens when moments and forces are applied on bodies. The objective is to find the required vector of joint torques $T$, based on the trajectory parameters obtained from the trajectory generation. Two main methods can be applied to obtain the dynamic model; Newton-Euler method and Lagrange method. The Newton-Euler method is more fundamental, it gets the dynamic equations to determine the required actuators' forces and torques to move the robot, as well as the joint torques. The complete dynamic model of the hexapod can found in [17], where many assumptions are assumed to facilitate the modeling. A brief explanation is presented herein for convenience.

Based on Newton-Euler formulation, the dynamic equation of one leg can be written as follows:

$$\tau = M(\Theta)\ddot{\Theta} + B(\Theta)[\dot{\Theta}\dot{\Theta}] + C(\Theta)[\dot{\Theta}^2] + G(\Theta) \tag{10}$$

where $M(\Theta)$ is the $n \times n$ mass matrix of the leg, $B(\Theta)$ is the matrix of dimensions $n \times n(n-1)/2$ of Coriolis coefficients, $[\dot{\Theta}\dot{\Theta}]$ is an $n(n-1)/2 \times 1$ vector of joint velocity products, $C(\Theta)$ is an $n\times$ matrix of centrifugal coefficients, $[\dot{\Theta}^2]$ is an $n \times 1$ vector, $G(\Theta)$ is an $n \times 1$ vector of gravity, $n$ is number of each leg's links. The parameters in Eq. (10) can be obtained as follows:

$$M(\Theta) = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ m_{31} & m_{32} & m_{33} \end{bmatrix}$$

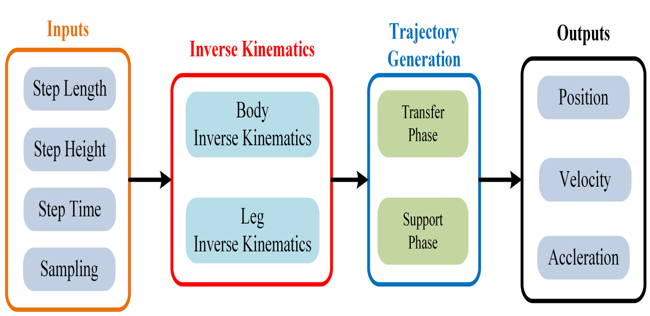



**FIGURE 6.** TRAJECTORY GENERATION

$$m_{11} = I_{xx_2} + \frac{I_{xx_3}}{2} + \frac{I_{yy_3}}{2} - I_{zz_1} + (I_{yy_2} - I_{xx_2})\cos^2\theta_2 + \frac{\cos(2\theta_2 - 2\theta_3)}{2}(I_{yy_3} - I_{xx_3} + \frac{L_3^2 m_3}{8}) + \frac{L_3^2 m_3}{8} + L_1^2(\frac{m_1}{4} + m_2 + m_3) + L_1 L_2 \cos\theta_2(m_2 + m_3) + L_3 m_3(\frac{L_2\cos\theta_3}{2} + L_1\cos(\theta_2 - \theta_3))$$

$$m_{12} = 0$$

$$m_{13} = 0$$

$$m_{21} = 0$$

$$m_{22} = I_{zz_2} + L_2^2(\frac{m_2}{4} + m_3) + L_3 m_3(\frac{L_3}{4} + L_2\cos\theta_3)$$

$$m_{23} = I_{zz_3} + L_3 m_3(\frac{L_3}{4} + \frac{L_2\cos\theta_3}{2})$$

$$m_{31} = 0$$

$$m_{32} = I_{zz_3} + L_3 m_3(\frac{L_3}{4} + \frac{L_2\cos\theta_3}{2})$$

$$m_{33} = I_{zz_3} + \frac{L_3^2 m_3}{4}$$

$$B(\Theta) = \begin{bmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{bmatrix}$$

$$b_{11} = \frac{\sin 2\theta_2}{2}(I_{xx_2} - I_{yy_2} - \frac{L_2^2 m_2}{4} - L_2^2 m_3) + \frac{\sin(2\theta_2 - 2\theta_3)}{2} (I_{xx_3 - I_{yy_3}} - \frac{L_3^2 m_3}{4}) - L_1 L_2 \sin\theta_2(\frac{m_2}{2} + m_3) - \frac{l_3 m_3}{2} (L_1\sin(\theta_2 - \theta_3) + L_2\sin(2\theta_2 - \theta_3))$$

