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ReBiS – Reconfigurable Bipedal Snake Robot

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Abstract—**Robots capable of switching between snake-like and bipedal motion have advantages of greater manoeuvrability. This paper introduces ReBiS (Reconfigurable Bipedal Snake) robot, a novel modular design mechanism which can quickly transform between various configurations without rearrangement of modules. This paper documents the design as well as the gaits implemented on ReBiS. Possible gaits are divided into three categories; snake gaits, transforming gaits and walking gaits. An example gait, belonging each of the three categories, is implemented and presented here. Experimental verification demonstrated that the reconfiguration of this robot is swift and without reshuffling of modules.**

I. Introduction

Choosing a locomotion strategy is critical in developing mobile robots. Wheeled locomotion is good for flat terrains but not suitable for rough terrains or stair climbing. Serpentine motion is one of the common alternatives to wheeled locomotion. Snake robots are versatile; are able to navigate rough terrains, move underwater and climb stairs. However, the absence of wheels translates to difficulties in obtaining odometric estimations. In snake robots, dead-reckoning is noisy and inaccurate. Further, there is lack of an intuitive reference frame to describe the motion of the robot with respect to the world. Hence, autonomous path planning is difficult. Another option to wheeled locomotion is walking robots. The advantage of legged motion is that the leg in contact with the ground can be used as a reference frame. However, these lack the stability, flexibility and speed of snake robots. Reconfigurable robots are capable of hybrid locomotion and have the ability to transform into different configurations. These robots are capable of self-assembly and self-reconfiguration. This makes the robot easy to adapt to different or changing environments.

There are several groups who have designed and constructed snake robots. These designs are included in the survey [1]. Some of the noteworthy designs included are: ModSnake [2] by CMU, PolyBot [3] by PARC, ACM-R5 [4] by Hirose. These systems mimic snake-like motion by bending their bodies while maintaining some contact with ground. ACM-R5 is based on passive wheel to resist lateral motion. Another research work [5] proposes a reference frame called virtual chassis to describe snake motion in terms of world frame. DARwIn-OP [6] and Aldebaran Nao[7] are some of the popular kid-sized walking robots. Survey [8] classifies various reconfigurable systems into chain, lattice, and mobile. ATRON [9], MTRAN III [10] and Superbot [11] are hybrid chain-lattice systems. An immanent feature of all these robots is that modules can attach and detach from other modules by using permanent magnets, electromagnets or retractable mechanisms.

This paper presents a novel reconfigurable robot, ReBiS (Reconfigurable Bipedal Snake). ReBiS is capable of both serpentine as well as legged motion. The ability to transform between snake and multiple walking configurations means that ReBiS has a multitude of locomotion strategies. Presence of a body frame and dead-reckoning makes the walking configuration of ReBiS more suitable for implementing path planning and SLAM algorithms [12] [13] as compared to snake robots. In snake configuration, ReBiS is ideal for navigating rough and uneven terrains, sneak through crevices and holes. ReBiS can, hence, reach places inaccessible to traditional Bipedal Robots. Another feature of ReBiS is its ability to transform without the need to detach and reattach any of its modules.

II. Robot Design

Our main objective was to design a modular mechanism which can transform from a snake configuration into a walking configuration without any detaching and attaching modules. This eliminates the need of additional actuators and mechanism for docking and undocking the modules. Using modular architecture makes it easy to replace modules or add additional ones to increase the Degrees of Freedoms (DoF).

A. Mechanical Design

Fig. 1 shows a pair of modules of ReBiS-I containing two modules. Each module consists of a single DoF revolute joint (±120 degrees). A module is made up of 3 parts: a) Dynamixel MX-28 Robotic Servo Motor b) Motor Clamp c) C-Link. The parts are fabricated using CNC milling of 2-mm thick aluminium sheet metal. The parts are then bent at 90

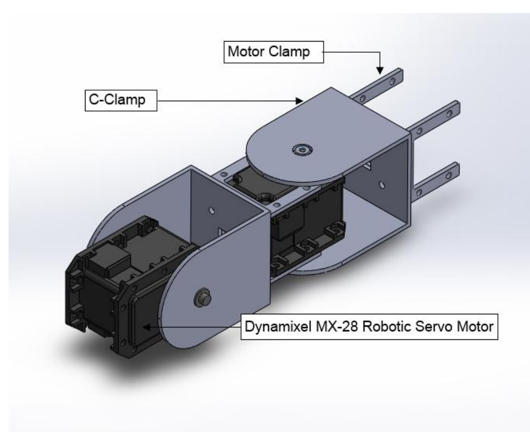

Fig. 1. CAD Model of a pair of ReBiS Module.

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degrees using a custom designed jig. The center of C-Link and the Motor Clamp has a rectangular extrude cut to pass the wires. The range of rotation of each joint is an important parameter as it largely affects the number of possible configurations and gait design strategies of the robot. However, a larger range of rotation increases the length of the module. Hence, we restricted the range of rotation to $\pm 120^0$. The robot has a square cross section to maintain symmetry. This is helpful in performing snake gaits such as rolling. The sides of the module are kept flat. This allows it to be used as a foot in walking configuration. The axis of rotation of each joint is rotated by 90 degrees with respect to its previous joint. This allows the robot to move in all 3-dimensions.

Dynamixel MX-28 robotic servos are utilized for actuation of joints. These motors provide a stall torque of 2.8 Nm at 12V and have an operation range of 360^0.

