An Overview on Development of Flying Snake-Like Robot for its Motion Adaptability

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Abstract— In field of Robotics, number of research on Snake-like Robots for their motion adaptability has been done. It's a revolutionary era in which the robots are not specifically designed to mimic the convectional type motions related to automobiles, instead represents the motion of animals and creatures in our environment. In this paper an overview of advantages of 3D-snake-like robot over conventional mobile robots in our environment for movement in most difficult and undulating terrains such as dessert, water, cave and tree etc. has been discussed which can adapt to many configurations. The studied and designs for various types of locomotion on ground or in air has been discussed. Most importantly, the experiments performed on Chrysopelea Paradisi (Flying Snake) have been discussed for its computational analysis. In this, various experimental results extracted from different Research is presented. The validation is provided for the mobility of this robot through various publications.

Key words: Chrsopelea Paradisi, Glide Ratio, Angle Of Attack, Lift and Drag Force

I. INTRODUCTION

Every species for its survival needs to adapt uniquely for their motion and movement according to their surroundings in day to day life. The snake is from one of them. The world is full of snakes which are found in numerous varieties almost everywhere. They have the ability to adapt to frequently changing environments. Thus these biological creatures have inspired many scientists for the development of snake-like robot which can be brought to use in many applications where motion in rough terrain is still a big challenge. The complexity involved in the motion of these reptile species can help in the design and development of such robots for their unique undulating locomotion. Following are the list of works related to the snake-like-robots studied and developed:

1) Hirose's along with his team developed "The ACM snake-like robot" in 1970s.
2) The snake like robot which has the ability to adapt 3D motions in "Active Cord Mechanism is the ACM-R3 robot", is the latest one.
3) A robot with 3 DOF was developed by Chirikjian. He proposed the kinematics of the spine of the snake through parallel mechanism.
4) A 3D climbing robot was developed by Nilsson, which could climb to a good height.
5) Dowling designed a snake-like robot was created for understanding and manipulating the crawling movement of snake.
6) "The GMD-Snake robot" developed by Klaassen and Paap had driven wheel mechanism for improving propulsion near the belly area.

So it is very clear that experiments have been conducted on the adaptability of the motion of the snake so as to develop a robot which can be as flexible as the species. The focus and interest of researchers have always been on the adaptation of the mobility of the reptile for locomotion's exhibited by them. Some of such movements are twisting, crawling, linear motion, side-winding and circular motion. But it is difficult to exactly manipulate their motion due to many naturally occurring reasons. Development and control of snake robots is generally quite challenging work.

Another Species of snake commonly found in south-east Asia and southern most China, India and Sri Lanka are Chrsopelea Paradisi. This species is known as flying snakes which belong to the family Colubriade. These are 0.6 m to 1.2 m in length and have the capability to climb up to 10 m of height.

Fig. 1(a): Advancement in Snake like robot from 1972-2015

II. PREVIOUS MODEL AND EXPERIMENTAL SETUP FOR FLYING SNAKE

In the current paper the experimental setup for a 21 flying snakes prepared by Jhon J. Schoa has been considered. Snakes of mass range of 3.0 to 82.7 are taken. They are ranging in length from 31.0 to 86.5 cm. This length is termed as as snout–vent length (SVL). The trajectories have been studied for desired results for 14 snakes. They made sure that the trajectories did match with their assumptions. A 2–4 months old was the youngest snake and adult snakes were considered as largest ones. The experiments were done on both males and females snakes.

Mainly tis study focused on the performance characteristics of the species. This setup was done in the animal room in the Reptiles Division of the Singapore Zoological Gardens. The protocols were sincerely followed. No public interactions were made. It was all setup in an open room. The temperature of approximately 25to 32°C was maintained. The relative humidity of 50–70% was also maintained. These were taken in accordance to the ambient conditions required for the snakes to survive. The reptile was carefully examined as permitted by the University of Chicago Animal Care and Use Protocol Committee (IACUC #70963).

A tower of height 9.62 m was installed. From which snakes jumped to the tree. The branches of the tree were straight (approx.). For Chrysopelea to have proper grip, the branches were given required roughness. In relation to tower front, the coordinate system was chosen. The x-axis was

taken as side of the tower. The y-axis projected perpendicular to front. The z-axis was taken vertical. At the top of the tower, 2 Sony DCR-TRV900 digital video cameras (NTSC standard; Tokyo, Japan) were installed. It was 12 m above the ground. It was mounted so as to give visualization of sides. It was positioned in a way to experience minimum vibration.

