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Research Article

Design, Fabrication and Gait Planning of Alligator-inspired Robot

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Abstract

This paper reports design, fabrication, and gait planning based on high walk diagonal trot gait pattern of an alligator-inspired robot having eight degrees of freedom. Each leg of the robot described in this paper has two revolute joints representing the hip and knee respectively which are actuated by servo motors. The body of the robot was fabricated on a CO_2 laser cutting machine. The 3D leg design was dividedinto two 2D components to enable manufacturing on a laser cutting machine to reduce fabrication cycle time. Finally, a general-purpose kinematics based model has been reported that is used to designand implement a high-walk gait on the developed robot.

Keywords: *gait design, bio-inspired robotics, multi-legged robots, high walks, kinematics, alligator, reptilian locomotion.*

1. Introduction

Legged locomotion is one of the most successful locomotion patterns found in the nature. Evidence of first locomotion among biological organisms is around 585 million years old. This means that it took the evolution process around 585 million years to evolve various forms of walking gaits. Quadruped walking in many mammals and reptiles have made them very successful in surviving against tough environments such as uneven terrains. In comparison, humans invented wheel-based locomotion around 4000 years ago. Nature evolved legged locomotion instead of wheels because more than half of Earth's landmass cannot be traversed by wheels, even today.

It is thus the imperative for the roboticists to learn the design and gait patterns from the phylogenetic analysis of biological organisms and try to mimic them as closely as possible to improve the performance of existing robots.

In this paper, design, fabrication, and gait programming of an alligator-inspired robot have been accomplished. Alligator exhibits a particular type of reptilian locomotion. Alligator locomotion is generally considered as an intermediate step in the evolutionary paradigm of vertebrate locomotion (Fish, 2001; Blob, 2001; Parrish, 1987). At one extreme, are the amphibians and lizards who are natural sprawlers. Their limbs are held laterally to the body. At the other extreme, are the mammals and dinosaurs exhibiting erect locomotion posture (ELP). Humans exhibit ELP too. In ELP, limbs are held directly under the body. Reptilian locomotion posture of crocodiles and alligators is considered to be an intermediate locomotion posture between these two extremes as a kind of transition from sprawl-to-erect (Renous, 2002; Reilly, 1998; Charig, 1972; Rewcastle, 1981).

Another interesting feature of alligator locomotion that has come to light is that alligators still use sprawl to negotiate muddy lands at low speeds while high walk is activated on drier lands at higher speeds. This transition between different gaits as a function of speed is a general locomotion feature (Hutchinson, 2013; Willey, 2004).

Most reptiles can actually adapt to an amphibious habitat. Thus, imitating a reptile can help in development of robots that can perform both terrestrial as well as aquatic locomotion. But building robot designs inspired by biological counterparts can enable us in imparting critical ethological functionality to robots. Moreover, it has been studied that artificial intelligence can be developed more efficiently in bio-inspired compliant designs (Pfeifer, 2006, 2007; Floreano, 2008).

Success of biological designs lies in the optimal cooperative and coordinated interplay among the following factors (Vincent, 2006):-

a.) Availability of optimal energy generation, storage and conversion mechanisms.
b.) Ability of memorising, storing, processing, internalising and passing information.
c.) Complaint and robust structural features that can adapt to various environment.

This is what has inspired the fields of biomimetics, biokleptics and bio-inspiration. However, exact mimicking of reptilian gait (biological gait in general) is plagued with following challenges:-

a.) Mechanical complexity of nature is overwhelming. Fabrication of intricate skeleton-muscular system, which gives enormous agility to animals, is very

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difficult to replicate using existing manufacturing technology.

b.) Imitating self-replicating biological units like cells cannot be fabricated in laboratory easily.

c.) Energy generation and storage mechanism in biological systems are not understood to an extent that it can be copied in robots.

Therefore, in the light of the above-mentioned motivations and challenges, many researchers have proposed the use of biological inspiration instead of exact replication of biological structures (Rawlings, 2012; Webb, 2001; Williams, 2003).

In this paper, the following work has been described:

a.) Design of an eight degree of freedom alligator inspired robot.

b.) Rapid fabrication methodology of physical structure of the designed robot using a programmable CO_2 laser cutting machine.

c.) Gait programming based on high walk gait pattern of alligator.

2. Literature Review

A lot of research has been done in the field of walking robots by deriving inspiration from biological counterparts. The bio-inspiration in case of mobile robots comes largely from tetrapods- both reptiles as well as mammals.Figures 1 and 2 show joints of reptilian and mammalian legs.

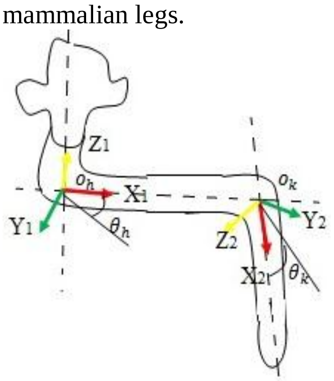

Fig.1. This image shows the relative arrangement of upper and lower limb for crocodiles and alligators. Note the ball-and-socket joint present at the knee and hip about which rotatory actuation takes place which results in locomotion. The approximate perpendicular orientation of the coordinate frames attached to the hip and knee joints is the salient feature of all members of the order *Crocodilia*.

For walking robots, both static and dynamic walking as well as both active and passive walking have been extensively researched (McGeer, 1990). Interest in legged walking robots over wheeled/tracked robots generated mainly because of:-

a.) more efficient traversal of difficult terrains,

b.) nature is the best designer hence just bio-mimic the design handed over to us by evolution,

c.) more robust and durable if designed on the principles of compliant mechanism, say by using flexible links

d.) more efficient motion planning can take place as a wider range of manoeuvrability is made available.

