A bio-inspired climbing robot: design, simulation, and experiments

P Chattopadhyay¹, A Majumder²*, H Dikshit², S K Ghoshal², A Maity¹

¹Central Mechanical Engineering Research Institute, Durgapur 713209, India
²Department of Mechanical Engineering, Indian Institute of Technology (ISM), Dhanbad 826004, India

*majumder.anubhab@gmail.com

Abstract. The application of bio-inspired robots on various engineering problem has become a fascinating subject. In this field, locomotion pattern of various insects has already been implemented in a notable way. The purpose of this paper is to add the magnetic adhesion principle with a bio-inspired modular robot which mimics the motion of an inchworm. This paper confines the climbing environment in a flat plane and describes a suitable climbing gait for the robot. The robot is modelled as a 4-link planar mechanism with three revolute joints actuated by DC servo motors. A 3D model is prepared and simulated in multi-body dynamics solver to investigate the kinematic and dynamic behaviour of the system. The simulated results provide an idea about the selection of servo motor specifications required to build the prototype.

1. Introduction
Climbing robot has been an area of interest since the demand of inspection of pipeline, nuclear power plant, and various big structure is growing up rapidly. Climbing robots reduce the human effort and add flexibility, intelligence to the working area. The two main aspects of designing a climbing robot are locomotion and adhesion principles. A large variety of experimental prototypes have been reported by various researchers with different types of locomotion and adhesion principles. In general, the locomotion of a climbing robot has been realized by means of wheels, tracks, legs or limbs. Conversely, research on bio-inspired limbless robots is often a fascinating development where the locomotion is solely dependent on body undulation. On the other hand, different adhesion principles have been adopted depending on the given task and working environment such as magnetic, pneumatic, mechanical, electrostatic and chemical adhesion [1].

In case of a bio-inspired climbing robot, the design is primarily guided by gait implementation philosophy. Hirose et al. [2] first investigated the shape of body articulation among the snake robots. The kinematic model of a snake like robot with a modified control strategy was proposed by Chen et al. [3] where travelling locomotion is generated in a vertical plane perpendicular to the supporting plane. From the application point of view, snake robots are suitable for complex terrain and can easily negotiate through narrow spaces but when it comes to serve the purpose of climbing, serpentine locomotion shows less capability [4]. In contrast, caterpillar locomotion provides more proficiency with simple kinematic structure. Wang et al. [5] reported a modular climbing caterpillar robot where
Vacuum suckers are used for adhesion and the prototype consists of two inchworm robots connected by a joint module. Wei et al. [6] presented a caterpillar mechanism comprises of five links connected serially through revolute joints. The caterpillar robot can propagate with different wave-like locomotion, such as a triangular wave, a trapezoidal wave, and a quadrilateral wave. However, inchworm locomotion involves alternate releasing and grasping of the front and rear modules instead of propagating waves [7]. These types of locomotion have received modest attention in literature. By considering the excellent mobility of inchworm in various terrain Kotay et al. [8] developed an inchworm robot consists of four links and electromagnets are attached to the link on both ends. The climbing robots with magnetic adhesion require a ferrous substrate and mostly applicable for smooth planar or near-flat surfaces, while the robots with suction adhesion do not have any material dependencies. Pneumatic or suction adhesion uses vacuum generators and need large suction areas to produce the desired amount of adhesion force, whereas magnetic adhesion units are able to generate strong adhesion forces on a very small area [1].

In this paper, a limbless climbing robot with magnetic adhesion is presented which can mimic an inchworm locomotion. The dynamic simulation has been analyzed by simulating the CAD model in a multi-body dynamics simulation environment. Finally, the inchworm gait has been implemented on an experimental prototype.

