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Modeling and Control of a Snake Robot using SimMechanics

Beenish Ansari[1], Mukhtiar Ali Unar[2], Farida Memon[3], Shahnawaz Shah[4*], and Fayaz Ahmed Memon[5]

Abstract:

Snake robots are biologically inspired robots designed to locomote in an unwanted environment. The mechanism comprises of serially connected links through rotational joints capable of rotating its body in one or more plans. Therefore, Control and stability of such kind of robot with many degrees of freedom is very challenging. In this paper, the proposed model consists of a 10-links that are physically connected through n-1 rotary joints in order to propel a snake robot on the serpentine aisle. The entire mechanical model of a snake is created in Simmechanics, MATLAB library tool within Simulink environment. The mechanics for the motion of snake robot including dynamics, kinematics and friction force models are developed in order to find the nth link location in a 3D environment. In addition, we have also established the joint angle to activate the robot's link on a serpenoid terrain. Each joint system is further composed of 3 proportional controllers able to take measurements from a sensor to actuate and control entire movement (position, speed and torque). The simulation studies showing performance of the system that are conducted to determine the control parameters of the system measured through joint sensor via scope, graph and display units. Furthermore, it is also shown that the snake robot followed the serpentine wave motion.

Keywords: *Robot kinematics robot dynamics, snake robot and SimMechanics*

1. Introduction

Nature has remained a source of inspiration for scientists because scientists are always trying to develop systems that are as much as close and exactly identical to their natural counterparts. Inspiration source for them is usually from animals because they perform well in uneven and irregular environments. Compared to other animals, snakes have no limbs, it moves without legs, slide on mountains, deserts and under sea. Therefore, snakes have many physical properties that are useful in many applications such as firefighting, surgery, and search and rescue. Snake-like robot contains serially connected links through joints having an elastic body, can move like a real snake.

[1] Department of Electronic Engineering, University of Sindh, Jamshoro, Pakistan
[2] Department of Computer Sysytems Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan
[3] Department of Electronic Engineering, Mehran University of Engineering and Technology, Jamshoro, Pakistan
[4] Department of Telecommunication Engineering, University of Sindh, Jamshoro, Pakistan
[5] Quaid-e-Awam University of Engineering, Sciences and Technology, Nawabshah.
Corresponding Author: shahnawaz@usindh.edu.pk

Modeling of snake robots requires many factors to be considered. A snake robot is the combination of links which is the main parameter that can affect the performance of snake robot [1]. By increasing the number of links in a robot, greater speed is achieved [1] that resemble a real snake. In previous work 5 links [2], 7 links [3] and 8 links [4] were used to model and design the snake robot.

For wheel-less snake robots only kinematic model for the motion is not sufficient, as the friction between the snake robot and the ground surface is necessary for locomotion. Therefore, friction needs to be considered for wheel-less snake robots. This motivates the inclusion of dynamics in the development of model-based controllers for snake robots.

The stability of such kind of highly redundant robot is the main issue. Snake robot locomotion on a horizontal plane is relatively stable but highly depend on number of sine wave shape (i.e., value of kn). However, when kn < 2 the rotor of last joint (joint 9) experience unexpected changes in torque results the whole structure suddenly hit the ground when it moves forward [3-4]. This research deals with the design of a snake robot with kn=1 by maintaining the stability of snake robot when it moves forward.

In this work, a physical model of a snake robot composed of 10-link is designed through MATLAB tool SimMechanics. A proportional control system is designed for each joint so that a snake robot is able to locomote on a serpentine gait. Moreover, kinematics and dynamics models are developed for locomotion of a robot in a right path using serpenoid curve, and results are verified through MATLAB simulation.