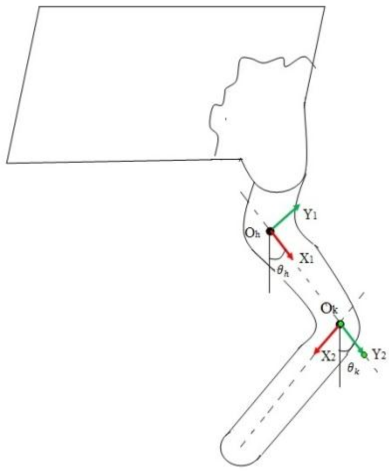

Fig.2. Note the relative arrangement of upper and lower limb which is approximately the same for all members of Class Mammalia including human beings. Note also the approximate parallel orientation of the coordinate frames attached to the hip and knee joints.

Much work has focused on biped and multi-legged robot walking. Work on biped robots has focussed on straight straight-leg design as well as multiple-joint legs. Major contribution was made by McGeer to realise passive dynamic walking in such biped robots. The burning issue is to ensure dynamic stability with the upper body movement and negotiate rough terrains with proper gait implementation in lower body (Huang, 2001).

To control the locomotion of bipeds on flat floor, the method of zero-moment point has been extensively researched (Erbatur, 2009; Yazdekhasti, 2010; Kajita, 2003; Sugihara, 2002).Several other new methodologies have been explored for navigation on flat floor as well as uneven terrains (Goswami, 1999; Sardain, 2004; Takao, 2003; Hirukawa, 2006).

For any legged robot, the most distinguished problem to solve is that of designing optimal gait. In this paper, gait is putatively taken to be the periodic finite state data of each foot (McGhee, 1968; Todd, 1990). For multi-legged robots, several gait diagrams have been inspired by the variety of gaits in nature.

Legged robots are mainly used because of their superior ability to adapt to different terrains compared to wheeled/tracked robots. Progress has been made for both hexapods (Waldron, 1986; Mcghee, 1979) and quadrupeds (Hiroshi, 2003). Quadruped gait design has been mainly developed in the area of mammalian walking gait (Raibert, 2008; Alexander, 1984; Hengst, 2000).

Attempt is made to mimic reptilian locomotion, especially that of an alligator. The robot successfully accomplishes active static walking though there will be slight compromise between static and dynamic walking. Four legs lend static stability due to availability of multiple footfall placement choices to achieve a stable support pattern but the gait design is such that at any given time, not all legs' footfalls coincide, thus the generated support pattern might add dynamism in walking, and in extreme scenarios, may require dynamic stability control, say active lateral stability (Collins, 2005; Bauby, 2000; Kuo, 1999).

3. Design and Fabrication of Alligator Robot

The alligator-inspired robotic platform has four legs to support the body and assist in its locomotion. Each leg is a simple 2-link rigid body mechanism and has two servos. One servo each is provided for hip and knee joint. Ankle joint at the moment has been ignored because our focus is on studying the salient feature that distinguishes mammalian gait from reptilian gait: orientation of rotating axes of hip and knee with respect to each other. The hip servo provides hip-yaw and knee servo provides knee servo provides knee roll. This is very different from mammalian arrangement. For mammals, the hip servo and knee servo both provide pitching action.

Table 1. Characteristics of the fabricated alligator robot: *ul* signifies upper limb whereas *ll* signifies lower limb.

S. No.	Characteristics	Value
1	M_{robot}	300 g
2	$M_{servo} + M_{Arduino} + M_{battery}$	120 g
3	$M_{ul}, M_{ul} - M_{servo}$	13 g, 5 g
4	$M_{ll}, M_{ll} - M_{servo}$	13 g, 5 g
5	width	120 mm
6	length	200 mm
7	limb length	50 mm
8	distance from front hip joint to front of robot	30 mm
9	distance fromback hip joint to back of robot	30 mm
10	centroid coordinate	(-60, 100, -50) mm
11	hip height from ground	38 mm
12	$maximum\ speed\ v_{max}$	0.01 m/s
13	Body Length per second, BL/s	0.05 m/s
14	Gait	Trot

The purpose of body in our platform at present is to contain the Electronic Control Circuit (ECC) as well as impart passive roll stabilisation. Servos are housed outside the body in slots created for each limb.

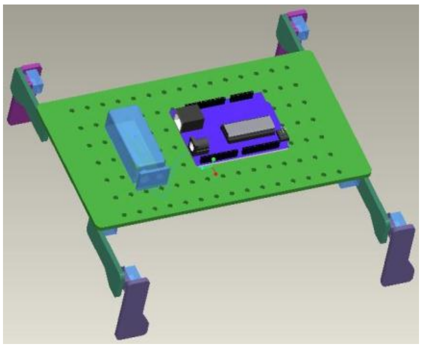

Fig.3. Note how the revolute joints at hips and knees have been realized using servo motors. The main purpose of body is to impart passive roll stabilization with respect to gait support pattern and house the ECC and batteries.

Based on actual limb arrangement of alligator, upper and lower limbs were fabricated. But unlike real alligators having oblique arrangement of limbs, our robot has its limbs inclined perpendicular to each other. As of now, any 2D design for leg will suffice. But each leg also has to house its own servo motor which is almost of the same size as the limb. To accommodate the servo, a sideways protrusion has to be provided to house the servo, thus transporting the limbal design into 3D domain.

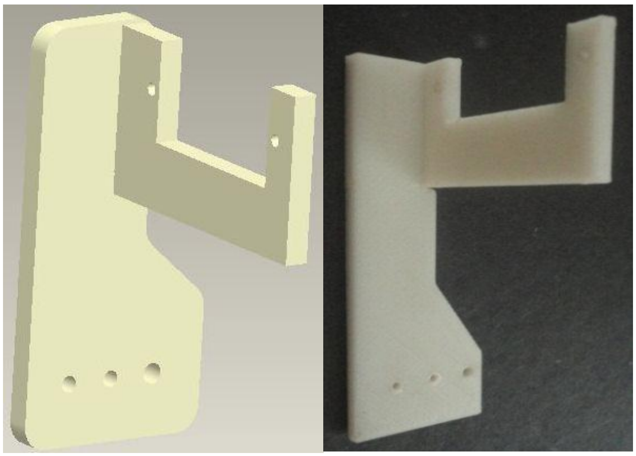

Fig.4. Left-hand image is that of the targeted robot leg design prototype developed in Pro/ENGINEER Wildfire 4.0 whereas right-hand image is that of actual robot limb fabricated in 3-D Rapid Prototype Printers using ABS*plus* in ivory at about 1.6 kW (RMS).