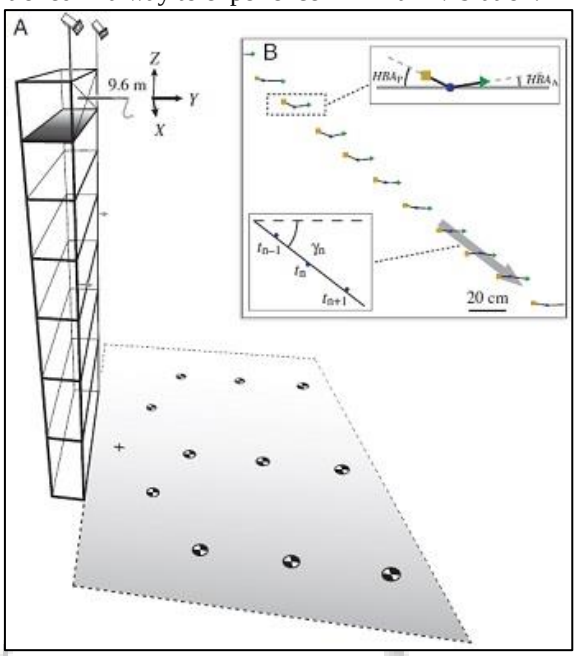

Fig. 1(b): Experimental Setup [4]

A. *Trajectory variables*

The following variables are used to measure the performance of the snake for its gliding mechanism during the aerial motion. A trajectory of glide originates at the time of complete aerial condition of the body.

1) Glide Distance ratio

It is the ratio of the horizontal distance traveled to height descended. It shows the performance of the glided body. Greater the glide distance ratio, the more is the distance travelled by the body while decreasing in height. The glide distance ratio is same as the ratio of lift force and drag force, for the balanced position. It is given by the cotangent of the glide angle. For calculating glide distance ratio, glide angle is taken to be minimum for a particular trajectory.

2) Ballistic dive angle

The velocity of the glider is less during the start of the flight. This is because the lift magnitude is small at the time of star and since the speed is proportional to the square root of the lift, sot it is also small. The time period for it to drop in a form of a projectile is called the ballistic dive. When a glider falls from rest with a positive angle of attack, it will have almost 90° glide angle, and this angle decreases with increase in speed.

3) Speed and acceleration

The speed of the snake in air while following the trajectory is calculated by the distance between the co-ordinates and the time travelled in the 3D space.

The falling speed and horizontal speed in air were calculated with the help of vertical and horizontal components of velocity, respectively. Method of least squares was used in calculating acceleration in the trajectory with the speed vs time plot.

4) Body angle of attack (α)

In aerodynamics, angle of attack is the angle between the chord line of the airfoil (the line that connects the leading and trailing edges) and the direction of oncoming airflow. Angle of attack is an important aerodynamic parameter – in general, as angle of attack increases, lift and drag increase until stall occurs (Bertin, 2001). Because the orientation of local camber was not recoverable based on the coordinate data alone, a body angle of attack was used as a proxy for true angle of attack. We defined body angle of attack as the angle between a segment's body axis and the local trajectory

5) Lift and drag coefficients

The lif and drag coefficients are calculated from the lift and drag forces per unit length for the given fluid density 'ρ', free-stream velocity 'u', area of cross-section 'a' and length 'c'. The lift and drag forces per unit length are calculated by integration of force distribution throughout the body. These forces act normal to the area of cross-section applied.

6) Vorticity

The vorticity is the component of flow which is perpendicular to the palne of flow, in 2D flows. It is calculated as the twice of rotation.

7) Pressure field

Pressure field is important criteria for calculating the glide performance because the force acting on a bluff body is mostly due to the differences in the pressure at the surface. Forces do not depend on friction much.

III. Computational Analysis

The computation of glide angles, forces and pressure field was considered for two snakes. They were allowed to take eight glide trials successfully. Their mass being 25.5 and 42.0 g, vent length being 60.3 cm and 74.0 cm, respectively. With the help of Adobe Premiere software (version 6.0), the output was analyzed with the help of video having 60 Hz images. Using Adobe Photoshop software (version2.0) visualization was improved and adjusted for the required points of identification, colour, contrast and brightness [1]. For the reconfigured landmarks on the snake body co-ordinates, the Residual Mean Square (RMS) method is used for error approximation. It measures all the error occurring in the co-ordinate space of the snake. The error at the start and end was high. It was least in middle of the glide. This was obtained from pattern recognition with the help of four cameras. But only two cameras were used since others showed the fields that were overlapping with each other. That means only at the start and at the end the sequence was measured. The measured value of usual RMS errors at the start, intermediate, and at end were 4.9, 0.7, 2.5 cm, 1.4, 0.7, 0.9 cm, and 19.5, 1.5, 9.8 cm in the X-, Y-, and Z-axes, respectively [2].

