Journal of Engineering and Applied Sciences 13 (Special Issue 7): 5529-5535, 2018
ISSN: 1816-949X

Design and Simulation of a Limbless Climbing Robot

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Abstract: This study represents kinematic and dynamic simulation of a wall climbing robot. This is a bio-inspired robot and mimics inchworm locomotion during climbing. The 3D Model of robot is prepared in a 3D CAD modeler. The simulation of this serial chain robot has been performed in a multi-body dynamics solver. Sinusoidal velocity gait pattern is used for reaching the approximation of inchworm locomotion. The joint torque graphs of three servo motors with respect to time have been verified and maximum torque for each of the joint is marked from the postprocessor data. The robot moves by applied periodic gait and solenoids attached at the end links produce attachment force of 50 N each. Simulation is being carried out in a simulated environment with some assumptions. The generated torque is used for selection of the servo motor.

Key words: Dynamic modeling, joint torques, serial links, sinusoid gait, solenoid, inchworm robot

INTRODUCTION

The locomotion of bio-inspired crawler robots is an articulation of exploiting the movement of various limbless natural creatures like caterpillar, snake, inchworm and millipede. The excellent features of these robots are their low centre of gravity, large contact area with substrates and the uniform distribution of mass. Locomotion of common robots are fully reliant on particular gait design and supporting features like active or passive wheels, treads, passive links, supporting links, etc. But limbless robots move using body undulation. The caterpillar worm moves by forming looping gait where its posterior and interior legs are alternately gripped and released (Ghanbari *et al*., 2008). Inchworm locomotion is achieved by periodic body undulation without any appendages. A typical inchworm motion comprises of these periodic gaits (Zhang *et al*., 2011). Kinematics and dynamics of inchworm robots have been studied using significant control response. It has been observed that worm-inspired robots have experienced complex combinations of open and closed kinematic chain (Wang *et al*., 2009). These multi-link systems are characterized by a complex dynamic system interaction between individual links connected by actuated joints. Several algorithms for crawler robots have been developed to simulate open and closed chains. A worm mechanism is developed dividing it into four sub-mechanisms and each sub-mechanism is modeled as manipulator. Newton-Euler iteration algorithm is used for kinematic formulation (Ghanbari *et al*., 2008). Modeling and dynamic analysis of a planer manipulators having N revolute joints with frictional contacts at their end are carried out using Lagrangian method. Later results are applied on an inchworm robot for deriving the equations of motion (Noorani and Ghanbari, 2011). Kinematic analysis using screw theory and dynamics analysis by Lagrangian algorithm are performed for analyzing an inchworm-like climbing robot model (Yao *et al*., 2015).

Another inchworm robot is also modeled by finite automation. Two algorithms such as single stride gaits with back ward motion and multi-stride gaits with standing wave feature are derived (Chen *et al*., 2001). Multi-body simulation frame work of M-TRAN robot is prepared for controlling its locomotion (Chariot *et al*., 2012). One mathematical model has been prepared to validate the closed-chain kinematics and four-link motional method used for kinematic gait of wall-climbing caterpillar robot (Yao *et al*., 2015). Kinematic model of caterpillar robot is built up and mechanical property of its closed chain kinematics comprised of four linkage model is analyzed (Wang *et al*., 2013). Concept of Central Pattern Gait (CPG) properties is implemented into a modular climbing caterpillar robot for enhancing its novelty (Li *et al*., 2015). In this study, an attempt has been made to present design and dynamic analysis of a bio-inspired robot using parametric cubic Spline function for joint actuation and step function for solenoid ON/OFF control.

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MATERIALS AND METHODS

Design of limbless robot: CAD Model of the robot assembly has been prepared for realization of inchworm configuration. The robot consists of four light weighted identical hollow cubes. End links perform as robotic end-effector or feet. Solenoids positioned on the feet allow the robot to fasten any vertical or inclined ferromagnetic surfaces (here, shown as cylindrical mass). These solenoids cum electromagnets are energized by sending power from 12 Volt battery source intended for surface gripping. The robot is able to negotiate vertical surfaces and complex structures such as steps and obstructed surfaces. Each module is coupled with successive module by a revolute joint which provide three Degrees of Freedom (DoF) (one rotation and two translations). These joints allow the robot for extending and contraction. First three joints are coupled with R/C (Radio-Controlled) servo motors and rotate the subsequent modules. One passive DOF on the end module is resulted from the mechanism. The first and fourth modules hold the solenoids. These modules are equivalent to the legs and pro-legs of inchworm which allow the inchworm to adhere surfaces during traversing and anchoring force needed to support the sliding.