But manufacturing of any 3D part requires not only a lot of time but is also expensive. Most commonly used 3D Rapid Prototyping Printers require considerable time as in:-

a.) melting of thermoplastic material (in our case, ABS*plus* in ivory),
b.) manufacturing time, and
c.) removal of support material (in our case, SR-30 soluble) by dissolution in reagent.

To save on resources, the 3D design was transformed into 2D by simply breaking the upper and lower limbs into two 2D shapes which will fit in via slot-fitting mechanism.

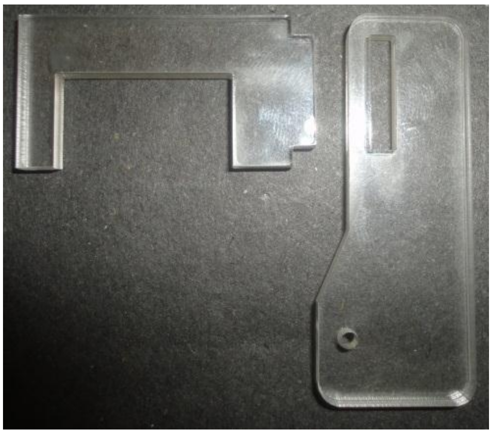

Fig.5.This imageshowshow the 3D design was simplified into two 2D parts and fabricated using CO_2-Laser cutting machine and 5 mm acrylic sheets within few minutes. Multiple robots can be produced with least effort.

Thus, instead of 3-4 hours, our job could be done in few minutes now in a laser-cutting or water-jet cutting machine.

To sum up, an extra link had to be provided at each limb to house the servo. Hence for two limbs at each leg, four rigid links were used.

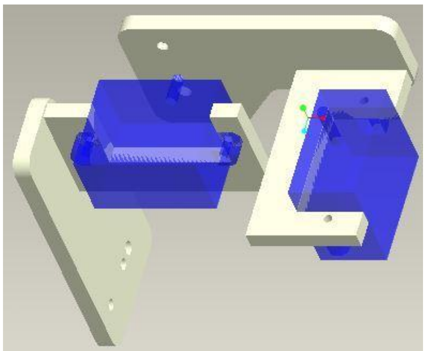

Fig.6.This is how each leg of the robot looks with one servo each at knee and hip joint. Note how the axis of rotation of servos lies in the same plane as that of the limb which they are supposed to actuate. Note also the salient feature that the axes at each leg are perpendicular to each other.

4. Control Architecture

Any hardware implementation in robotics requires clarity of the controls it employs. And controls tend to be multi-layered for complex systems. But here focus was on gait design, so a basic 3-layered control architecture was used. However it must be pointed out here to avoid future confusion that when planning/control algorithms are implemented on the alligator-robot, the nature and layers of control will become more complex.

Firstly, there are lower-level controls (LLCs) in the form of angular positions of the eight servo motors. Each leg has 2 DoF – one due to servo in upper limb for hip-yaw and another due to servo in lower limb for knee-roll, thus summing up to a total of 8 DoF for the quadruped with regard to LLCs. Thus the eight LLCs are the eight servo angles. Each LLC is associated with a range of angles it can turn to and the control set. The control set is the usual 2-tuple: clockwise and counter-clockwise rotation by 1 degree.

Secondly, the turning of servo motors controls the hip yaw and knee roll at each leg. These 4 pairs of angular orientations form the middle-level controls (MLCs). In the next section, where the kinematics model of the joints and limbs has been explicitly derived, the MLCs play a pivotal role in the analysis because MLCs map directly to the robot configuration which is the higher-level control. Like LLCs, each MLC is associated with a range of angles and corresponding control set. The control set is still the 2-tuple: clockwise and counter-clockwise rotation by 1 degree. The only difference will be the phase-shift between LLCs and MLCs, i.e., a servo angle at one of the upper limb of 37 degree may correspond to a hip yaw of 15 degree depending on the initial arrangement.

Finally, there are higher-level controls (HLCs) in the form of surge, sway and yaw. For the robot, choose its body reference point anywhere, say, the centroid of the rectangular body. Then set up a BODY coordinate frame as shown in figure7.

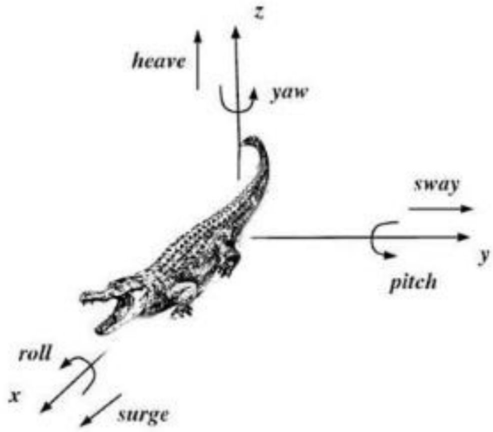

Fig.7.The coordinate frame, BODY, used here for kinematic analysis is the same as that used for standard analysis of any vehicle/locomotion dynamics.