2. Literature Review

Snake can move on any irregular surface because of high mobility [5]. Serpentine movement is the common form of locomotion in real snakes. In 1946 J. Gray [6], is the first biologist that gave a qualitative analysis on snake-like robots. Hirose [7] and his group in the early 1970's were the first researchers who designed and made a snake robot having passive wheels. Through their analysis they gave the serpentine curve which made the snake robot to move sinusoidally. Moreover, researchers also proposed techniques of controllability of snakbots based on kinematics [8], dynamics [9], and controller [10] with wheels for finding an accurate position of robot. Snake robot uses its body to make a force in order to locomote but they used wheels to produce friction force which was not close enough to real snake. Therefore, in 2001 scientists [11-13] designed a snake robot with no legs or wheels and analyzed snake movement through computer simulations based on serpenoid curve given by Hirose [7]. Further studies based on the friction forces [14] that can move snake robots and gave an energy statement for stability of joint movement [15]. Based on instant curve formed a universal gait suit for variety of applications [16]. Pal Liljeback and his group of researchers contributed a lot to produce control techniques for snake robot that follow a serpentine gait [17-21]. The group of researchers also developed a gait for rectilinear and fusion of more gaits based on serpentine motion [22]. A rope mechanism [23] and CPG system for controller [24] is also establish for locomotion pattern of snake robot. Scientists also made a system composed of legs [25] connected to the central module and a snake robot that can give 3D motion [26]. These robots are able to move around (inside and outside) narrow and crowded pipes [27-30]. In recent time study is based on the implementation of snake robot without wheels [31] that can easily move through obstacles [32] for the stability and control [33-34].

From existing work, it is found that up to 8-links snake robots are proposed and control systems are designed for only position control just for one or a little portion of snake robot links. Besides this, most controllers are designed mainly for velocity and heading control of a snake robot. In this paper a 10-link snake robot is modelled, developed and simulated using MATLAB environment. In addition, a control system for joints is also developed to control the overall movement of snake body and results are validated through simulations.

3. Methodology

3.1 System Block Diagram

The complete system block diagram of a 10-link snake robot is shown in Fig.1. The whole body of robot is built in SimMechanics. SimMechanics is a platform where mechanical systems are made through different mechanical tools and machines. The snake robot model comprises of inflexible links connected end-to-end via rotating joint. All the links in a model have some similar parameters like mass, force of inertia, its length and material's diameter. Every revolute joint in a system contains an actuator/motor and has a 1-degree of freedom.

To develop a kinematic model, a curvature function is used here which helps to find the individual link's position and the angular position of each joint of the snake robot. Using forward kinematics, the link's reference system and gravity center from the relative angles of joint are calculated. While in the reverse kinematics, angle of each joint is found via links positions. Furthermore, to examine the locomotion of the snake model; a sinusoidal wave is used.

For the snake robot to derive forward a friction model is also designed. When a robot moves on a smooth surface, its body touches the ground that experiences a friction force. This makes placing ground friction a significant portion of the dynamics of snake robots. After simulation in SimMechanics, dynamics model is obtained for the physical model of the snake robot. At first, snake robot's energies like kinetic (K.E) and potential (P.E) energies are calculated and then position of snake-robot, velocity and finally torque are measured. In order to get accurate measurements, a feedback proportional controller is designed for every joint.