2. Design overview

A 3D CAD assembly of the inchworm robot is shown in Figure 1. The robot consists of four light weight module made of aluminum. Two successive modules are attached with socket set screws which also acts as a bearing during rotation of the modules. Each active module possesses a 1-DOF revolute joint and the modules are integrated with three DC servo motors. Arduino Uno board with ATmega 328 microcontroller has been selected to drive the motors as it is an open source electronic platform based on easy-to-use hardware and software. It has 14 digital input/output pins out of which 6 can be used as PWM output, 6 analog inputs, a 16MHZ crystal oscillator, a Universal Serial Bus (USB) connection, a power jack, an ICSP header and a reset button [9]. The microcontroller performs necessary computation according to given programming algorithm and sends PWM signals to the servos. The serially connected configuration can be considered as a 4-link planar mechanism with revolute joints actuated by servo motors. Each joint has a range of motion from $-90^\circ$ to $+90^\circ$. The first and last module feature electromagnets which produce required adhesion force while climbing on ferromagnetic surfaces. These modules are equivalent to the legs and pro-legs of an inchworm which allows the inchworm to remain anchored to the substrate during looping. Modularity is a significant aspect of the design which makes the robot more reliable and cost effective. In case of failure, it is easy to repair the robot by interchanging a damaged module with an identical spare module. The design specifications of the model are given in table 1.

![Figure 1. CAD assembly of the inchworm robot.](image-url)
Table 1. Specifications of inchworm robot.

| Specification                     | Value       |
|-----------------------------------|-------------|
| Mass of each module              | 52.89 gm    |
| Module dimension                 | 120mm × 68mm × 64mm |
| Mass of Servo motor              | 57.95 gm    |
| Mass of electromagnet            | 45 gm       |
| Joint to Joint distance          | 91.01 mm    |
| Payload (i.e. mass of batteries) | 80 gm       |

3. Gait description

In this paper, we assume that the robot moves forward along a straight line on a planar vertical surface, where three joints are actuated to execute a redundant inchworm locomotion. The sequence of gait generation can be divided into four successive steps as shown in Figure 2. For the duration of time $t_0$ to $t_1$, the front module is attached to the surface and the joint angles remain constant after that simultaneous rotation is given to all the joints for the period of $t_1$ to $t_2$ in such a way that the rear module slides towards the front module. After time $t_2$ the front module is released and the rear module is remained attached to the surface throughout the succeeding steps and during $t_3$ to $t_4$, simultaneous rotation is given to all the joints but in the reverse direction to extend the front module in the forward direction.

To accomplish the proposed locomotion strategy, the joint trajectories are formulated as piecewise sine functions bounded by time domain [10]. The functions which govern the pattern of rotation of servos can be abbreviated as Joint orientation functions (JOFs). Equations (1) to (3) denotes the JOFs for one cycle of the gait.

$$
\varphi_1(t) = \begin{cases} 
\theta_1, & t \in [t_0,t_1] \\
\theta_1 + (\theta_2 - \theta_1) \left[ \Delta_1 - \frac{\sin(2\pi \Delta_1)}{2\pi} \right], & t \in [t_1,t_2] \\
\theta_2, & t \in [t_2,t_3] \\
\theta_2 - (\theta_2 - \theta_1) \left[ \Delta_2 - \frac{\sin(2\pi \Delta_2)}{2\pi} \right], & t \in [t_3,t_4]
\end{cases}
$$

Figure 2. Sequence of gait generation.
\[ \varphi_2(t) = -2 \varphi_1(t) \]  
(2)

\[ \varphi_3(t) = \varphi_1(t) \]  
(3)

Where, \( \Delta_1 = \frac{t-t_1}{t_2-t_1}, \Delta_2 = \frac{t-t_2}{t_3-t_2} \), the minimum and maximum angle of the second module with respect to the line of motion is designated as \( \theta_1 \) and \( \theta_2 \). The time dependent JOFs of joint 1, joint 2 and joint 3 are expressed as \( \varphi_1, \varphi_2 \) and \( \varphi_3 \) respectively.

The net displacement per complete cycle, \( d \) can be calculated using equation (4) where, \( l \) is the distance between two adjacent joints.

\[ d = 2l(\cos \theta_1 - \cos \theta_2) \]  
(4)

**4. Dynamic simulation**

The simulation model provides an inclusive view of a system behaviour without testing the system in the real world. It is possible to derive a dynamic model by analytical methods, but in certain cases, the mathematical model involves some assumption and approximation. Due to that, the analytical results are not accurate enough, thus simulation is endorsed as an efficient way to validate the feasibility of the system.

A simplified 3D CAD assembly is exported to MSC ADAMS in order to perform the motion simulation. The reason for the selection of simplified virtual prototype is to reduce the computational iteration. The virtual model is shown in Figure 3 which comprises of four identical modules, three servo motors, two electromagnets attached to the front and rear modules and batteries. Three revolute joints are defined to connect the modules such as all the axis of rotation remain parallel to each other. A vertical plate is modelled 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 0.61 and 0.47 respectively. Joint orientation functions (JOFs) are defined for the corresponding revolute joints as an input function to the system.