$$b_{12} = \sin(2\theta_2 - 2\theta_3)(I_{xx_3} - I_{xx_3} - \frac{L_3^2 m_3}{4}) - L_3 m_3 (\frac{L_2\sin\theta_3}{2} + L_1\sin(\theta_2 - \theta_3) + \frac{L_2\sin(2\theta_2 - \theta_3)}{2})$$

$$b_{13} = 0$$

$$b_{21} = 0$$

$$b_{22} = 0$$

$$b_{23} = L_2 L_3 m_3 \sin\theta_3$$

$$b_{31} = 0$$

$$b_{32} = 0$$

$$b_{33} = 0$$

$$[\dot{\Theta}\dot{\Theta}] = \begin{bmatrix}\dot{\Theta}_1\dot{\Theta}_2 & \dot{\Theta}_1\dot{\Theta}_3 & \dots & \dot{\Theta}_{n-1}\dot{\Theta}_n\end{bmatrix}$$

$$C(\Theta) = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix}$$

$$\begin{aligned}
c_{11} &= 0 \\
c_{12} &= 0 \\
c_{13} &= 0 \\
c_{21} &= \frac{\sin 2\theta_2}{2}(I_{yy_2} - I_{xx_2}\frac{L_2^2 m_2}{4} + L_2^2 m_3) + \frac{\sin(2\theta_2 - 2\theta_3)}{2} \\
&\quad (I_{yy_3} - I_{xx_3} + \frac{l_3^2 m_3}{4}) + \frac{l_2 L_3 m_3 \sin\theta_3}{2} + \frac{L_3 m_3}{2}(L_1 \sin(\theta_2 - \theta_3) \\
&\quad + L_2 \sin(2\theta_2 - \theta_3)) + L_1 L_2 \sin\theta_2 (m_3 + \frac{m_2}{2}) \\
c_{22} &= 0 \\
c_{23} &= L_2 L_3 m_3 \sin\theta_3 \\
c_{31} &= \frac{\sin(2\theta_2 - 2\theta_3)}{2}(I_{yy_3} - I_{xx_3} + \frac{l_3^2 m_3}{4}) + \frac{L_3 m_3}{2}(L_1 \sin(\theta_2 - \theta_3) \\
&\quad \frac{L_2 \sin(2\theta_2 - \theta_3)}{2} - \frac{L_2 \sin\theta_3}{2}) \\
c_{32} &= -\frac{L_2 L_3 m_3 \sin\theta_3}{2} \\
c_{33} &= 0
\end{aligned}$$

$$[\dot{\Theta}^2] = \begin{bmatrix} \dot{\Theta}_1^2 & \dot{\Theta}_2^2 & \dots & \dot{\Theta}_n^2 \end{bmatrix}$$

$$G(\Theta) = \begin{bmatrix} 0 \\ \frac{gL_2 m_2 \cos\theta_2}{2} + gL_2 m_3 \cos\theta_2 + \frac{gL_3 m_3 \cos(\theta_2 - \theta_3)}{2} \\ \frac{gL_3 m_3 \cos(\theta_2 - \theta_3)}{2} \end{bmatrix}$$

where $L$ is the length of the link, $I_{xx}$, $I_{yy}$, and $I_{zz}$ are the mass moment of inertia about the $x$, $y$, and $z$ axes, respectively. The subscript 1, 2, and 3 denote the coxa, femur, and tibia, respectively.

In order to consider the contact forces between the leg tip and the ground, Eq. (10) should be modified as follows:

$$\tau_i = M(\Theta)_i \ddot{\Theta}_i + B(\Theta)_i [\dot{\Theta}\dot{\Theta}]_i + C(\Theta)_i [\dot{\Theta}^2]_i + G(\Theta)_i + J^T F_i \quad (11)$$

where $J$ is the Jacobian matrix, and $F_i$ is the vector of ground reaction forces for the $i^{\text{th}}$ foot, $i \in \{1, 2, \dots, 6\}$.

## MODELING VIA SIMMECHANICS

As illustrated in Section Two, it is clear that the hexapod model is complicated. The reason for this is the higher degree-of-freedom, as it has a large number of joints and links. Therefore, SimMechanics$^{\text{TM}}$ is applied to model such complex system, as it is independent of model's kinematic and dynamic equations.

