

Design, Construction and a compliant gait of “ModPod”: a Modular Hexpod robot.

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Abstract—In this paper we describe the mechanical design, gait and control for a modular hexapod robot which makes it compliant to terrain while climbing slopes up and down. The robot uses a unique electronically actuated 2DOF universal spine similar to the spine of the Snake and the four legged animals like leopard, tiger etc. By controlling the amount of stiffness of the spine we were able to make the robot compliant to the surface. To our knowledge this is the first modular hexapod robot which achieves controllable compliance by both mechanical design and electronically actuating the robots spinal backbone. This design was biologically inspired based on the structure of a caterpillar with legs. Also we present the hardware and software architecture of the robot in this paper

Keywords—bio-robot, legged robot, modular robot

I. INTRODUCTION

One of the important problems of legged robots is their compliance with the surface on which they are moving. This can be solved using both mechanical novelty, algorithmic solutions for the kinematics and dynamics of the robots and by using sensors for measuring leg contact, leg angle, current, obstacles sensors etc. The impact force between the leg and the surface while landing also governs the stability of the robot and thus its compliance. Improved compliance to the terrain reduces the mechanical wear of the robots parts as well. Rhex[9] the six legged robot uses semi circular passive legs to improve compliance with the ground. These passive legs also helped this robot surpass other robots in its class in climbing human level stairs [1]. Its simplicity is in its design and the minimal actuators it uses. It uses a modified tripod gait (3 legs in contact with the ground at a time) for locomotion. Rhex also used four bar mechanism for legs but was later replaced by semi-circular legs which provided more points of contact. We also designed a four bar mechanism (fig.1.1) but did not employ it in further tests because of its reduced angular freedom. We later used the design of the leg show in fig.1.4. The robot RHex[1] gait was improved using video analysis of the previous test runs. But in our case since the robot's API and control is tied to the virtual model we were able to calibrate the leg position with respect to the ground (flat surface). As a result the tripod gait was successfully accomplished on the robot during the very first trial thereby verifying the efficacy of our simulator.

The paper [8,9] describes an innovative hybrid wheel and leg mechanism which helps the robot in covering terrain with mild to medium slope, hard packed sand, loose sand etc. Also the paper[2] gives details on some of the minute but important aspects of the robot's construction which include the choice of material used for the legs, the linkages, the heat dissipation etc which improved its over all efficiency.

The compliance in advanced 4 legged robots like the little dog [3] is implemented by complex gait planning and control strategies. This also involved the use of an external high speed camera tracking system (VISOR)[3] with infrared LEDs mounted on the robot to get its pose and position. Double dynamic gait was implemented on the little dog at MIT [4]. We extended the double dynamic gait's kinematics to our robot “ModPod” and we observed that it matched with the tripod gait of the cockroach. In the double dynamic gait two legs of the little dog are in contact and 2 are in air. In our extended gait during simulation we observed that the 3 legs of the robot were in air and 3 in contact with the ground. Such ideal contact was achieved in some cases during testing on the real robot as well.

In Omnithread [6]: a modular snake robot, pneumatic joints were used. By controlling the air pressure in the joint the stiffness was controlled. Use of pneumatic actuators however increases the risk of mechanical failure due to puncture. The robot Kathrina's [11] IVS (Interactive Virtual simulator) simulator helped in optimizing its design and reduced the time for development hugely. In our case instead of testing each trail of the gait on the real robot several trials were conducted in the simulator for the ModPod. Thus it helped in debugging the gait and improving it quickly. Since the real robot exactly resembles our custom virtual model in the simulator the gaits generated were a success either immediately or with in a few trials. The advantages of such custom simulator have also been discussed in paper [11] for the 6 legged robot Kathrina.

II. MECHANICAL DESIGN

The built of the robot is modular in nature and thus with the addition of similar modules the robot can be changed from a six legged robot to a caterpillar. The robotic spine is composed of 2 DOF joints which connect the leg modules. Several leg designs were tried as given below. Each leg of the robot is like a 2 degree of freedom robotic arm. Also the modular legs

are connected with orthogonally linked servos to imitate the universal joint found in a snake's vertebrae. This gave the robot the ability to change its gait direction in the horizontal plane and also overcome vertical obstacles. To improve the compliance the current to the vertical servos is reduced so that the stiffness is controlled but still actuated. Even the natural snakes improve their compliance when moving over small rocks and uneven terrain by controlling their backbone stiffness. Also each leg has a silicon tip at the end so as to improve its contact and reduce slippage. Silicone gel has been used in some Snake robots (like the modular Snake robots at CMU [10]) especially while traversing a vertical passage to improve traction. In wall climbing robots like Gecko robot [15] Stanford's sticky bot[16] and Mini whigs adhesive silicon was used to improve the traction. We fabricated the structure using light weight aluminum. The robot has 16 servos for the six legged configuration.