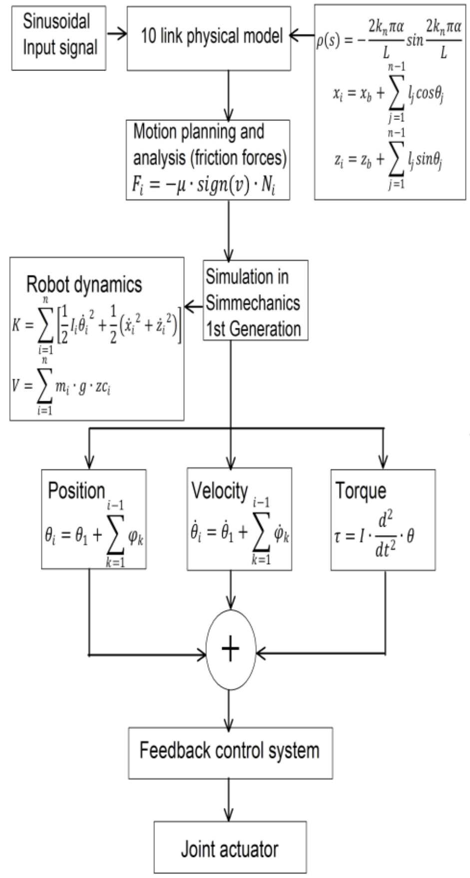

Fig. 1: System Block Diagram of a 10-link Snake Robot

3.2 Robot Kinematics

A complete mathematical model for 10-link snake robot is presented to accurately model and understand the traveling motion. For snake mobility, the right position of every link in the three-dimension reference system must be obtained. The proposed model contains serially connected 10-links each with 2-Degrees of Freedom (DOF) at x, z-axes, and is connected via angular joint having 1-DOF. By changing its joint angle, robots can move its body sinusoidally. This work presents a 10-link snake robot with only a single S-shaped wave, where every link has some unique position calculated by a curvature function shown in Fig. 2.

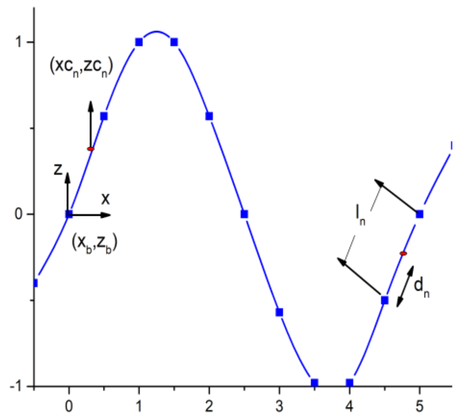

Fig.2: Curvature function w.r.t position of snake

Fig. 2 shows the serpentine curve of 10-link model of a snake robot where (xb, zb) and (xn,zn) are the coordinate system of the head and individual link of snake body. (xcn, zcn) are the center of gravity of nth link, ln is the length of nth link and dn is the distance from beginning/start of the n-th link to its center. Here the angle ‘θ’ is the angle of joint through x-axes and index ‘n’ shows the n-th angle of joint respectively. The function of curvature of snake curve depends on link’s position, replaces its value when the shape of a curve changes, warp and roll. Robot link’s position is determined through curvature function as,

$$\rho(s) = \frac{-2k_n \pi \alpha}{L} \quad (1)$$

Where L is the overall length and kn is the number of cycles executed by the snake robot, initial winding angle is α, and s is length of body. Inverse kinematics is used to determine the joint parameters that provide a desired position for each of the robot's link to reach at desired location.

3.3 Robot Dynamics

After describing the whole kinematics of robot, next task is to locomote snake body and to obtain actuator’s torque. Snake dynamics can be calculated by the interaction of forces between the snake body and its surroundings [1].

3.3.1 Ground Friction

Friction force is the reaction of two surfaces when they come into exposure. These reaction forces come into existence from distinct mechanisms and mainly depend on geometrical configuration and features of the material for dissimilar bodies. Ground friction force is necessary for the snake to move or shift itself on a sinusoidal terrain. Friction force is calculated as [1, 35].

$$f_i = u_i \cdot sign(v) \cdot G_i \quad (2)$$

Where i = t, m (tangential and normal friction coefficient) and μ is the coefficient of friction; sign(v) depends on velocity i.e., sign(v) = 1 if v > 0, 0 if v = 0, and –1 if v < 0. Gi is the normal force on the ground given as,

$$G_i = mg \quad (3)$$

Normal force Gi is equal to the product of mass and gravity (9.8 m/s^2).

3.3.2 Torque of Snake Robot

The snake’s body moves in a linear way as well as in rotational manner. The body is made by the revolute joint that requires a rotor or some mechanism for torque installation. The torque of joint for every link in forward dynamics is calculated to determine the locomotion of the snake robot. This is done by using:

$$\tau = I \cdot \ddot{\theta} \quad (4)$$

Where τ is the torque of n-th joint and $\ddot{\theta}$ is an angular acceleration of n-th link. ‘I’ is the inertial movement of snake’s body which is directly proportional to the mass (mn) and square of length (ln^2) of n-th link.