The first step of hexapod's model development is the identification of its parameters. Table 2 shows the main parameter of the Phantom ax-12 hexapod. Second, the 3D physical model of hexapod is developed via Inventor as shown in Fig. 7. This physical model is exported into the SimMechanics, where the robot model is is automatically converted to blocks as shown in Fig. 8. The inputs to each leg is the generated trajectory for coxa, femur and tibia, respectively, that move the leg's links to reach its desired position.

Fig. 9 shows a detailed model of one leg. The three joints are connected together to perform the leg, where the coxa's joint is connected to the hexapod body. A ground plane is defined, in which the hexapod will move on. The leg's tip is defined as four contact points with the ground. Fig. 10 presents the contact between the leg's tip and the ground plane, which is the block named (contact force logging) in Fig. (9). With the contact force library [20], the leg's contact points have two outputs; one for the measurements of both normal and friction forces, and the other output to ensure the connection of the tip with the ground. Therefore, the hexapod can move along the ground plane. Finally, Fig. 11 shows the SimMechanics physical model of the hexapod.

**TABLE 2**. PHYSICAL PARAMETERS FOR EACH LEG

| link parameters | | link 1 | link 2 | link 3 |
|---|---|---|---|---|
| Mass ($10^{-3}kg$) | $m_i$ | 21.931 | 120.017 | 73.685 |
| Length ($10^{-3}m$) | $L_i$ | 52 | 82 | 140 |
| C.G ($10^{-3}m$) | $x_i$ | 26.5 | 41.5 | 75.816 |
| | $y_i$ | .001 | -0.035 | -1.747 |
| | $z_i$ | .001 | -20.076 | -21.392 |
| Moment of inertia | $I_{xx}$ | 8633.6 | 19819.5 | 31076.2 |
| ($10^{-6}g.mm^2$) | $I_{yy}$ | 9496.5 | 127028.3 | 233156 |
| | $I_{zz}$ | 9496.5 | 120839.4 | 210833 |
| Product of inertia | $I_{xy}$ | -0.040 | -1.937 | -1.832 |
| ($10^{-6}g.mm^2$) | $I_{xz}$ | 0.040 | -0.294 | 254.103 |
| | $I_{yz}$ | 0.000 | -0.734 | -0.734 |