Then the 3 DoFs are obvious: surge, sway and yaw. Each HLC is associated with a range of values it can take and the control set. For surge, the range is theoretically [0, ∞). The robot does not operate in the sway direction directly but only due the combined effect of surge and yaw. This phenomenon is summed up in the equations below.

$$\dot{y} = u\sin\psi + v\cos\psi \approx u\sin\psi = u\sin\left(\int r\,dt\right) \quad (4.1)$$

$$\dot{\psi} = r \quad (4.2)$$

The symbols have usual meaning (Fossen, 2011).However, the range for sway is theoretically unrestricted. Yaw is also theoretically unrestricted as it is the amount by which the robot turns. And for convenience of manoeuvrability, no restrictions were placed. Thus,

$$x \in [0, \infty) \quad (4.3)$$

$$y \in (-\infty,\infty) \quad (4.4)$$

$$\psi \in [0,2\pi) \quad (4.5)$$

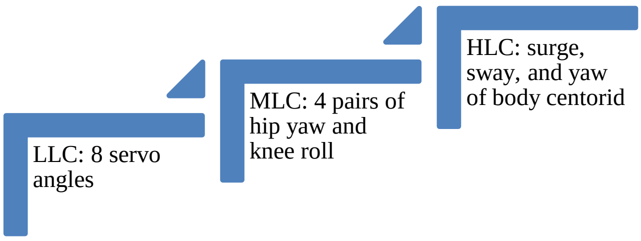

Fig.8.In computing, priorities are assigned tofeatures based on their proximity of interaction with respect to external environment/end user and abstraction of implementation details thereof. Just like that, priorities to controls have been assigned in above control architecture.

However, due to discretisation of control set related to the three HLCs determined by the respective geometric/kinematic as well as kinetic constraint on forces and moments that can be developed, etc., not all configurations are attainable.

To control locomotion, signals sent to the eight servo parameters via Arduino Uno get transformed into a unique 3-tuple of $[x \ y \ \psi]^T$ depending on its initial configuration and, of course, the signal command. This transformation takes place via the middle-level controls (MLCs) of hip yaw and knee roll.

Below is a flowchart representation of the algorithm implemented to move the alligator forward. The key to understanding the flowchart is that the notation RF_HS represents Right Front Hip Servo and so on for Left Hind and Knee Servos.

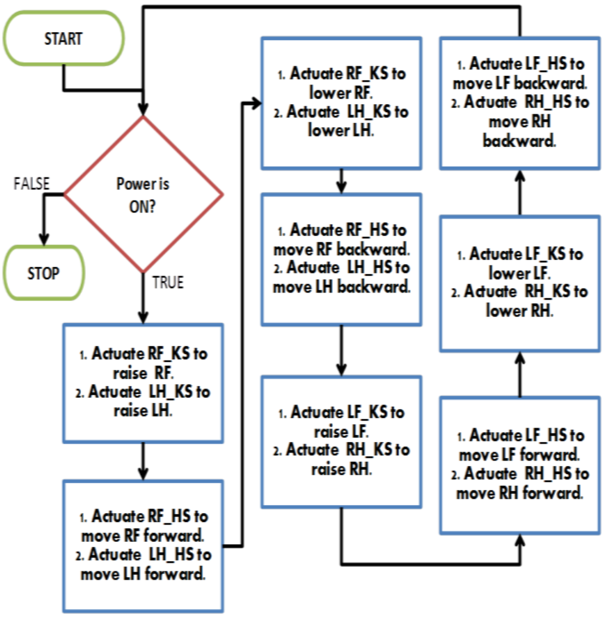

Fig.9.The algorithm to move the alligator forward is summed up as a flowchart. The actual amount of actuation to be given and the time delay for the different actuations involved was based on gait diagram described earlier. This flowchart was generated using FlowBreeze, a flowchart automation add-in for MS-Excel.

Summing up, there are 8 controls and 3 degree-of-freedom s for our robot and hence this is theoretically an over-actuated system because control to degree-of-freedom ratio, 8/3>1. But, the exact nature of actuation of the system varies over time due to:-

a.) Presence of sufficient coupling between upper and lower limb of each leg,
b.) Symmetricity and periodicity constraints laid down by the gait diagram.
c.) Inertia of rigid body and lack of compliance.
d.) Wear and tear.
e.) Manual modification of robot body.
f.) Change of operating environment of robot.

Thus, the nature of actuation of a robot is not simply a function of its control to degree-of-freedom ratio; it also relies on other factors mentioned above.

5. Kinematics Modelling of Reptilian Leg Mechanism

To control locomotion, the end-effector configuration of each of four legs must be known as function of the link angles which in turn must be known as function of servo angles.

$$\begin{bmatrix} X_{ee,i} \\ Y_{ee,i} \\ Z_{ee,i} \end{bmatrix} = \begin{bmatrix} f_1(\psi_{1,i},\phi_{2,i}) \\ f_2(\psi_{1,i},\phi_{2,i}) \\ f_3(\psi_{1,i},\phi_{2,i}) \end{bmatrix} \quad (5.1)$$

i runs from 1 to 4 for four foot positions.

$$\begin{bmatrix} \psi_{1,i} \\ \phi_{2,i} \end{bmatrix} = \begin{bmatrix} g_1(\Theta_1) \\ g_2(\Theta_2) \end{bmatrix} \quad (5.2)$$

ψ_1 and ϕ_2 are respectively the upper limb yaw and lower limb roll; Θ_1 and Θ_2 are respectively the hip and knee servo angles.

For determining the first set of functions, which willbe called Limb-Angles-to-End-Effector (LAEE) functions from now on in this paper, two analytical approaches exist. The first is straight-forward and intuitively more appealing.

Choose the body-fixed reference frame BODY (Fossen, 2011) as usual for vehicle dynamics analysis. Now choose a particular leg, say right-hind. Denote the length for the four rigid links by $\ell_1, \ell_2, \ell_3, and\ \ell_4$. Denoting the reference point where the upper limb is joined to the body by O, for a positive yaw of theta1 of the upper limb and positive roll of lower limb, end-effector/foot position can be determined.

Thus, Hip joint ≡ O = [0 0 0]. Initially, Knee joint ≡ A = $[-\ell_1 \ -\ell_2 \ -SUS]$; where SUS is a parameter defining the offset on account of upper servo motor size in the xy-plane.