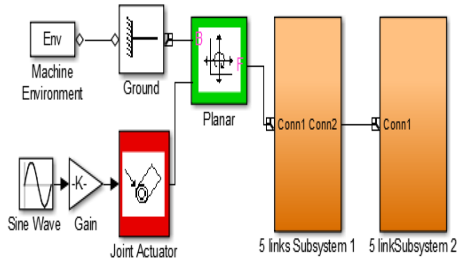

Fig. 3: Snake robot in a Simmechanics environment

3.4 System Design

System models consist of two phases: modeling and designing physical links and a joint control system for a snake robot. The whole system model is developed in SimMechanics [see fig. 3] that provides a multibody [35] simulation tool to obtain a 3-dimensional model inside the simulation domain. This 3-D design tool is composed of hard material blocks of body having various shapes and sizes, hold restraints, distinct joint elements and lot of force components for developing a complete system. Further, the system design is divided into two parts; one part is related to the design of physical link and other is related to the joint system [see fig. 4].

3.4.1 Simulink Model of 10-link Snake Robot

Snake robot consists of 10 links connected side by side through rotational joint while head of the snake at the ground via planner joint is shown in Fig. 3. Snake robot at its beginning state of motion, all three DOF are at ground (0, 0, 0) level via Machine Environment (ME) block. The ME block is used to give mechanical, visualization and simulation environment to the system so that dynamics of the system can easily determine.

All subsystems in Fig. 3 have identical blocks with only one link which is linked via rotational joint. This link-joint system is shown in fig. 4. The first lint in a model is the tail link which is directly connected to the machine environment tool via ground to provide mechanical domain to snake robot. Each joint has a 1-DOF and holds a motor that actuates the snake model at a specific angle get through the robot kinematics. Joint sensor block is used to get position, velocity and acceleration of the particular joint of the snake robot and these values are measured through scope block. While a display unit [see Fig. 4] is used in order to calculate locomotive parameters for every link-joint subsystem in a 10-link snake robot.

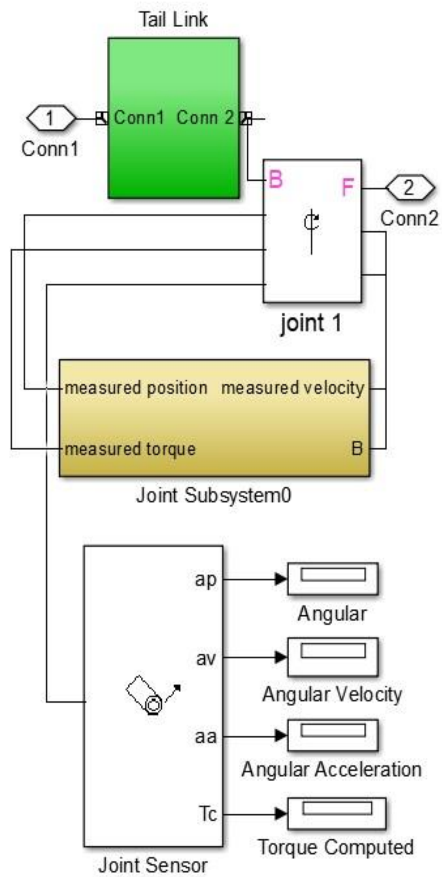

Fig. 4: Link joint subsystem of 10-link snake robot

3.4.2 Joint control system

Snake robot has greatly flexible physical structure of many degrees of freedom having complicated design movement. Robot movement needs complicated and demanding control system. With the help of kinematics and dynamic systems of the snake's locomotion, a feed-back proportional controller is developed in order to perform snake locomotion. The snake-robot is the combination of 10-links having same geometrical and material properties are linked side by side via 09 joints. The starting link of a snake robot is a passive component and is free to move through planar joint, but the remaining links are actuated by a simple motor block.