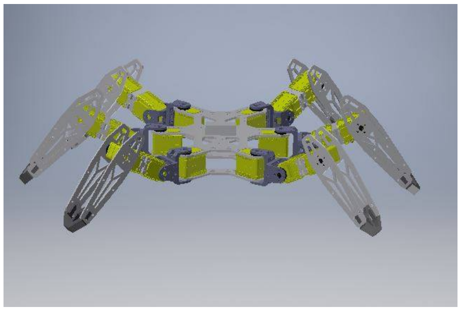


**FIGURE 7**. 3D PHYSICAL MODEL OF THE HEXAPOD IN INVENTOR

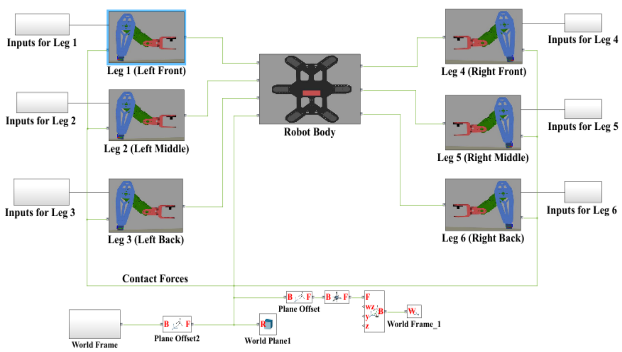



**FIGURE 8**. HEXAPOD MODEL VIA SIMMECHANICS

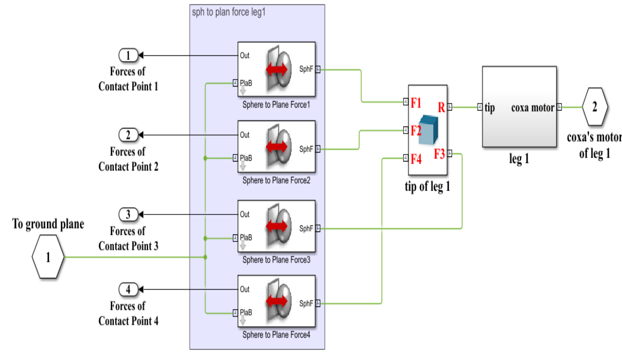



**FIGURE 10**. MODEL OF CONTACT BETWEEN LEG TIP AND GROUND PLANE

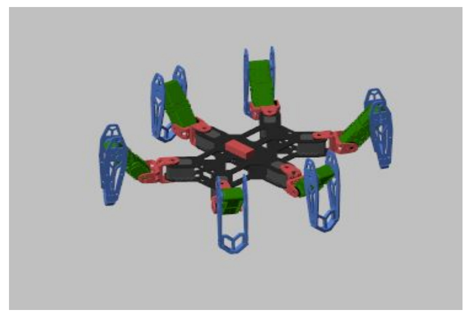


**FIGURE 11**. PHYSICAL MODEL OF HEXAPOD VIA SIMMECHANICS

## SIMULATION RESULTS AND DISCUSSION

In this section, simulation results have been presented. The simulation scenario is that the hexapod walk in straight path on a smooth level terrain for 10 sec. All the videos of the simulation performed in this paper can be found in [21].

To achieve the desired motion of the robot, the trajectory has been generated. According to Fig. 6, the inputs are: the step length, step height, step time, and sampling. They are selected to be 40 mm, 30 mm, 2 sec, and 41 samples, respectively. To achieve the initial conditions of the hexapod motion, a mapping is performed for joint angles, to achieve the tripod gait. $5^{th}$ degree polynomial is applied to generate a smooth trajectory. Fig. 12 shows the trajectory of legs 1, 2, and 3. As shown, in the first half of the curve (0 to 1 sec.) leg 1, 3, and 5 are in the transfer