After a yaw of upper limb by ψ_1 about z-axis,

Knee joint, A = $\begin{bmatrix} -\{\ell_1 \cos\psi_1 - \ell_2 \sin\psi_1\} \\ -\{\ell_1 \sin\psi_1 + \ell_2 \cos\psi_1\} \\ -SUS \end{bmatrix}$ (5.1.1)

Initially, end-effector/foot , EE = $\begin{bmatrix} -(\ell_1 + SLS) \\ -(\ell_2 + \ell_3) \\ -(SLS + \ell_4) \end{bmatrix}$ (5.1.2)

where SLS is a parameter defining the offset on account of lower servo motor size in the yz-plane.

After a yaw of upper limb by ψ_1 about z-axis and subsequent roll of lower limb by ϕ_2 about x-axis,

End-effector/foot,$EE =$

$$\begin{bmatrix} -\{X_{knee} + (SLS\cos\psi_1) - \ell_3\cos\phi_2\sin\psi_1 + \ell_4\sin\psi_1\sin\phi_2\} \\ -\{Y_{knee} + (SLS\sin\psi_1) + \ell_3\cos\phi_2\cos\psi_1 + \ell_4\cos\psi_1\sin\phi_2\} \\ -\{Z_{knee} + \ell_3\sin\phi_2 + \ell_4\cos\phi_2\} \end{bmatrix} \quad (5.1.3),$$

where$X_{knee} = A(1), Y_{knee} = A(2), Z_{knee} = A(3)$.

Thus foot position of all four legs can be accurately determined. Note here the derivations have been shown for one leg only. For others, the approach is similar.

The second method is based on the well-established forward (or configuration) kinematic equations for rigid robots using the Denavit-Hartenbergconvention. Firstly, setup the coordinate frame as in figure 10 and determine the DH-parameters. Following the general procedure of forward kinematic analysis, find out the transformation matrices involved to get the end-effector configuration. (Craig, 1989;Spong, 1989).

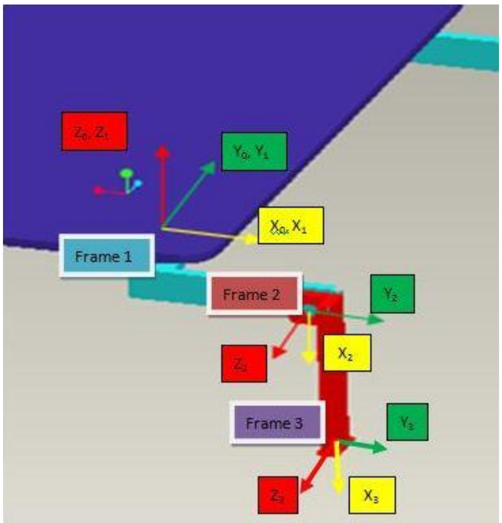

Fig.10. Robot leg has been modeled as a manipulator as shown. This model forms the basis for kinematics modeling. Adding more links will lead to hyper-redundancy which can be explored from planning/control perspective.

Otherwise, simply represent the LAEE functions in form of look-up tables (Knepper, 2006; Culberson, 1998). To create the LAEE look-up table will require a suitable discretisation of upper limb yaw and lower limb roll angles. The choice of discretisation will be guided by the size of the alligator body and the accuracy desired in the alligator to navigate in its environment. This accuracy in turn will depend on robot size and the requirements of job at hand. The resolution of discretisation for a robot supposed to follow a moving soldier will be quite different from that of a robot trying to explore a featureless, barren large piece of land.

The second set of functions, whichwill henceforth be called Servo-Angles-to-Limb-Angles (SALA) functions, can be handled by a look-up table. An analytical analysis is also quite straight-forward but depends on the initial servo motor angular configuration which will vary from robot to robot and on the relative mounting and assembly of the motors on the robotic platform. Say the initial upper servo angle Θ_1=82 degree. Say an open-loop control input causes Θ_1=83 degree. Based on this 1 degree of rotation the new upper limb yaw can be easily determined for a particular robot.

Based on whichever approach is chosen, finally LAEE and SALA functions are available. The knowledge of these functions is critical for autonomy of the robotic platform. For example, in an uncertain and cluttered environment, efficient navigation is contingent on high accuracy of LAEE and SALA functions. And it solves both the forward and inverse kinematics problem for the robot, thus making it possible to both control its locomotion by the usage of inverse kinematics and simulate its locomotion by the usage of forward kinematics.

6. Quadruped Gait Design Inspired by Alligator

Alligators adopt two kinds of gaits generally: High walk gait and sprawl gait (Baier, 2013; Munns, 2005; Reilly, 2003; Gatesy, 1991). Our model attempted to mimic the high walk gait of alligator. Reptilian gaits are different from mammalian gaits. And several quadrupeds have been designed to mimic different types of mammalian gaits.

What sets apart reptilian gait is the orientation at which upper and lower leg limbs rotate with respect to each other. The upper limbs rotate about hip joint and the lower limbs rotate about knee joint. The axes about which the rotation takes place are approximately perpendicularly inclined to each other. For mammals, the axes are almost parallely oriented. Gaits are dynamic by default and change with different speeds, terrains and environmental factors. The change may occur in two ways. Either switching between different gait designs takes place or relative footfall timings change within same gait. Hence, there are different and similar gaits.

A particular high-walk gait diagram was picked and implemented for a speed of 0.07 m/s. When actually implemented on our model forward speed was 0.01 m/s. A reduction by seven times can be attributed to following factors: robustness of robotic platform, servo motor power rating, and lack of compliance in mechanism. Servos were chosen to actuate and mimic alligator gait in our robotic platform but nature does not do so. Here rigid-body mechanism has been used to realise our robot. However, nature uses compliant mechanism. This has led us to begin improving our design based on compliance.

High walk gait of alligators is neither regular nor symmetric as no real gait ever is (Hildebrand, 1966, 1977). Also none of the leg-touchdowns coincide with the lift-offs of other legs; hence wave gait analysis cannot be applied. This is slightly convenient for dynamic stability of robot as high walk of alligator is basically a diagonal trot; so support of entire body is on two legs for lesser time.