The arrangements of modules and the motors for the first three modules to generate relative motion are depicted by a 3D assembly in Fig. 1. The first module is the passive module with single articulated joint and remaining modules are active modules. Thus four modules are connected by coupling three servomotors for realization of inching and sliding locomotion of a worm robot. A±90° angular rotation at each subsequent module is theoretically assumed for pitching movement through servo motors (in general servo motors can rotate from (0-155°). Thus, pitching or D plane motion of robot is occurred when rotational axes of the servo motors are perpendicular to the base plane. Adhesion technology has been devised by providing the electromagnets at bottom surface of rear end module. The socket set screws are provided for carrying bearing load during rotation of each module.

The active joints are intended to allow the proposed robot for generation of transverse like wave motion by

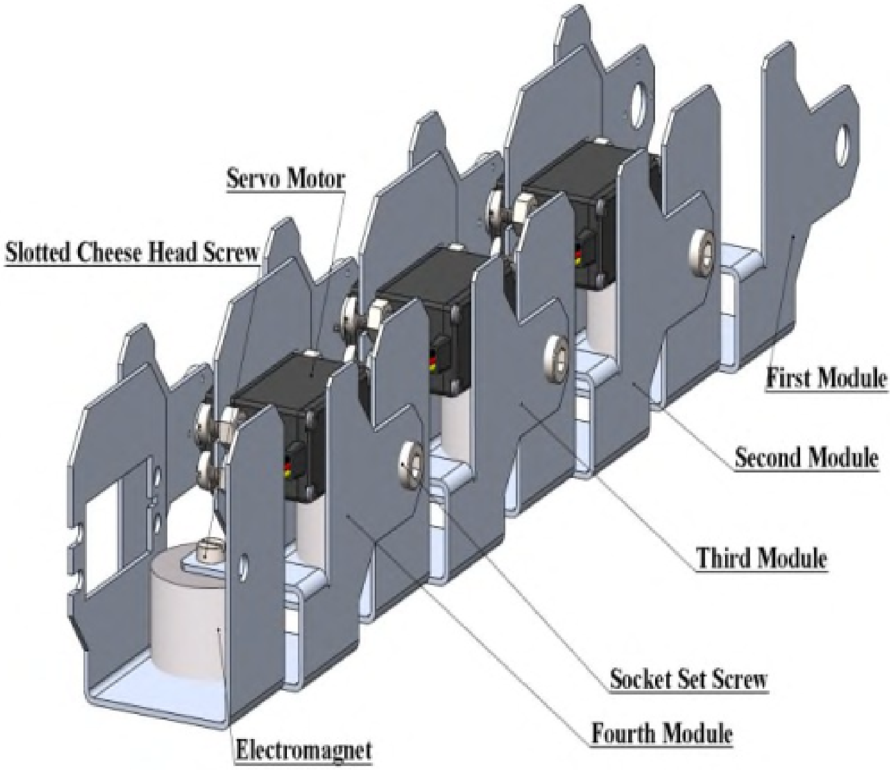


Fig. 1: The 3-dimensional CAD assembly of a four module inchworm robot is presented where servo motors are used for actuation and electromagnets are provided for adhesion during climbing only. The set screws as provided in the model are acted as bearing