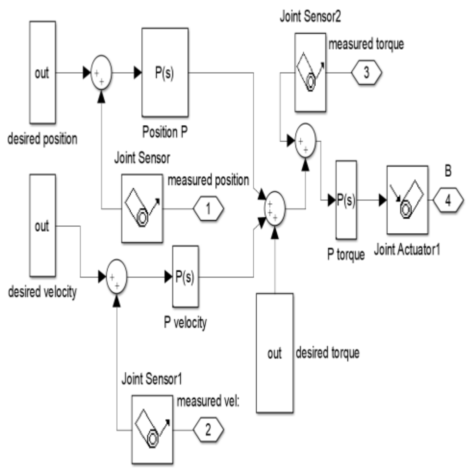

Fig. 5: Joint control subsystem

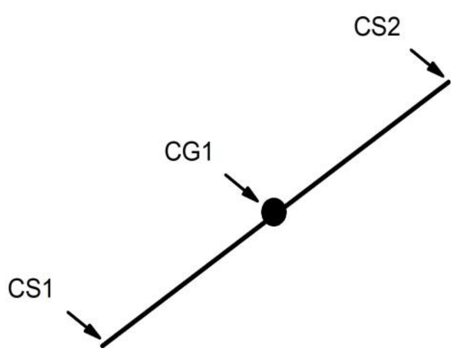

Fig. 6: Link coordinate system

The control system for each joint of the robot is shown in Fig. 5. The snake's movement can be found by three different elements which are position, velocity and acceleration. So, for controlling these three factors, feedback proportional controller is formed. Position as well as velocity for every joint constitute a desired torque command that further unites with calculated torque to offer an output torque and is controlled by a feed-back (proportional) controller. actuator1. A proportional feed-back control system is developed for every joint of the snake's model.

4. Results and Discussions

4.1 Physical Link of a 10-link Snake Robot

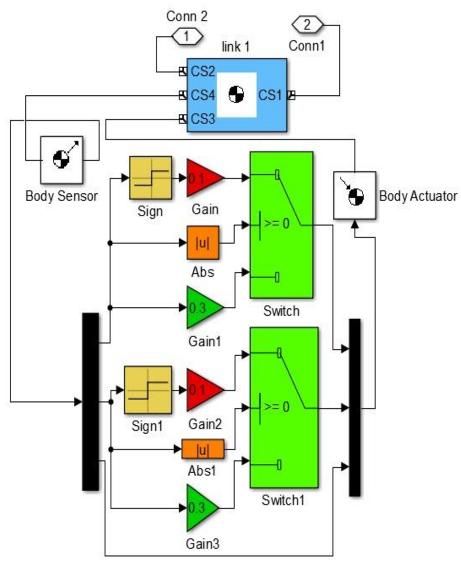

Fig. 7: Coulomb's friction module of an individual link

Snake module is developed by applying many blocks using SimMechanics followed by its mathematical model. Each link in a snake robot model is a slender rod made of steel. Its length(ln) is equal to 0.5m, and mass (mn) is set to 0.1kg. Mass of the body component is a positive quantitative value, and its inertia tensor represents as 3x3 matrix, In= [100.36 0 0;0 104166.66 0; 0 0 104166.66]. Reference systems and gravity center (CG) of a body component show the real position and orientation and indicates where it is placed and determine rotation in space. All these effects specify the initial position of body component when developing the module and remain similar even by starting simulation. The CSs of a body component are fixed hardly so it can move w.r.t to reference coordinate system. The gravity center of the body block is midway between the two coordinate systems.

Other coordinate systems like CS1 and CS2 are used to attach different components through the joint element along side by side (left and right) to the body component. The reason behind is that every component in a module like sensor needs a different CS as shown in Fig. 6. The inertia tensor of the body does not change with snake's motion and computed w.r.t the absolute World axes. A snake robot is a combination of body components linked via joints allowing locomotion of snake robot. Every link of the robot's model must touch the ground, so it is required to calculate the ground friction force. Body sensor block is used to calculate velocity of the center of each link [3].