Let us designate the left hind leg as 1, right front leg as 2, left front leg as 3, and right hind leg as 4. Since it is diagonal trot, gait patterns for leg 1 and 3 as well as for leg 2 and 4 will be similar.

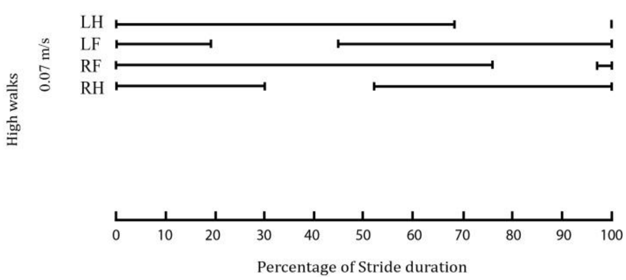

Fig.11.The above gait diagram (Reillly, 1998) wasimplemented for the alligator robot and imparted a speed of 0.01 m/s as opposed to 0.07 m/s in a real alligator.

Based on the above notation, duty factor β and phase ϕ of each leg used for our model is given below (Siciliano, 2008).

ϕ_1=0; ϕ_2=0.97; ϕ_3=0.44; ϕ_4=0.52;(6.1)
β_1=0.7; β_2=0.78; β_3=0.74; β_4=0.78;(6.2)

7. Implementation

The design of the reptilian robot has been kept as simple as possible so as to be able to focus on the gait design. The upper and lower limbs were previously designed in ProEngineer as 3D modelsand manufacturedon a 3D RPT printer. However, 3D printing based fabrication is time-consuming, expensive and yields less strong components. Hence, the 3D design was further simplified into an assembly of 2D models. This allowed us to take advantage of the speed and cost-effectiveness of a VLS 3.60 CO_2 laser-cutting machine with a power of 60W.

One limitation of laser-cutting machine is that it can cut polymer sheets only up to 6mm thick. For components requiring greater thickness, water-jet cutting machine may be used. Alternatively, CO_2-LASER cutting machine may be used to cut thicker parts by cutting multiple thinner layers and gluing them up using chloroform.

Table 2. The diagonal trot gait has been parameterised in terms of phase and duty factor of each leg. This parameterisation is based on the finite-sate modelling of the gait.

Legs	Phase	Duty Factor
1	0	0.7
2	0.97	0.78
3	0.44	0.74
4	0.52	0.78

To implement the gait, the periodic footfall pattern of real alligators was coded into Arduino Uno. Since the gait was parameterised in terms of duty factor and phase for each leg, two parameters were defined in the code to map the two original gait parameters. The duty-factor parameter controlled the amount of distance moved per step or the amount angle rotated per turning. The phase parameter controlled the frequency of stepping and turning. It is these two parameters that will be optimised based on the objective demanded.

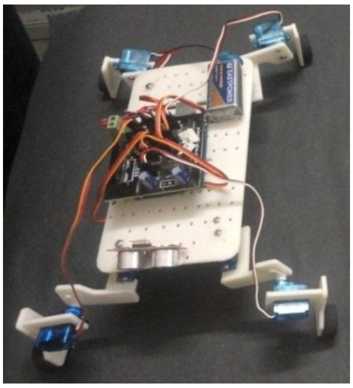

Fig.12. The alligator robot finally assembled was tested for several gait designs and achieved efficient negotiation of difficult terrains. Changing gait parameters led to different speeds. Refer to the link: http://www.youtube.com/watch?v=A-aUs5BfoDA&feature=youtu.be

After experimenting with several gait designs, a conclusion was reached that same gait design will produce different speeds on a robotic platform and for a natural alligator. Hence, the issue of bio-mimicking is critically based on mimicking design features of alligators as closely as possible. Also, a gait that produced optimal moving speed in alligators could give abnormal moving speeds for the robot based on size factors, joint rigidity or design robustness and compliance.

8. Discussion

Research in gait design can be engaged in two directions: either explore design optimisation to match moving characteristics between a robotic alligator and real alligators as closely as possible for the same gait diagram, or given a scaled alligator model whose locomotion is inspired by alligator's anatomy, design a gait diagram that mimics different moving characteristics of real alligator as closely as possible. The former idea was experimented with but focus was laid on the latter idea.

As discussedat the end of section 4, there is a need for a new parameter tobe defined to describe the actuation of the robot body with more clarity. This parameter, call it degree of bio-mimicking, must be a complicated function of several factors described earlier.This same parameter can be calculated for the living organism which the robot is trying to mimic. And there ratio can give a good idea as to how successfully the mimicking has been achieved.

Our entire gait analysis is based on the finite state modelling of locomotion. A better gait-modelling approach may be developed based on studying energy conversion mechanism during locomotion (Cavagna, 1977; Taylor, 1982; Blickhan, 1993; Kar, 2003; Reilly, 2007).

9. Conclusion and Future Work

The paper describes the design and fabrication of an alligator-inspired quadruped robot. Also designed and implemented was the gait plan of the developed robot based on high gait pattern of alligators. The reptilian robot was tested to move robustly on soils well as pavements. The successful application of gait showed that indeed efficient, controlled and guided walking could be achieved on flat terrains of different nature.

In future, further enhancement of the developed robotic platform will be attempted in the ways listed below.

a.) Enhance the design of the robot body as well as the gait to enable it to negotiate steep slopes and climb stairs.
b.) The fatigue build-up at the joints causes the joints to wear down in current design requiring development dynamicsbased model using Adams™ software and optimise the design.
c.) Use of compliant joints in future to optimize the design and improve functionality.
d.) Use of a machine learning technique known as NEAT (neuroevolution of augmenting topologies) to

optimize the gait pattern (Clune, 2009;Yosinski, 2011; Lee, 2013).

e.) Enhance the current design of the robot by adding an active tail that can enable the robot to balance the body weight during walking.

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References

F.E.Fish, P.B. Frappell, R. V. Baudinette, P.M. Macfarlane, (2001),Energetics of terrestrial locomotion of the Platypus*OrnithorhynchusAnatinus*, *The Journal of Experimental Biology* 204, 797–803.