Few co-ordinates were lost at some places. This was because during the measuring of glide points, some features overlapped [1], [2]. Third order polynomial was used for filling the gaps due to missing points. Co-ordinate gaps were filled using a third-order in which the missing points were replaced by adding two values before and after them. All calculations were done within the specific time duration. Then after gap noise of high frequency was filtered. A Butterworth filter was used. The Second-order polynomial was taken into account for calculating the cut-off frequency, shown in eq. 1 and 2 [4]:

$$h_c=(0.06h_s- 0.000022h_s^2+5.95)/rms \quad (1)$$

$$\text{rms} = \frac{\sum_i (x_i - x_i^f)^2}{\sum_i (x_i - x_i')^2} * 100 \qquad (2)$$

Where, h_s is the sampling frequency (60 Hz). The rms is the residual mean square. The x_i is the raw data. The x' is the average and x^f is the filtered data [2].

Now calculations for instantaneous center of mass were done. Thus, postures of the body changing with time and mass distribution were analyzed [5]. The five landmark points were insufficient to show complete position of body. Thus, curve fitting of the spline of snake was utilized.

Nevertheless, the methods used initially didn't provide desired results but to improve upon, model of snake was rectified. The snake model was divided in four fragments of equal mass. The position of each fragment was determined using the eq. 3 in reference to the assumed center of mass [4]:

$$D_{CoM}=(D_{Head}+2D_{quater}+2D_{mid}+2D_{3quater}+D_{vent})/8 \qquad (3)$$

Where, D is the 3D position for particular landmark. The co-ordinates were rotated so as to align with the path prescribed in XZ plane [6]. This was due to the reason that snake trajectory was a bit distorted. Also it involved various rotations. Using center of masses of adjacent co-ordinates, vector for displacement was implemented [4]. It defined rotations relive to XZ plane. Further this angle was used to rotate all co-ordinates. It was recurred along the whole path of the snake trajectory. This enabled the path to form straight line without changing other variables. The total displacement of the center of mass was kept same [1]. Calculations for the instantaneous velocity (v), acceleration (a), and glide angle (θ) at any time (t) were done in XZ plane using eq. 4a,b and c [2]:

$$v_\iota(t) = \frac{P_\iota(t+\Delta t) - P_\iota(t-\Delta t)}{2\Delta t} \qquad (4a)$$

$$a_\iota(t) \frac{P_\iota(t+\Delta t) - 2P_\iota(t) + P_\iota(t-\Delta t)}{\Delta t^2} \qquad (4b)$$

$$\theta(t) = \tan^{-1} \frac{v^x(t)}{v^y(t)} \qquad (4c)$$

Where, t = 1 min or 1/60 s during the simulation time. The five landmarks are denoted by 'lm' or the CoM. X and Z constituents of velocity are signified as v^X CoM and v^ZCoM.

A. Mathematical Modeling

The lift is to drag ratio (C_L/C_D), was computed using the two eq. 5 and 6. It gave the value of loading at the wing or on the body in air. It is denoted as WL. It is also theoretically computed. Also with these equations of motion the velocity during take of was calculated for the glide body. Simulations were done numerically. It was assumed that forces due to lift, drag and weight are steady [2]. 2D simulations were performed for the prescribed trajectories with the help of the following equations:

$$\text{Lift} = \frac{1}{2} A\rho C_\iota (v_x^2 + v_v^2) \qquad (5)$$

$$\text{Drag} = \frac{1}{2} A\rho C_D (v_x^2 + v_v^2) \qquad (6)$$

Where, 'A' is the area of cross-section. 'ρ' is the density of air (~1.2 kg/m^3). 'C_L and C_D' are the lift and drag coefficients, respectively. 'v' is the mean velocity. In the ODE Solver, these equations are computed. It is an ordinary differential equation solver set [3].

In this solver Isoda functions were written to solve the total values velocity, acceleration and position with respect to time. These were calculated separately for vertical and horizontal components. It was done by calculating the lift and drag force in their respective direction. Thus, was fed to Isoda function. All values assumed were WL in mg/m^2, 'g' is taken as 9.8 m/s^2 and 'ρ' density of air (~1.2 kg/m^3). They were considered constant throughout computation. The best, worst and medium performances were analyzed. To have more clarity the ration of C_L/C_D were considered for different loading [2].