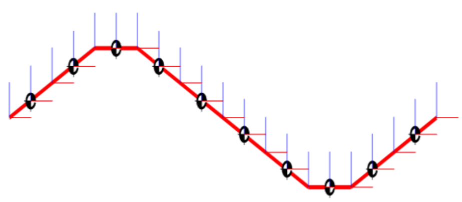

Fig. 8. Whole Snake body in Simmechanics environment.

4.2 Coulombs friction model

Each link of snake body requires a Coulomb's friction model [4] as shown in Fig. 7. A single body component is used to specify the hard cylindrical bar with mass, inertia, coordinate system attached to it (CS1 and CS2 with gravity centers CGs) to determine the snake's position along the surface area. The body's sensor block computes the velocity of body element because to shift forward, coulomb's friction module requires a velocity component. μt and μm are the friction coefficients defined as the tangential (related to x axis) coulomb friction force and the normal coulomb friction force (related to z axis) of a body component. Snakes drive their body to locomote forward is completely dependent on the difference of these two friction coefficients of normal as well as tangential forces. Sensor element attached to the body, senses and computes the velocity of a body block and output to the demux. Furthermore, demux decomposes this velocity component into three separate inputs, the tangential, normal force, and the real velocity, computed via body component as shown in Fig. 7.

Gain blocks are used to describe ground friction. Gain1 and 2 are equal to 0.1 and define the normal coefficient of friction, whereas gain 3 and 4 are equal to 0.3. Values of μ_m=0.3 and μ_t=0.1 are utilized, switch pass the 1st input (μ_t) if state one is valid, and pass 2nd input (μ_m) if state two is valid, otherwise it goes to 0. For signum function a sign block is connected between the two CFF, it is +1 for positive velocity and -1 for negate velocity element otherwise, equals to 0. The parameters Kn, α, l, m, n, tangential CFF μ_t, and normal CFF μ_m are the main characteristics which impact on the final execution of a snake robot module. To perform a locomotion of snake, the initial properties should be described for every framework of the link.

4.3 Snake physical model in simulation environment

Simulation uses a robot module, that comprises of 10-links and 9-joints. Every Joint used in robot module has a single rotational DOF along y-axes having an angle θn. Approximation for every link is done by a uniform slender rod which is 0.5m long, so that the total length of snake robot is 5m.

Serpenoid curve parameters are used for defining body shape. Fig. 8 shows an output window showing the snake's whole body after simulation. The coordinate system is attached to the starting point of each link. The coordinate system shown in black is the center of gravity for every link. Each link bents through joint angle torque.

In addition, 9th joint specifications including angular position, velocity, and acceleration, the measured torque are computed and analyzed via display unit. Here 9th joint is selected because it is a last joint of snake robot and gives highest measured values. Display-1 shows the angular position and is equal to 0.08928 deg. Display-2, display-3 and display-4 in Fig. 4 represent the angular velocity, acceleration and measured torque equals 0.08391 deg/s, 0.08949 deg/sec2 and 21.32 N.m respectively. Fig. 9 and 10 show the actual and computed angular position.