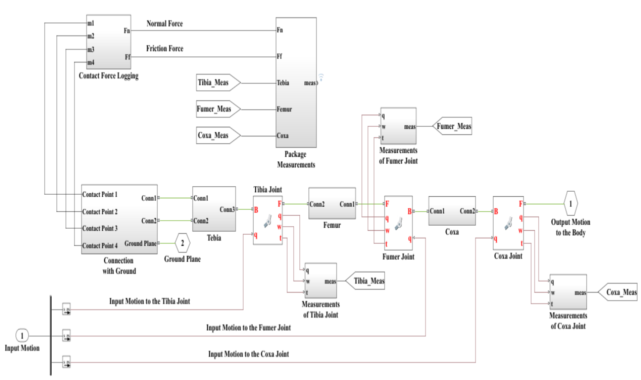


**FIGURE 9**. MODEL OF HEXAPOD'S LEG

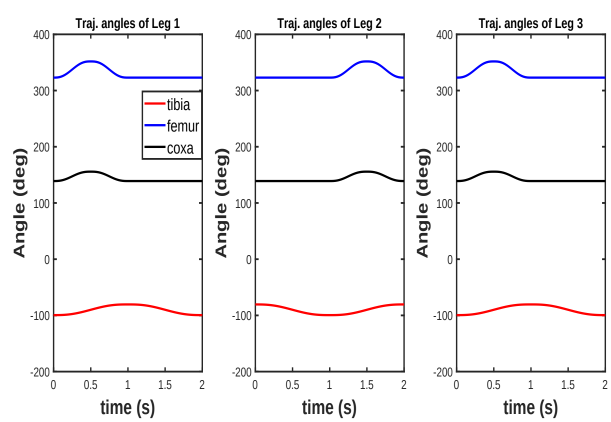



**FIGURE 12**. TRAJECTORY OF LEGS 1, 2, AND 3

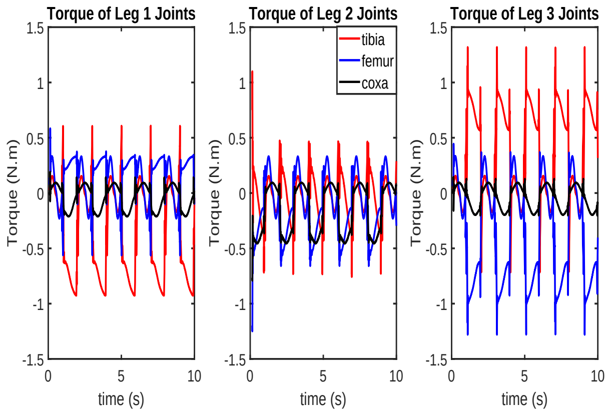



**FIGURE 13**. JOINTS' TORQUE OF LEGS 1, 2, AND 3

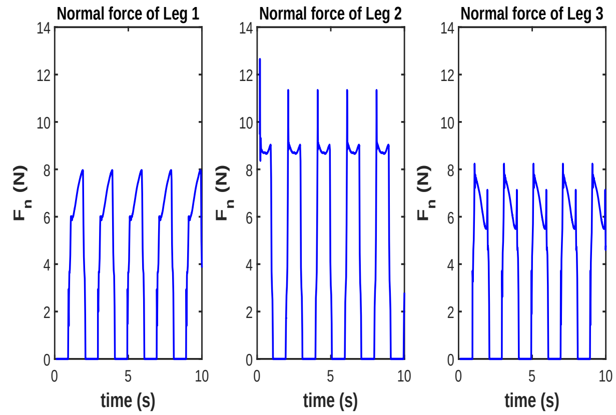



**FIGURE 15**. NORMAL FORCE OF LEGS 1, 2, AND 3

phase, where coxa, femur, and tebia joints has values. While legs 2, 4, and 6 are in the support phase, where only the coxa joint has values, and femur and tebia joints are fixed. In the second half of the step time (1 to 2 sec.), the opposite happens. This trajectory is repeated each 2 sec., and reverse itself to keep moving by transfer from one phase to the other phase.

Figs. 13 and 14 shows the variation of toques applied at each joint of all legs. Legs 1, 3, and 5 are initially in the transfer phase, while legs 2, 4, and 6 are in the support phase. Figs. 15 and 16 illustrates the normal force on each leg tip. In the transfer phase, the summation of normal force equal zero, as the legs do not touch the ground. While, in the support phase, the summation of normal forces on the three legs are almost equal to the weight of the robot, which is about 26 N. When legs 2, 4, and 6 in the support phase, the normal reaction on leg 2 is greater than the normal reaction on legs 4 and 6. The same occurs when legs 1, 3, and 5 are in the support phase, where the normal reaction on leg 5 is greater than the normal reaction on legs 1 and 3. As the equilibrium conditions of the hexapod applied, the normal force on legs 2 and 5 are greater, as they are on one side, while there are two legs on the other side.

## CONCLUSION

The dynamic simulation of hexapod robot via SimMechanics$^{TM}$ is addressed in this paper. Forward and inverse kinematics are considered to develop a complete dynamic model of the hexapod. For tripod walking gait, trajectory of each leg is generated for support and transfer phase. The dynamic model is presented to determined the joints' torque for each leg. Furthermore, feet-ground interaction forces was also considered to obtain the feet force distributions. The main advantages of the SimMchanics$^{TM}$ model is its simplicity compared to the traditional modeling tools, as it is independent of robot differential equations. This advantage arises for complex systems such as the hexapod. Also, different gaits configurations, and different terrain conditions can be easily applied to the model.