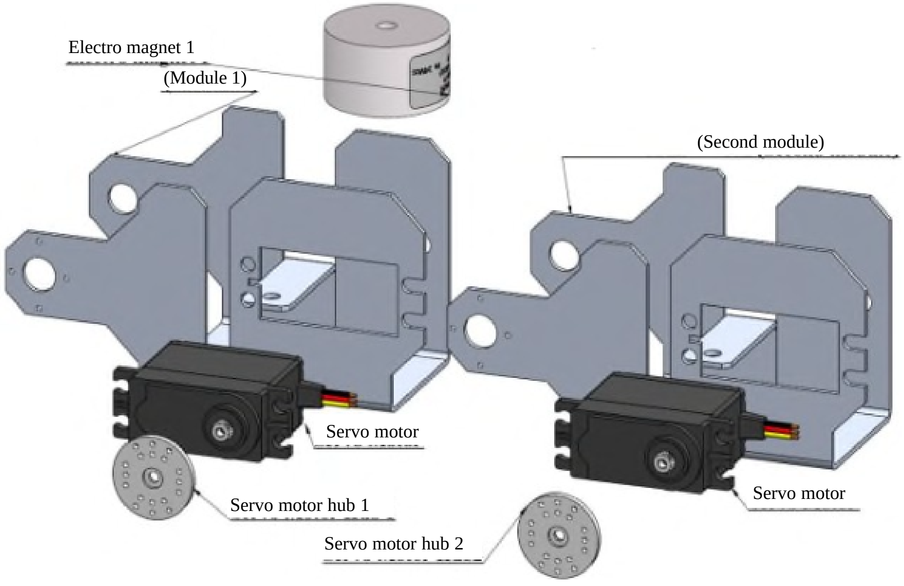


Fig. 2: The exploded view of first two modules of the robot assembly is illustrated for understanding the joint module systems and its main accessories

Table 1: Specifications of inchworm robot

Variables	Values
Module mass (g)	52
Motor mass (g) (provisional)	59
Electromagnet mass (g)	50
Payload (g)	5
Module dimension (mm): length×width×height	120×68×64
Overall length (mm)	393
Number of faces	3
Working space	[-90° 90°]

pure body undulation. The assembly technique of first two modules has been depicted in Fig. 2. The first motor is attached to the first module but rotation of the second module is actuated by the first servo. Thus three active rotational joints are available for a four module multi-link robot (Fig. 2). A flow-chart of CAD/CAE methodology adopted in order to model and simulate the robot (Fig. 3).

Each module of the robot body is 120 mm in length, 68 mm width and 64 mm in height and made of aluminium alloy (density = 2.7e^{-6} kg/mm^3). Specification of the robot is listed in Table 1.

Dynamic modeling

Mechanism of climbing: The climbing method of robot is prepared by three initiative stages. These stages can be termed by Fig. 3, lift the end and slide towards front end Fig. 4a, propagate the hump Fig.4b and stretch the front end Fig. 4c. The robot comprises of four identical bodies which forms serial link multi-segmented structure. The designed robot has to pass three steps which comprises of G_1-G_3. Servo motor rotations are denoted by M_1-M_3.

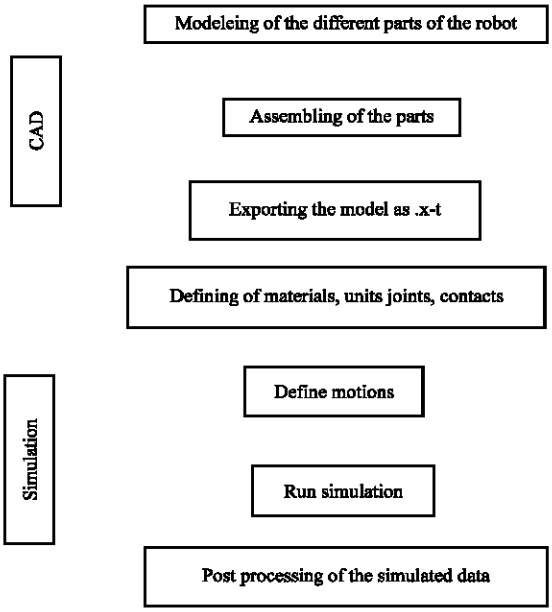


Fig. 3: A flow-chart of CAD/CAE

Two electromagnets are designated by E_1 and E_2. Figure 4a-c shows the moving principle of the inch-worm inspired robot. At initial position G_1, there are no rotations of servo motors but two electromagnets grip the surface by producing normal forces (E_1>0, E_2>0). Servo actuators rotate in a sequence (assuming counter clockwise) of fixing the rear electromagnet thus contracts the body as shown in Fig. 4b depicts as phase G_2. Then