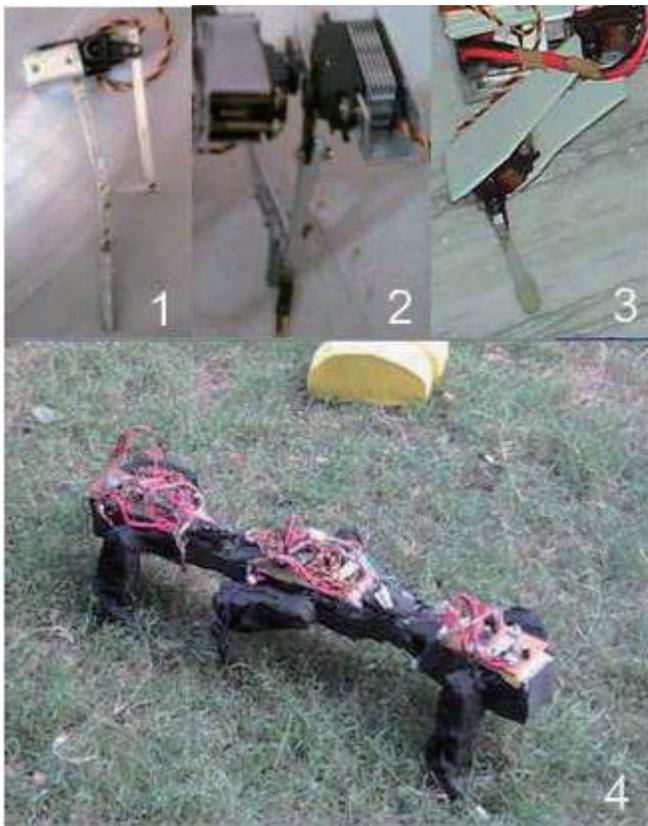


Figure 1. Showing the legs and the mechanical built of the robot

III. SOFTWARE ARCHITECTURE

The robots simulation model was integrated with the real robot as follows:

- An API plugin in ruby was developed for Newton dynamics physics engine.
- The API was accessed using a C code through a DLL talking to the ruby plugin.

- The gaits were defined as path and phase lagged semi-elliptic paths in Opencv. The 2 degree of freedom leg was made to follow the path using Inverse kinematics.
- The respective angles were modified to servo angle values and were sent over USB-RS232 port and an Xbee RF modem. At the robot end the microcontroller received it with an Xbee RF modem and generated the respective PWM signals for the servos.

We observed that the advantage of integrating the robot's virtual model with the real model is that the robots reaction to regular geometric terrain and gait control could be predicted, observed, corrected and thus controlled real time from the virtual model running in the physics engine.