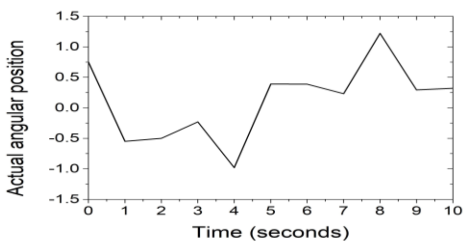

Fig. 9: Actual angular position of 9th joint

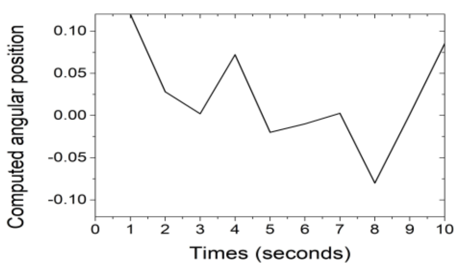

Fig. 10: Computed angular position of 9th joint

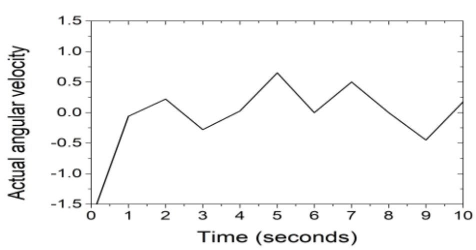

Fig. 11: Actual angular velocity of 9 joint

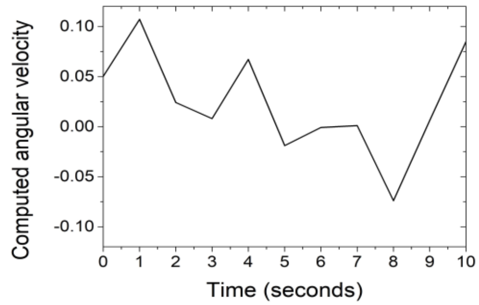

Fig. 12: Computed angular velocity of 9 joint.

Fig. 9 displays the angular position for 9th-joint via signal builder component. Snake robots built in this research has only one wave-shape therefore two peaks (+ve and –ve) are obtained at 4-sec and 8-sec. While Fig. 10 shows the output computed via sensor after simulation. The longest peak of the wave is 0.08 deg set down at 8 sec. The 3-D module system of the snake's robot is lifted up to the ground plane and then falls onto it again after 7-sec as shown in Fig. 12. The 1-sec delay is produced when compared to the input as shown in Fig. 11.

In a physical model, curve shape (k_n) of snake's module is equivalent to 1, therefore it has single touching point to the surface. Thus, force of friction at the surface is unimportant. The robot module falls over at an angle of 30-degrees or π/6 w.r.t the floor. The acceleration of 9th-joint as shown in Fig. 13, becomes 0.08948. Sensor components are used to compute it. Sensor is also utilized to compute torques for nth joint through the scope. The individual joint torques act like an input for simulation, while its output is the whole robot motion. This joint torque, and the slide of snake body in normal direction depend on the number of wave-shape (k_n), the initial winding-angle (α=0), and the environment change through the friction force (fi). Simulation results obtained show how snake-robot does glide and move forward. The torque for 9th-joint of robot is computed when it moves as shown in Fig. 14. The maximum value of torque derived after simulation is 21.32 N.m.

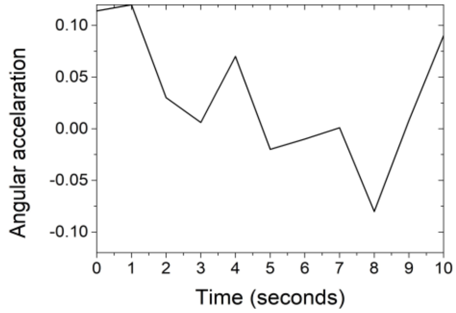

Fig. 13: Angular acceleration of 9th joint

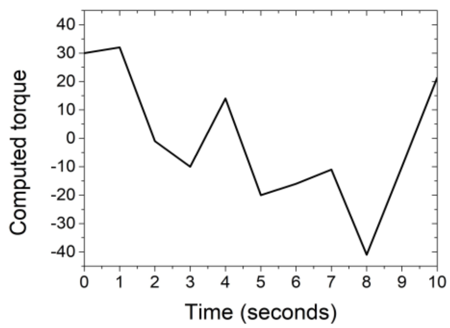

Fig. 14: Computed torque of 9th joint

5. Conclusion

A physical model of snake robot consists of 10-link is modelled and controlled by proportional joint controller. Complete module is designed via SimMechanics tool, that gives a 3-D mechanical structure to develop and simulate the complete snake robot system. Each joint in a snake robot is controlled separately, so proportional joint controller for every joint is developed. Further, kinematics, dynamics and friction force models are also developed which are necessary for motion of snake robot and are fundamental to discover the position of all 10 links in a 3-D environment. Furthermore, joint angles are calculated to rotate the robot's link on a serpenoid terrain. Simulation results reveal that, snake robot trails in a right path and follows a serpentine locomotion.

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