The system has been simulated for 24 seconds with a step size of 0.05. The angular velocities of module 2 and module 3 are shown in Figure 4. The required joint torques are obtained from the dynamic simulation. Figure 5 demonstrates the variation in joint torques with respect to time where the maximum torque value is about 0.302 N-m. The simulated torque value indicates that the servo motors (rated torque capacity of 10.3 kg-cm or 1.01 N-m) are capable enough to drive the robot during the experiment.
5. Experiments

Based on the design parameter value, the experimental prototype of the climbing robot has been developed (Figure 6). The robot has been tested successfully on a ferromagnetic flat surface. At present, the robot is driven by an isolated DC power supply through a wire and can climb a maximum 

![Figure 5](image5.png)

**Figure 5.** Torque simulation of the joints.

![Figure 6](image6.png)

**Figure 6.** The experimental prototype.

![Figure 7](image7.png)

**Figure 7.** One cycle of the inchworm robot while climbing on a vertical ferromagnetic surface.

![Figure 8](image8.png)

**Figure 8.** Angular rotation of joint 1 during one cycle.
distance of 2m (i.e. the height of the available ferromagnetic surface) in a straight line until a “stop” command is received. A gyro sensor is used to measure the angular displacement of the joints. A series of snapshots are presented in Figure 7 which apprehends the inchworm motion for the progression of one gait. The time of one complete cycle is 18.25 seconds. Figure 8 shows the experimental angular rotation of joint 1 during one cycle. The maximum distance covered by the robot after one cycle is measured as 2.55 cm. Hence, the average climbing speed of the robot can be calculated as 0.139 cm/s.

6. Conclusion

This paper describes the development of a bio-inspired climbing robot with a reconfigurable modular structure. The design configuration of the robot comprises of four identical module connected by three revolute joints which can be considered as the basic and simplest design as an inchworm robot. Experimental results show that the robot can climb safely according to a predefined locomotion gait. Since the robot is designed as a planar mechanism, it can only follow a straight path.

In future work, the number of degrees of freedom can be increased for each revolute joints so that the robot can steer while navigation. An additional control system can also be introduced for driving the servo motors which will enhance the precision and smoothness during the operation.

References

[1] Schmidt D and Berns K 2013 Climbing robots for maintenance and inspections of vertical structures — A survey of design aspects and technologies Rob. Auton. Syst. 61 1288–305
[2] Morishima A and Hirose S 1990 a Mobile Robot with an Articulated Body Int. J. Rob. Res. 9 99–114
[3] Chen L, Wang Y, Ma S and Li B 2003 Analysis of traveling wave locomotion of snake robot Rissp 2003 365–9
[4] Wang K, Wang W and Zhang H 2013 The mechanical properties of a wall-climbing caterpillar robot: Analysis and experiment Int. J. Adv. Robot. Syst. 10 1–11
[5] Wang W, Zhang H X, Wang K, Zhang J W and Chen W H 2009 Gait control of modular climbing caterpillar robot IEEE/ASME Int. Conf. Adv. Intell. Mechatronics, AIM 957–62
[6] Wei H, Cui Y, Li H, Tan J, Guan Y and Li Y D 2013 Kinematics and the implementation of a modular caterpillar robot in trapezoidal wave locomotion Int. J. Adv. Robot. Syst. 10 1–11
[7] Plaut R H 2015 Mathematical model of inchworm locomotion Int. J. Non. Linear. Mech. 76 56–63
[8] Kotay K and Rus D 2000 The Inchworm Robot : A Multi-Functional System Auton. Robots 8 53–69
[9] Zolkapli M, Al-Junid S A M, Othman Z, Manut A and Mohd Zulkifli M A 2013 High-efficiency dual-axis solar tracking development using Arduino Proc. 2013 Int. Conf. Technol. Informatics, Manag. Eng. Environ. TIME-E 2013 43–7
[10] Maity A and Majumder S 2011 Serpentine robot moves and postures IEEE Conf. Robot. Autom. Mechatronics, RAM - Proc. 202–7