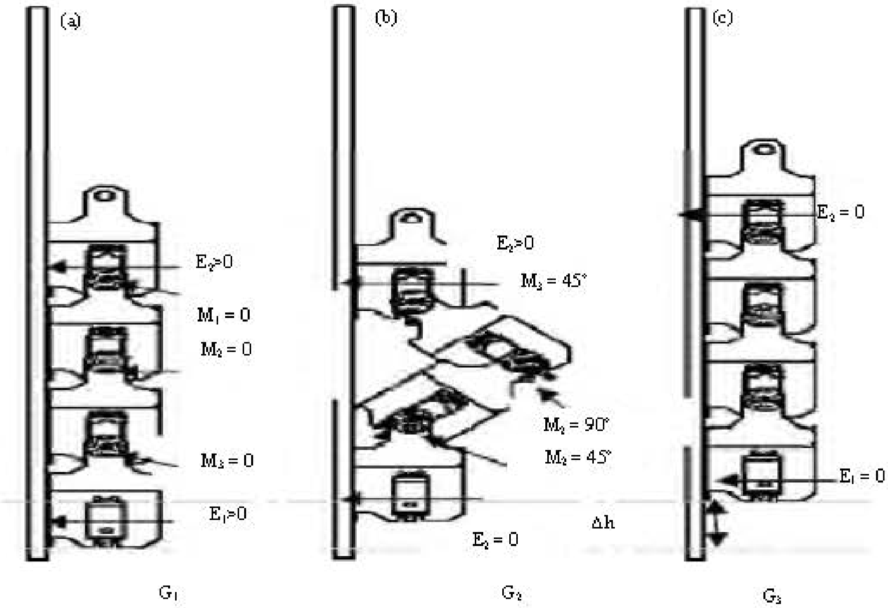


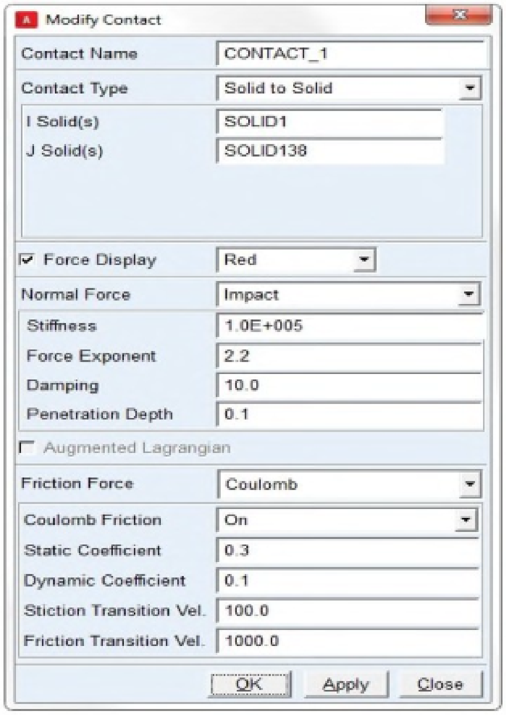
Fig. 4: a-c) The schematics of inchworm climbing using triangular wave. The step length is denoted by Δh which is the vertical distance achieved by robot after completion of one cycle. The postures at G_1 and G_3 are called open-chain state while the state at G_2 is termed as closed-chain state. During closed chain state three joints rotate simultaneously

Table 2: Kinematic and dynamic parameters of robot

Parameters	X	Y	Z
Centre of mass (location)	123.80 mm	23.265 mm	112.39 mm
Centre of mass (orientation)	176.80°C	12.41°C	183.26°C
Mass moment of inertia (kg-mm²)	Ixx 5292.1 1	Ixy 1068.92	Ixz ---
	Iyx ---	Iyy 1.41E04	Iyz 1015.06
	Izx 5263.6 1	Izy --	Izz 9496.77
Total mass	0.3810 kg		

fixing the front end electromagnet the generated triangular hump is released. The servo motors are rotated in opposite direction (clockwise direction). This operation is continued further and the robot covers longitudinal distance after completion of one cycle. Each cycle comprises of three phases G_1,-G_3. The posture and gait of the robot are devised using following condition. At G_1, $M_1 = 0°$, $M_2 = 0°$, $M_3 = 0°$, E_1 = on, E_2 = on, at G_2, $M_1 = -45°$, $M_2 = 90°$, $M_3 = -45°$, E_1 = on, E_2 = off and at G_3, $M_1 = 0°$, $M_2 = 0°$, $M_3 = 0°$, E_1 = off, E_2 = on. Then next cycle initiates.