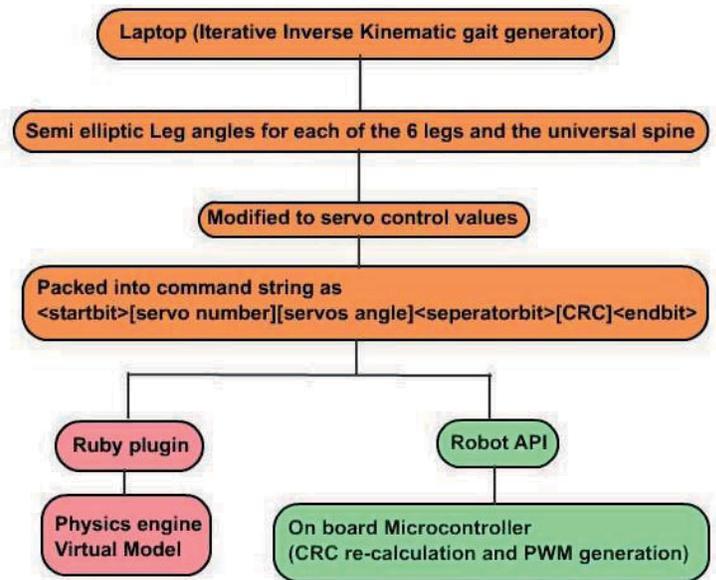


Figure 2. Software architecture and flow

IV. EMBEDDED ARCHITECTURE

The robot has an Atmega8 microcontroller which receives servo command packets from the PC using an Xbee RF modem. The controller generates 16 PWMs simultaneously. Also CRC based error control is implemented to overcome communication error under noisy conditions. The current consumption of each servo is around 4 Amps. Here we used plug in power modules "PTH08T220W Turbo trans module" from Texas instruments and on board Lithium polymer batteries to provide stabilized high current to the servos. The current / voltage of the Turbo trans power module of the 2DOF universal spinal joints can be adjust to either increase or decrease the maximum possible torque and thus its compliance to the surface.

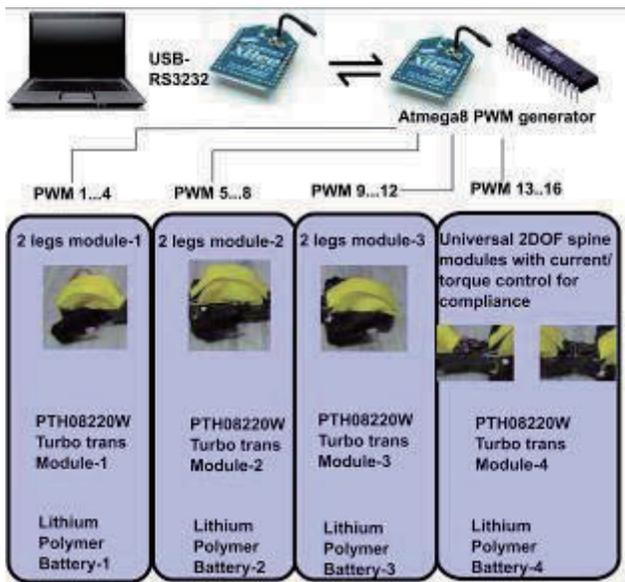


Figure 3. Embedded architecture of ModPod

V. LOCOMOTION

We were able to generate the following gaits.

- 1) Galloping
- 2) Tripod gait based on the extension of double dynamic walk as observed on the little dog robot.

One important thing we observed is that the only difference between the galloping gait and Tripod gait is the initial path and phase difference. Also the motivation to develop this robot was to act as a platform for further research towards using such robots for search and rescue. The search and rescue environments will have challenging terrain where robots with high dexterity will be required. The idea is to use such robots and reduce the risks to humans in the loop. This paper talks about the robot Asterisk[5] which uses limb mechanism with legs having 4 d.o.fs. It uses foot contact sensing and an accelerometer to measure inclination and adjust the body appropriately in compliance with the step.

Also legged robot can overcome obstacles which are at a height greater than the hip height of the robot. This was also verified in Asterisk. We have implemented an open loop gait controller. Also this paper described a 2.4 g autonomous robot called roach. Roach uses SCM (Smart composite machining) to produce flexible micro joints. The compliance in this robot was achieved by using a combination of Shape memory alloys and return springs designed with SCM process. This provides the compliance similar to the muscles and tendons in animals. This idea is very close to how compliance and stiffness is controlled in the backbone of legged robots by using a combination muscle, bones and tendons. Our robot Modpod implements skeletal level compliance. Roach achieves alternating tripod gait with two linear actuators and is thus in this case is optimal than RHex.

Compliance in wall climbing robots like Gecko and Stanford's sticky bot is achieved by using silicon rubber and nano scale fibers [15]. The use of materials for foot contact is also an important consideration for reducing slippage and thus compliance. Hence we used cylindrical silicon tips (fig 1.3) for improved contact. Also the power to weight ratio is an important consideration for modular robots. Since our robot was able to lift the modules in air about the spinal linkage we confirm that we have a considerably good power to weight ratio (p46 [12]). If the design is complex the robot becomes unnecessarily heavy and decrease its power to weight ratio.

Cockroach motion has been studied and implemented in robots like Whegs [8]. The tripod gait of the cockroach gives the wheel legged robot ability to overcome obstacles about 1.5 times its height and locomotion over uneven terrain. Here in our robot the two legs on one side and the mid leg on the opposite side are always in phase and thus a zero path difference. These 3 legs are about 180 degrees out of phase with their corresponding pair of legs on the opposite side. Some robots use passive compliant legs with springs. In all these legs the impact is absorbed by the spring which also helps prevent transferring the shocks to the mechanically sensitive parts of the robot and thus protect against its wear and tear. But, the level of compliance cannot be controlled using spring loaded legs designs as suggested here. But by controlling the maximum possible torque which is governed by the magnetizing current flowing through the coil of the motor one can control the level of compliance and this was implemented in our robot.