R.W. Blob, A.A. Biewener, (2001), Mechanics of limb bone loading during terrestrial locomotion inthe green iguana (iguana iguana) and American alligator (Alligator Mississippiensis), *The Journal of Experimental Biology* 204, 1099–1122.

J.M. Parrish, (1987),The Origin of Crocodilian Locomotion, *Paleobiology* , Vol. 13, No. 4 , pp. 396-414

S. Renous, J.P.Gasc, V. L. Bels, R. Wicker, (2002), Asymmetrical gaits of juvenile *Crocodylusjohnstoni*, galloping Australian crocodiles. *Journal of Zoology*, 256: 311–325.

S.M. Reilly, J.A. Elias, (1998), Locomotion in alligator mississippiensis: kinematic effects of speed and posture and their relevance to the sprawling-to-erect paradigm, *The Journal of Experimental Biology,* 201, 2559–2574.

A.J. Charig, (1972) The evolution of the archosaur pelvis and hind-limb: an explanation in functional terms. *Studies in Vertebrate Evolution*. Oliver & Boyd, Edinburgh, pp. 121–55.

S.C. Rewcastle, (1981). Stance and gait in tetrapods: an evolutionary scenario. *Symp.zool. Soc. Lond*., 48, 239–267.

J.R. Hutchinson,V. Allen, K.T. Bates, Z. Li, (2013),Linking the evolution of body shape and locomotor biomechanics in bird-line archosaurs. *Nature*., 497 (7447):104-7.

J. S.Willey, A. R. Biknevicius, S. M. Reilly, K. D. Earls, (2004),The tale of the tail: limb function and locomotormechanics in Alligator mississippiensis, *Journal of experimental biology*, *207*(3), 553-563.

R. Pfeifer, J. C. Bongard. (2006), *How the Body Shapes the Way We Think: A New View of Intelligence (Bradford Books)*. The MIT Press.

R. Pfeifer, M. Lungarella, F. Iida, (2007), Self-organization, embodiment, and biologically inspired robotics. *Science*, *318*(5853), 1088-1093.

D. Floreano, C.Mattiussi. (2008). *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies*. The MIT Press.

J. F. Vincent, O. A. Bogatyreva, N. R. Bogatyrev, A. Bowyer, A. K. Pahl, (2006),Biomimetics: its practice and theory. *Journal of the Royal Society Interface*, *3*(9), 471-482.

A.E. Rawlings, P.J. Bramble, S.S. Staniland, (2002), Innovation through imitation: biomimetic, bioinspired and biokleptic research. *Soft Matter*, 2012, 8, 6675-6679.

B. Webb, T. Consilvio, (2001). *Biorobotics*.Mit Press.

K. Williams, (2003),*Amphibionics: Build Your Own Reptillian Robot* (1 ed.). McGraw-Hill, Inc., New York, NY, USA, pp. 191-269.

T. McGeer,(1990), Passive dynamic walking. *Int. J. Rob. Res.* 9, 2 (March 1990), pp. 62-82.

Q. Huang, K. Yokoi, S. Kajita,K. Kaneko,H. Arai, N. Koyachi,K. Tanie,(2001), Planning walking patterns for a biped robot, *Robotics and Automation, IEEE Transactions on* , vol.17, no.3, pp.280,289.

K. Erbatur, O. Kurt, (2009), Natural ZMP trajectories for biped robot reference generation. *Industrial Electronics, IEEE Transactions on*, *56*(3), 835-845.

S. Yazdekhasti, F. Sheikholeslam, M. Ghayour, (2010), Stability analysis of biped robot with direct control of zero moment point. *The 2nd International Conference on Computer and Automation Engineering (ICCAE),* Vol. 2, pp. 528-532

S. Kajita, F. Kanehiro,K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, H. Hirukawa, (2003), Biped walking pattern generation by using preview control of zero-moment point. *IEEE International Conference onRobotics andAutomation, 2003.Proceedings.ICRA'03.* Vol. 2, pp. 1620-1626.

T. Sugihara, Y. Nakamura, H. Inoue, (2002), Real-time humanoid motion generation through ZMP manipulation based on inverted pendulum control. *Proceedings.ICRA'02. IEEE International Conference on Robotics and Automation, 2002.* Vol. 2, pp. 1404-1409.

A. Goswami, (1999), Postural stability of biped robots and the foot-rotation indicator(FRI) point, *Int. J. Robot. Res.* 18(6), 523–533.

P. Sardain,G. Bessonnet, (2004). Forces acting on a biped robot.center of pressure-zero moment point. *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on*, *34*(5), 630-637.

Takao, Y. Yokokohji, T. Yoshikawa, (2003), FSW (feasible solution of wrench) for multi-legged robots.*Proceedings.ICRA'03.IEEE International Conference on Robotics and Automation, 2003.*Vol. 3, pp. 3815-3820.

H. Hirukawa, S. Hattori, K. Harada, S. Kajita, K. Kaneko, F. Kanehiro,M. Morisawa, (2006), A universal stability criterion of the foot contact of legged robots-adios ZMP. *Proceedings 2006 IEEE International Conference on Robotics and Automation, 2006. ICRA 2006.*pp. 1976-1983.

R.B.McGhee,(1968), Some finite state aspects of legged locomotion, *Mathematical Biosciences*, Volume 2, Issues 1–2, Pages 67-84.

D.J. Todd, (1990), Machines that walk: The adaptive suspension vehicle, S. M. Song and K. J. Waldron, The MIT Press, Cambridge, MA,*Int. J. Adapt. Control Signal Process*, 4: 247.

K.J. Waldron, R.B. Mcghee, (1986), The adaptive suspension vehicle, *Control Systems Magazine, IEEE* , vol.6, no.6, pp.7-12.

R.B. Mcghee, G.I. Iswandhi,(1979), Adaptive Locomotion of a Multilegged Robot over Rough Terrain, *Systems, Man and Cybernetics, IEEE Transactions on* , vol.9, no.4, pp.176-182.