Simulation of robot model: The multi-link robotic system is required to study the performance of functionality and exhibit its capability. The 3D mechanical design assembly is exported to simulation software in order to perform the motion simulation. The robot assembly undergoing the simulation is to understand how various components relate and what forces those components exert during operation. Thus, testing of virtual prototypes and design performance are evaluated in a simulated environment before any actual physical prototype. A simplified CAD Model of serial link inchworm robot is simulated in computer aided simulation tool. The reason for selection of simplified virtual prototype is to reduce the computational iteration. This virtual model comprises geometry of four identical modules and three servo motors, joint motion functions and external forces. One horizontal base plate is used as ground. Each motor is fixed to corresponding module by fixed joint. No motor has been fixed to the last module. Each motor is connected to the subsequent module by a revolute joint. Thus three revolute joints and fixed joints have been used for constraining the virtual model. The base plate is constrained to the ground by a fixed joint. The serial link robot has to move against gravity. The kinematic and dynamic parameters obtained from the simplified model are listed in Table 2. Following assumptions are made to simplify the rigid serial link multibody dynamic analysis.



Contact Name	CONTACT_1
Contact Type	Solid to Solid
I Solid(s)	SOLID1
J Solid(s)	SOLID138
☑ Force Display	Red
Normal Force	Impact
Stiffness	1.0E+005
Force Exponent	2.2
Damping	10.0
Penetration Depth	0.1
☐ Augmented Lagrangian	
Friction Force	Coulomb
Coulomb Friction	On
Static Coefficient	0.3
Dynamic Coefficient	0.1
Stiction Transition Vel.	100.0
Friction Transition Vel.	1000.0

Fig. 5: Contact parameters and constraints used during simulation

- The robot climbs forward in a straight flat surface with a triangular wave gait
- The profile of the servo motor motions has been represented by the cubic spline equation
- The electromagnetic forces are represented by a step function equation

Simplified model with constraints and impact based contact parameters have been defined between bodies and ground (Fig. 5).

The joint motions for each of the revolute joint are defined through run time spline function. The rotational displacement motion of motor 1 is shown in Fig. 6. Three revolute joints are defined to connect the modules such as all the axis of rotation remains parallel to each other. A vertical plate is modeled to act as a surface which is constrained to the ground by providing a fixed joint. Contact friction between the module and surface is assumed to be coulomb friction. The static and dynamic friction coefficients are taken as 0.3 and 0.1, respectively. Joint Orientation Functions (JOFs) are defined for the corresponding revolute joints as an input function to the system. The values of $0_1$and 0_2 are given as 15 and 35°, respectively. The simulation has been run for 5 sec and 500 time steps to study the at most three complete cycle. The time step illustrates an integration method in which new displacements orientations, velocities and acceleration are computed based on the acting forces on them. Joint trajectory, i.e., angular rotation of joints for two complete cycles has been shown in Fig. 6. Angular velocities of first two modules are depicted in Fig. 7 which represents STEP function with phase change.

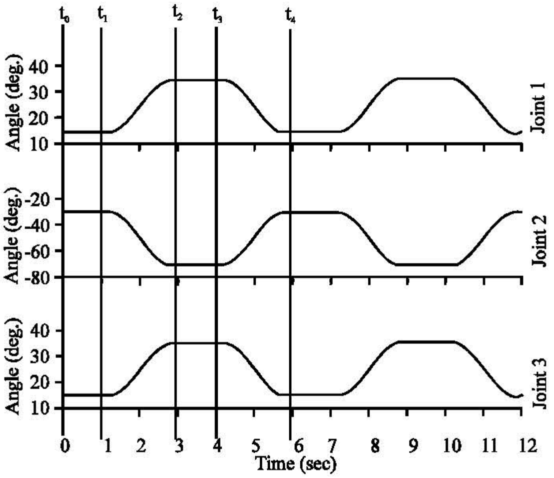


Fig. 6: Joint trajectories of three joints of robot for two complete cycle

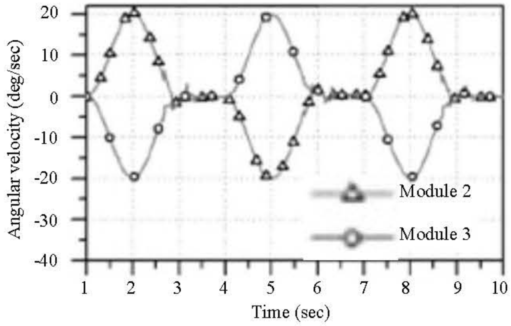


Fig. 7: Angular velocity step function for the first two modules or segments

RESULTS AND DISCUSSION

The dynamic simulation has been verified using simulation software. Simulation shows that the inchworm robot can climb vertical flat surfaces against the gravity (forward climbing) and with the gravity (inverted climbing) (Fig. 8).