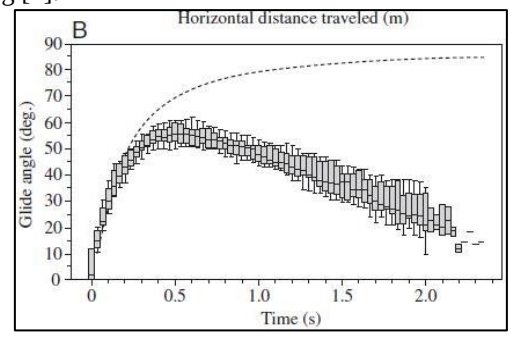

Fig. 2: Glide angle vs Time trajectory [4]

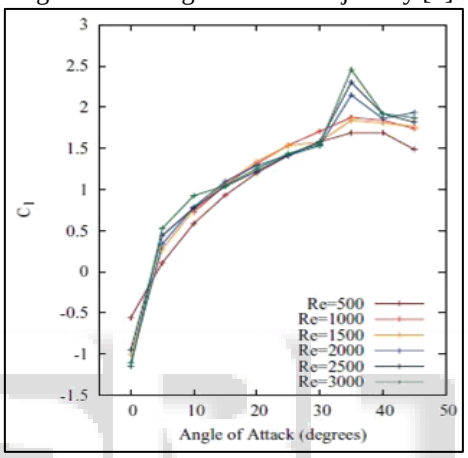

Fig. 3: Average lift force – Coefficient of lift vs AOA [2]

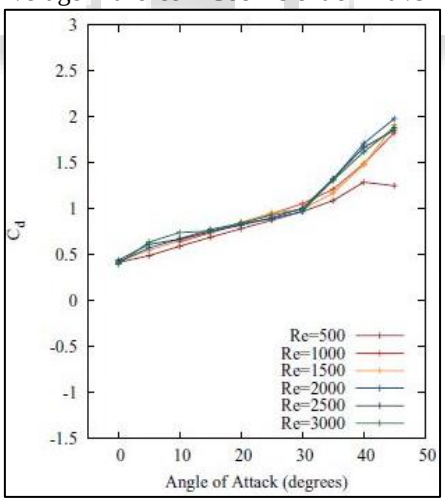

Fig. 4: Average drag force- Coefficient of drag vs AOA [2]

IV. RESULTS AND DISCUSSION

From the above computational study performed by Daniel Holden and Socha, the following results were concluded for the aerodynamic behavior of a flying snake:

- The lift coefficients (C_L) and drag coefficients (C_D) on the snake profile are obtained as a part of aerodynamic study.
- Flatten the snake profile: negative lift coefficient at 0 degree

- The value of lift coefficient increases from 5 to 40 deg. Angle of attack during which drag coefficient also increases.
- At high Re= 2000 to 3000 there is sudden jump in lift coefficient curve with value peaking to 1.6
- The lift coefficient increases upto 35 deg. gives best aerodynamic performance for the snake profile.
- The pressure fields and velocity distribution around snake profile for angles 0, 35, 45 and 50 at different Reynolds number of 1000, 2000 and 3000 are shown in the figure.