I. Hiroshi,K. Masayoshi, (2003), Adaptive gait for a quadruped robot on 3D path planning, *Robotics and Automation, 2003. Proceedings.ICRA '03.IEEE International Conference on*, vol.2, pp.2049-2054.

M. Raibert, K. Blankespoor, G. Nelson, R. Playter,(2008),Bigdog, the rough-terrain quadruped robot., *Proceedings of the 17th World Congress*. pp. 10823-10825.

R.M. Alexander, (1984),Thegaits of bipedal and quadruped animals. *The International Journal of Robotics Research*, *3*(2), 49-59.

B. Hengst, D. Ibbotson, S.B. Pham, C. Sammut, (2000), The UNSW united 2000 sony legged robot software system. *RoboCup 2000: Robot Soccer World Cup IV*, 64-75.

S.H. Collins, A. Ruina, (2005),A bipedal walking robot with efficient and human-like gait. *Proceedings of the 2005 IEEE International Conference on Robotics and Automation, 2005. ICRA 2005*, pp. 1983-1988.

C.E. Bauby, A.D. Kuo, (2000), Active control of lateral balance in human walking. *Journal of biomechanics, 33*(11), 1433-1440.

A.D. Kuo, (1999), Stabilization of lateral motion in passive dynamic walking.*The International journal of robotics research*, *18*(9), 917-930.

T.I. Fossen, (2011), *Handbook of Marine Craft Hydrodynamics and Motion Control*, John Wiley &Sons, Ltd, Chichester, UK,pp. 15-41.

J. J. Craig,(1989). *Introduction to Robotics: Mechanics and Control* (2nd ed.). Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA. pp. 101-200.

M. W. Spong,(1989), *Robot Dynamics and Control* (1st ed.). John Wiley & Sons, Inc., New York, NY, USA, pp. 62-91.

R.A.Knepper and A. Kelly, (2006), High Performance State Lattice Planning Using Heuristic Look-Up Tables, *IEEE/RSJ International Conference on Intelligent Robots and Systems*, October, 2006, pp. 3375 - 3380.

J.C. Culberson, J. Schaeffer, (1998), Pattern Databases, *Computational Intelligence*, Vol. 14, No. 3, pp. 318-334.

D.B. Baier, S.M. Gatesy, (2013), Three-dimensional skeletal kinematics of the shoulder girdle and forelimb in walking Alligator. *Journal of Anatomy*.S.L. Munns,

L.K. Hartzler, A.F. Bennett, J.W. Hicks, (2005), Terrestrial locomotion does not constrain venous return in the American alligator, Alligator mississippiensis. *Journal of experimental biology*, *208*(17), 3331-3339.

S.M. Reilly, R.W. Blob, (2003), Motor control of locomotorhindlimb posture in the American alligator (Alligator mississippiensis). *The Journal of experimental biology*, *206*(23), 4327-4340.

S.M. Gatesy,(1991), Hind limb movements of the American alligator (Alligator mississippiensis) and postural grades. *Journal of Zoology*, *224*(4), 577-588.

M. Hildebrand, (1966), Analysis of the symmetrical gaits ofTetrapods, *Folia Biotheor*, 6: 9–22.

M. Hildebrand, (1977), Analysis of the asymmetrical gaits. *J.Mammal*. 58: 131–156.

B. Siciliano, O.Khatib, (2008),*Springer Handbook of Robotics*. Springer,pp. 361-387.

G. A.Cavagna, N. C. Heglund, C. R. Taylor, (1977). Mechanical work in terrestrial locomotion: two basic mechanisms for minimizing energy expenditure, *American Journal of Physiology-Regulatory, Integrative and Comparative Physiology*, *233*(5), R243-R261.

C. R. Taylor, N. C. Heglund, G. M. Maloiy,(1982), Energetics and mechanics of terrestrial locomotion. I. Metabolic energy consumption as a function of speed and body size in birds and mammals, *Journal of Experimental Biology*, *97*(1), 1-21.

R. Blickhan, R.J. Full, (1993), Similarity in multilegged locomotion: bouncing like a monopode. *Journal of Comparative Physiology A*, *173*(5), 509-517.

D. C.Kar, IssacKurien, K. Jayarajan, (2003), Gaits and energetics in terrestrial legged locomotion. *Mechanism and machine theory*, *38*(4), 355-366.

S. M. Reilly, E. J. McElroy, A. R. Biknevicius, (2007), Posture, gait and the ecological relevance of locomotor costs and energy-saving mechanisms in tetrapods. *Zoology*, *110*(4), 271-289.

J. Clune, B.E. Beckmann,C. Ofria,R.T. Pennock,(2009), Evolving coordinated quadruped gaits with the HyperNEAT generative encoding, *Evolutionary Computation, 2009. CEC'09. IEEE Congress on* (pp. 2764-2771). IEEE.

J. Yosinski,J. Clune, D. Hidalgo,S. Nguyen, J. Zagal, H. Lipson, (2011),Evolving robot gaits in hardware: the hyperneat generative encoding vs. parameter optimization, *Proceedings of the 20th European Conference on Artificial Life*, pp. 11-18.

S. Lee,J. Yosinski, K. Glette,H. Lipson,J. Clune, (2013), Evolving gaits for physical robots with the HyperNEAT generative encoding: the benefits of simulation, *Applications of Evolutionary Computation*, pp. 540-549.

3D Printing or Laser Cutting, Pursuit of Unorthodox Ideas, [online] 2013, http://unorthodoxideas.blogspot.in/2013/06/3d-printing-or-laser-cutting.html (Accessed: 12 July 2013).

Laser Cutting Vs. Waterjet Cutting , Thomasnet, [online] 2013, http://www.thomasnet.com/articles/custom-manufacturing-fabricating/laser-cutting-waterjet-cutting, (Accessed: 21 September 2013).

Open Source Robotic Crocodile Assembly Video, Youtube, [online] 2012, http://www.youtube.com/watch?v=saiOWluyfW0(Accessed: 2 May 2013).