The leg design of KOLT robot [14] uses a single motor coupled with the hip and knee joint using pulley and cables. Also there are two springs connecting the knee-hip and ankle-knee which provide compliance. The leg used in our ModPod here has a single servo in the hip and one servo for the knee with both axis parallel to each other. Also for steering it was initially thought to have single steering servo in each of the leg. But, this would increase the number of actuators as well as the weight and power consumption. The use of 2DOF universal Spinal joint helped for steering the robot in the left and right in the horizontal direction as well as up and down in the vertical direction. Compliance was implemented using in legged robots like one legged hopper, 3D bipedal and Kangaroo using spring loaded legs [13].



Figure 4. Opencv Graphic's and Physics engine simulation

VI. BIO-INSPIRATION AND GAIT ALGORITHM

The universal robotic spinal joint, the modular legs used in this robot has been inspired from the backbone of reptiles like Snake, caterpillar and animals like leopard etc. The Snake's vertebrae is a ball and socket joint [12]. There are about 100-200 depending on the type and length of the Snake. When the Snakes is moving over uneven terrain the excursions in the vertebra are adjusted such that the Snake body hugs the surface. Even the caterpillar shows such compliance. The caterpillar has several similar leg like projections which help for its forward motion. Also the Leopard's spine helps it in giving the flexibility and compliance when it is running. Using these ideas we tried to mimic this in our robot by using 2DOF legs and 2 DOF orthogonal joints for connected the legs.

The spine of the animals like leopard and reptiles like Snake is controlled by muscles actuating them and even its stiffness. We also found that the mechanical wear and tear of the servos was reduced because of this electronic compliance by reduction of impact shock when the legs strike the ground. Shock absorbing foam was used to cover the robot. Also the robot uses a fail safe circuitry to prevent the servos from overheating or damage due to high currents. The top of the body was partially covered with vents for air flow to dissipate the heat. Also the modular nature of electronics ensured that even if one of the Power modules gave out some amount of mechanical motion existed with the rest of the legs with the failed legs just slipping. Modular power electronics here prevented the robot from having a single point of failure which is unique to this modular hexapod.

Algorithm for 3 leg simultaneous gait (modified tripod):

Each of the robotic leg can be viewed as a 2 degree of freedom arm. The position of the foot of each of the robot is made to follow a semi-elliptic path. The path and phase difference between each of the legs path determines the posture and their subsequent positions in time determine the overall gait generated. This particular gait implement on the robot ensures that 3 legs of the robot are in contact at any point of time and the other 3 legs are in air. This was particularly inspired from the Kinematics of the Double dynamic gait of the little dog robot developed at IHMC and MIT.

Semi- Elliptic path defined as :

$$180 \leq \theta \leq 360$$

$$X = H_x \cos(\theta) + X_c$$

$$Y = H_y \cos(\theta) + Y_c$$

$$\theta_2 = \theta_1 + d\theta$$

Where H_x and H_y determine the maximum Horizontal and vertical stride of the leg for a given ellipse with center X_c, Y_c . The next point in the semi elliptical curve is determined by $d\theta$ if $d\theta$ is small there will be more points on the curve

defined and the curve will be smooth but the velocity of the leg about the curve will be small and vice versa.

$$0 \leq \theta \leq 180$$

$$Y = H_y \cos(\theta) + Y_c$$

$X = X + dX$ determines the next point during the horizontal stride. If dX is large the velocity of the leg along the path will be more and vice versa. Angles below are mentioned in fig.7

Pesudo code:

For $I = 0$ to 10

Calculate

$$b = (pt2.x * pt2.x) + (pt2.y * pt2.y);$$

$$si1 = a \tan 2(pt2.y, pt2.x)$$

$$si2 = a \cos(legu * legu + b * legl * legl) / (2 * legu * \sqrt{b})$$

$$\alpha1 = q1 + q2$$

$$\alpha2 = a \cos((legu * legu + legl * legl - b) / (2 * legu * legl));$$

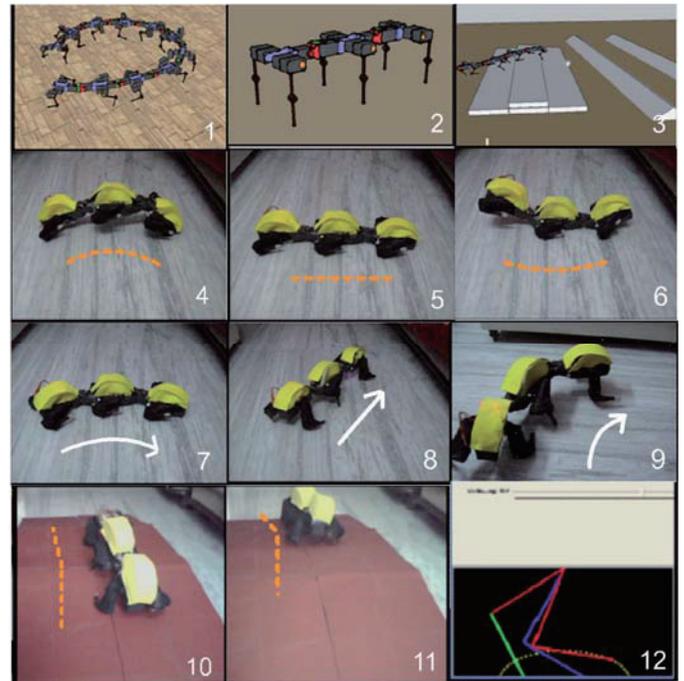


Figure 5. 1-3 show design and simulation of caterpillar over obstacles. 4-6 orange line indicate the backbone shape. 7-9 show maneuvering by changing backbone shape 10,11 show backbones compliance to slopes while climbing up and down. 12 shows a single point control gui for physics engine model and real robot.

VII. SIMULATION AND TESTING

We simulated the caterpillar robot and the hexapod robot over small vertical obstacles and slopes as shown in Fig 5.(3). We tested the same in real time on the robot and our robot's spine successfully adjusted to the changing slope while climbing up and down as shown in Fig 5.(10-11). We developed the robot's API in such a way that we could change the robot's speed, leg's horizontal and vertical stretch from a single point using

the GUI fig 5.12. We tested the robots maneuvering capability by changing the excursion in its backbone in simulation. We were able to successfully do the same in both the horizontal direction left-right and in vertical direction as shown in fig 5.4-5.9. By controlling the shape of the backbone gave us precise control over directing the robots motion. Also we observed that whenever the phase difference or path difference between 3 legs in phase on one side changed with respect to the other 3 legs the robot slipped. We were able to get zero slippage by maintaining an initial phase difference of 180 deg.

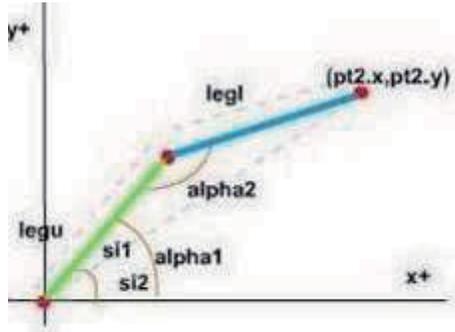


Fig6 .Angles for inverse kinematics calculation.

The table below shows the parameters of our robot Modpod.

TABLE I. ROBOT CHARACTERISTICS

S.no	Robot Parameter	Value
1.	Length of the robot	95 cm
2.	Breadth	11.5 cm
3.	Height	24cm (2 legs)
4.	Weight of the robot	6.4 kg
5.	Operation time	25-30 minutes
6.	Max torque joint	34 kg-cm
7.	Max horizontal stride	28 cm
8.	Max vertical reach	34 cm
9.	Max leg swing joint 1 and joint 2	+/-70 (140) deg

VIII. FUTURE WORK AND CONCLUSIONS

Inspired from the biologically inspired modular robots like Snakes robots and their scalability we built this six legged version of modular hexapod. We hope to scale it to a full length caterpillar version and test its maneuverability and its ability to move over several kinds of terrain. We report the successful design, construction, implementation of “Mod Pod” and its electronic compliance to medium sloped surfaces. . The novelties of this paper includes a successful maneuverability and compliance to surface of the hexapod through spinal actuation which has been inspired from biological organism like snake, caterpillar and 4 legged animals like leopard. Also the custom simulator built for this robot allowed for rapid designing, prototyping and testing of the “ModPod” robot. Specifically many of the gaits were quickly transferred from simulation to real time testing without too many modifications and changes to the robot as a result of the simulator.

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