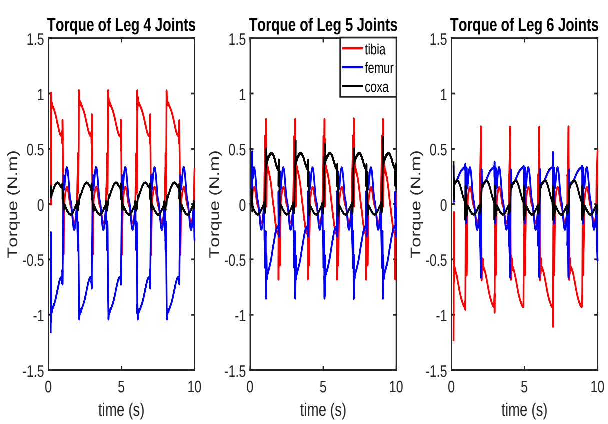



**FIGURE 14**. JOINTS' TORQUE OF LEGS 4, 5, AND 6

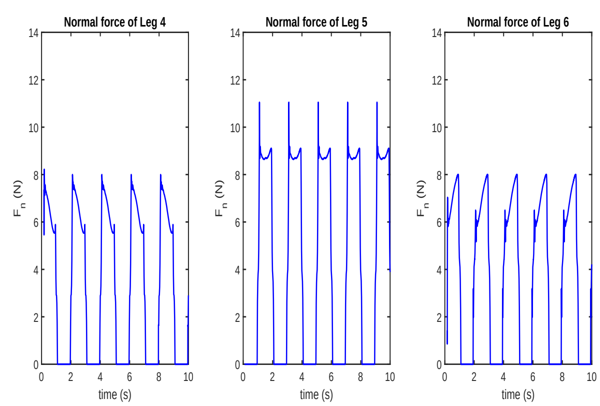



**FIGURE 16**. NORMAL FORCE OF LEGS 4, 5, AND 6

## REFERENCES


[1] Tzafestas, S. G., 2014. *Introduction to Mobile Robot Control*. Elsevier.

[2] Silva, M., Barbosa, R., and Castro, T., 2013. "Multi-legged walking robot modelling in MATLAB/SimMechanics and its simulation". In EUROSIM Congress on Modelling and Simulation (EUROSIM).

[3] Walas, K., and Belter, D., 2011. "Messor-verstatile wal king robot for serach and rescue missions". *Journal of Automation Mobile Robotics and Intelligent Systems,* ***5***, pp. 28–34.

[4] Cyberbotics., 2011. Webots: the mobile robotics simulation software,. `http://www.cyberbotics.com`. Retrieved: April 30, 2018.

[5] AG, S., 2010. Simpack - multi-body simulation software. `http://www.simpack.com`. Retrieved: April 30, 2018.

[6] Software, M., 2013. Adams - the multibody dynamics simulation solution. `http://www.mscsoftware.com/Products/CAE-Tools/Adams.aspx`. Retrieved: April 30, 2018.

[7] Incorporated, V. S., 2014. VisSim-a graphical language for simulation and model- based embeded development. `http://www.vissim.com/Products/vissim.html`. Retrieved: April 30, 2018.

[8] Mathworks, 2018. SimMechanics-model and simulate multi-body mechanical systems. `http://www.mathworks.com/Products/products/simmechanics`. Retrieved: April 30, 2018.

[9] Hajiabadi, M., 2013. *Analytical Workspace, Kinematics, and Foot Force Based Stability of Hexapod Walking Robots*. Worcester Polytechnic Institute.

[10] Sorin, M., and Niulescu, M., 2012. "Hexapod robot leg dynamic simulation and experimental control using matlab". *IFAC Proceedings Volumes,* ***45***(6), pp. 895–899.

[11] Sorin, M.-O., and Mircea, N. "The modeling of the hexapod mobile robot leg and associated interpolated movements while stepping". In International Conference on System Theory, Control and Computing (ICSTCC), pp. 1–5.

[12] Asif, U., and Iqbal, J., 2010. "Design and simulation of a biologically inspired hexapod robot using simMechanics". In Robotics International Conference (Robo), pp. 128–135.

[13] Zhao, X., and Liu, Y., 2010. "Modeling of biped robot". In Chinese Control and Decision Conference (CCDC), pp. 3233–3238.

[14] Naf, D., 2011. "Quadruped walking/running simulation". Master's thesis, ETH Zurich.

[15] Ponticelli, R., and Armada, M. "Vrsilo2: dynamic simulation system for the biped robot silo2". In International Conference on Climbing and Walking Robots.

[16] Woering, R., 2011. "Simulating the first steps of a walking hexapod robot". Master's thesis, University of Technology Eindhoven.

[17] Zaghloul, A. S., 2014. "Modeling and control of six-legged robot". Master's thesis, Military Technical College.

[18] Robotics, T., 2011. PhantomX AX hexapod kit. `http://www.trossenrobotics.com/phantomx-ax-hexapod-mk1.aspx`. Retrieved: April 30, 2018.

[19] Craig, J. J., 2005. Introduction to robotics: mechanics and control. Tech. rep.

[20] Mathworks, 2014. MATLAB and simulink robotics arena. `https://www.mathworks.com/academia/student-competitions/roboticsarena.html`. Retrieved: April 30, 2018.

[21] Ibrahim, S., 2018. Youtube channel. `https://www.youtube.com/watch?v=VmtCQSLLveI&feature=youtu.be`. Retrieved: April 30, 2018.