Analysis of motor torque requirements: Torques required in joints are obtained after performing dynamic simulation and represented by T_1-T_3. The maximum requirement of servo motor torque for each joint is

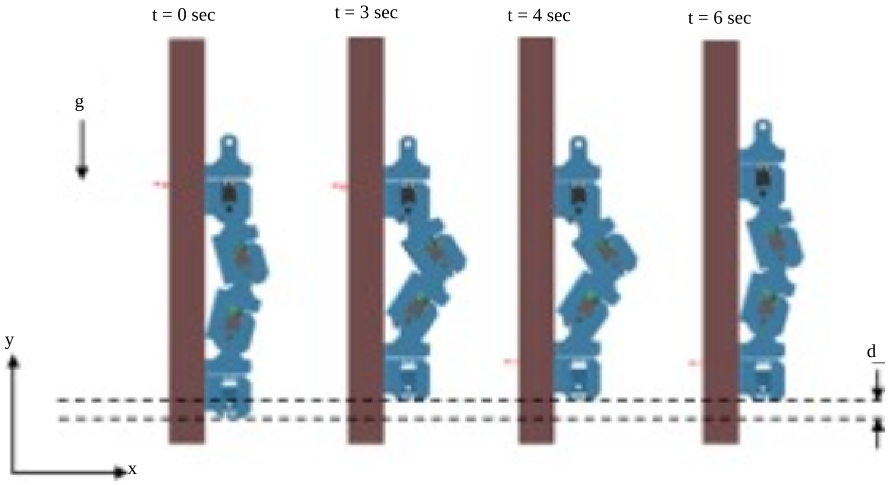


Fig. 8: Simulation results

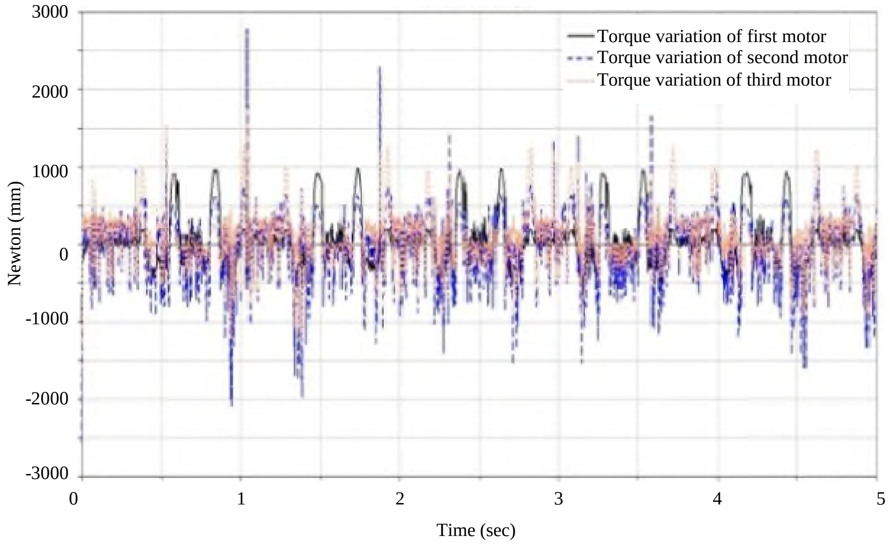


Fig. 9: Joint torques of servo motors

evaluated in solution. Then using proper gear ratios servo motors are selected. Analysis is performed here for generating torque plot of robot mobility variation. The maximum torque and its occurrence in a given range of motion have been found out based on the torque plot. The maximum peak torque values are pointed out as 10.61, 27.83 and 17.66 kg-cm, respectively (Fig. 9).