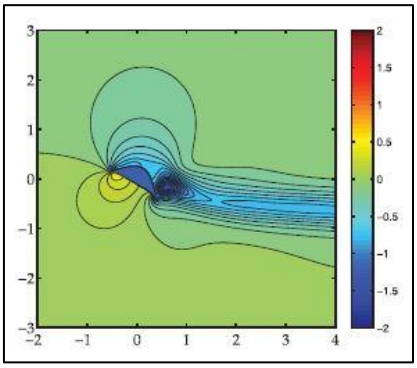

Fig.5. For Re=1000, angle of attack is30˚

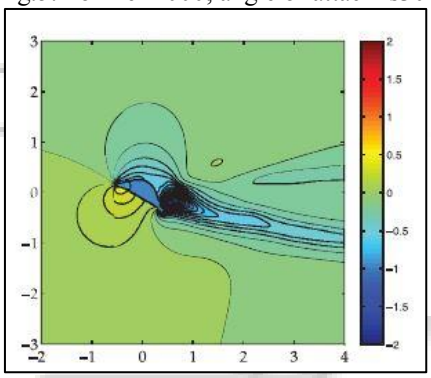

Fig. 6: For Re=2000, angle of attack is 30˚

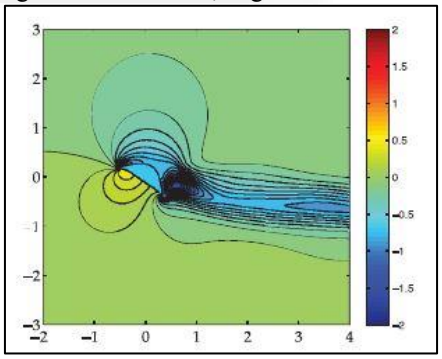

Fig. 7: For Re=1000, angle of attack is 35˚

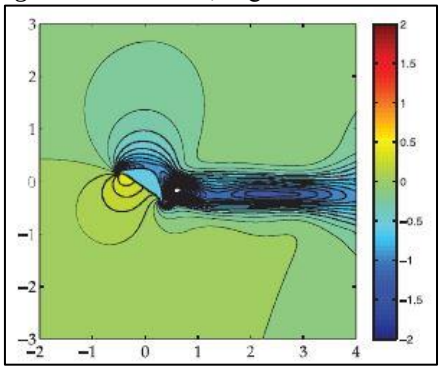

Fig. 8: For Re=2000, angle of attack is 35˚

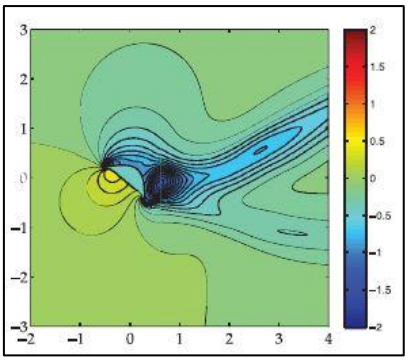

Fig. 9: For Re=1000, angle of attack is 40˚

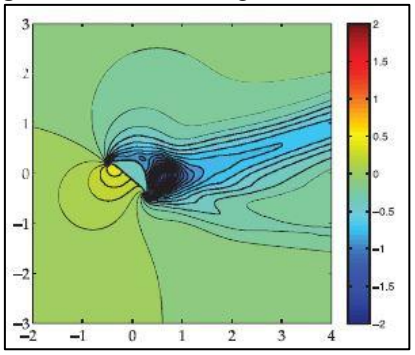

Fig. 10: For Re=2000, angle of attack is 40˚

Figure 5 -10 shows the average value of pressure fields during glide for *Re* varying from 1000 to 2000 and for particular AOA as 30◦, 35◦, and 40◦ [1][2]

From the previous works we can also say that snake do not have any typical cross-section. Due to which at AOA of 30 degrees it can stall. It can even delay it up to 30 degrees. This generates a dynamic behavior in the snake. Such lifts are very unstable and also difficult to compute stalls at this position. The vortex flow along with lift can be utilized for quasi-static processes. The results are generated for approximated body cross-sections. It may establish a laminar flow analysis on such aerodynamic bodies. It also leads to the analysis of boundary layer. The interaction of body with the flow develops a boundary along its surface. Future aspects lie in studying the concept of boundary separation and their affects for these bluff bodies. The current study shows that such devices can also be made. Based on the biologically inspired snake, devices can be used for different applications. Indeed it is very challenging work to do. But such experiments increase the possibility of designing devices which are inspired from living organism.

V. CONCLUSION

The analysis and simulations were performed for snake body and profile. The position and orientation as results were obtained. For different postures of snake aerodynamic studies were conducted. It was helpful for understanding snakes movement while gliding. Also a clear prospective of performance characteristics was given. All these are done on actual snakes so an airborne vehicle can also be designed with the help of these parameters. From this we can conclude that, flexible bodies behave as fluid-structure-interaction (FSI), when flowing in the air. The body of snake in air is similar to the buff body. Thus, load applied by the flow will help the bluff body to glide. This is due to the momentum exerted by the flow. It appears streamline but is not considered as an airfoil.

The vorticity is also induced in it. This can be measured through the frequency of undulation. When the amplitude of undulation increases, body moves away from head. In turn changes to the frequency characterized by the body. It has a distinct range for each segment. This increases possibility of vorticity during lift.

The characteristics of the snake gliding for this particular cross-section were presented. These are satisfactory aerodynamic characteristics. The kinematics can further be improved. It is quite sufficient for the design of airborne devices with similar cross-sections. Analysis in presence of smaller Reynolds number can provide more improvement in performance of such devices if developed.

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