Math: Recurring sets of extension and contraction pattern of the inchworm segments are observed during travelling. A sinusoidal velocity pattern of the triangular wave has been applied to approximate the motion of an inchworm segment as shown in Eq. 1:

$$v\ (t) = A.B \sin\ (\sin\left(\left(\omega t+f\ \right)\right)+b' \tag{1}$$

where, A is the amplitude. B is the positive number greater than A/2. ω is the angular velocity (rad/sec). φ is the phase shift (rad). The dynamic equation for the each segment in motion can be represented as in Eq. 2:

$$\begin{cases} I_1\ \theta_1+C_1\ \theta_1+K_1\ \left(\theta_1\text{-}\theta_2\right)=0 \\ 1\text{-}2\ \theta\text{-}2+C\text{-}2\left(2\ \theta\text{-}2\text{-}\theta\text{-}1\text{-}\theta\text{-}3\right)+ \\ K_2\ \left(2\ \theta_1\text{-}\theta_2\text{-}\theta_2\ \right)=t_1 \\ 1\text{-}3\ \theta\text{-}3+C\text{-}1\left(2\ \theta\text{-}3\text{-}\theta\text{-}2\text{-}\theta\text{-}4\right)+ \\ K_2\ \left(2\ \theta_1\text{-}\theta_1\text{-}\theta_4\ \right)=t_2 \\ l_4\ \theta_4+C_4\ \theta_4+K_4\ \left(\theta_4\text{-}\theta_3\right)=t_2 \end{cases} \tag{2}$$

CONCLUSION

The study discusses design and simulation of a limbless climbing robot. The 3D CAD Software has been used to design the robot assembly model. The robot assembly comprises of four identical segments, three servo actuators, two solenoids at rear end segments and three socket screws. The adapted climbing mechanism mimics inchworm climbing gait for vertical surface climbing. Locomotion of robot is simple and modular segments canre place each other, if any segment breaks or fails. It will also reduce cost for manufacturing of robot parts. Each robot module is made of light weight material, i.e., aluminum as it has to climb against gravity. Maximum joint torques is derived from CAE analysis and later servo motor is selected based on dynamic simulation and motor selected is HS-5645 MG. However, selection of electromagnet is done based on trial and error method and availability such system.

REFERENCES

Chariot, I.C., E. Filippi and O. Verlinden, 2012. Simulation framework of modular robots using easy Dyn. Proceedings of the 9th National Congress on Theoretical and Applied Mechanics (NCTAM), May 9-11, 2012, Bulgarian Academy of Sciences, Sofia, Bulgaria, pp: 1243-1252.

Chen, I.M., S.H. Yeo and Y. Gao, 2001. Locomotive gait generation for inchworm-like robots using finite state approach. Robotica, 19: 535-542.

Ghanbari, A., A. Rostami, S.M.R.S. Noorani and M.M.S. Fakhrabadi, 2008. Modeling and Simulation of Inchworm Mode Locomotion. In: Intelligent Robotics and Applications, Xiong, C., Y. Huang, Y. Xiong and H. Liu (Eds.). Springer, Wuhan, China, ISBN:978-3-540-88512-2, pp: 617-624.

Li, G., W. Li, H. Zhang and J. Zhang, 2015. Integration of sensory feedback into CPG model for locomotion control of caterpillar-like robot. Proceedings of the IEEE International Conference on Industrial Technology (ICIT), March 17-19, 2015, IEEE, Seville, Spain, ISBN:978-1-4799-7800-7, pp: 303-308.

Noorani, S.M.R.S. and A. Ghanbari, 2011. Explicit dynamic formulation for NR planar manipulators with frictional interaction between end-effecter and environment. Intl. J. Adv. Rob. Syst., 8: 91-100.

Wang, K., W. Wang and H. Zhang, 2013. The mechanical properties of a wall-climbing caterpillar robot: Analysis and experiment. Intl. J. Adv. Rob. Syst., 10: 1-34.

Wang, W., K. Wang and H. Zhang, 2009. Crawling gait realization of the mini-modular climbing caterpillar robot. Prog. Nat. Sci., 19: 1821-1829.

Yao, J., S. Gao, G. Jiang, T.L. Hill and H. Yu *et al*., 2015. Screw theory based motion analysis for an inchworm-like climbing robot. Robotica, 33: 1704-1717.

Zhang, Y., S. Jiang, X. Zhang, X. Ruan and D. Guo, 2011. A variable-diameter capsule robot based on multiple wedge effects. IEEE. ASME. Trans. Mechatron., 16: 241-254.