The fig. 2 shows the entire assembly of the ReBiS robot using 9 modules.

B. Electrical Design

Dynamixel MX-28 [14] has an on-board ST Cortex-M3 processor (STM32F103C8 @ 72MHz) to control the angle and speed of the shaft. An internal PID loop is implemented using feedback from magnetic encoders attached on the shaft of the motor. The gain parameters are tuned to fit the application. These servos provide a half-duplex TTL bus for communication and can be connected in daisy-chain. This allows for the robot to have only three wires running through its entire length. The servos are coordinated by a PC connected to the robot. An ARM Cortex-M4 controller (TI's TM4C123GXL) acts as a bridge between the PC and the motors. The on-board magnetic encoder also provides position as well as velocity feedback. As of now, ReBiS is powered using an off-board 12V 2A DC power supply.

Software for ReBiS is implemented using ROS Framework in Ubuntu 12.04 LTS. The framework uses inter-process communication via message passing to link various processes, also known as nodes, running on a machine. The software implementation consists of a communication node, snake gait node, walking gait node and an initialization node. The communication node handles the transmission of desired angle and speed to the motor. It acquires desired angle and speed values converts it to Dynamixel MX-28 compliant protocol and transmits it via a virtual serial port to the ARM Cortex-M4, controller which is acting as the bridge. It also retrieves the speed and angle values from the motor; converts it from Dynamixel Protocol to float and passes it to the gait generator. Fig. 3 summarizes the software architecture of ReBiS.

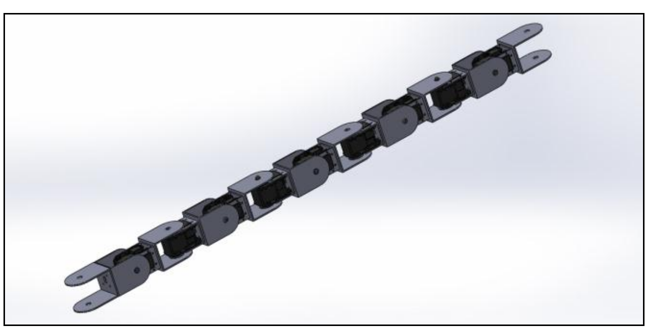

Fig.2. CAD Assembly of ReBiS

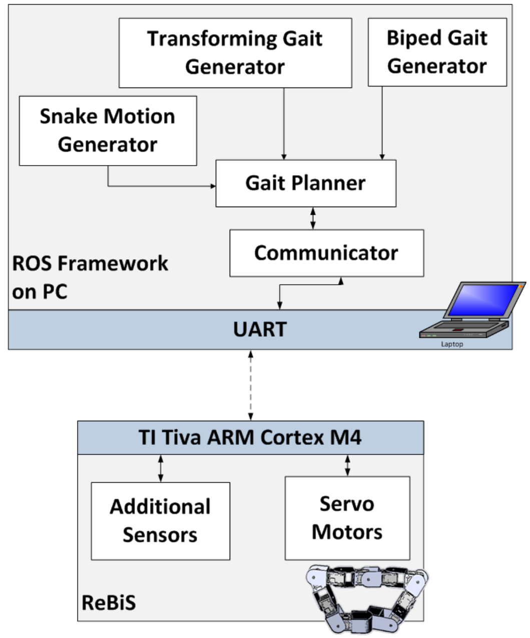

Fig. 3.Software Architecture of ReBiS

III. Gait Design and Experimentation

ReBiS is capable of snake as well as bipedal gaits. Also, a special gait needs to be implemented to transform the robot from a snake-like configuration to a bipedal robot. This section describes the gaits implemented on the robot.

A. Snake gaits

To mimic snake motion, we implemented gaits based on sinusoidal curves. An overview of snake gaits presented in literature [15]. The gaits implemented on ReBiS are summarized in this section. The snake gaits consists of two sinusoidal waves; one in each horizontal and vertical plane.

$$angle(n,t) = \begin{cases} A_x * \sin(\omega_x t + n * \delta_x), where\ n = even \\ A_y * \sin(\omega_y t + n * \delta_y + \emptyset), where\ n = odd \end{cases} \quad \ldots (1)$$

Where, n is the motor number when motor at each joint is numbered sequentially. A_x, A_y represent the amplitudes; δ_x, δ_y represents the spatial frequency; ω_x, ω_y represent the temporal frequency and ϕ represents the phase difference between the sine waves in horizontal and vertical plane.

Table 1 shows gaits that can be achieved using this approach. Fig. 4 shows rolling and sidewinding gaits implemented on ReBiS. In the rolling gait, the snake robot curves itself into a C-shaped arc and rolls about its own axis.

TABLE I. Parameter Values for Snake Gaits

Gait	Parameters			
	Amplitude	***Frequency***	***Phase Difference***	**ϕ**
Lateral Undulation	$A_x = 60^0$ $A_y = 0^0$	$\omega_x = 5\pi/6$ $\omega_y = 5\pi/6$	$\delta_x = 2\pi/3$ $\delta_y = 0$	$\phi = 0$
Sidewinding	$A_x = 30^0$ $A_y = 30^0$	$\omega_x = 5\pi/6$ $\omega_y = 5\pi/6$	$\delta_x = 2\pi/3$ $\delta_y = 2\pi/3$	$\phi = 0$
Rolling	$A_x = 60^0$ $A_y = 60^0$	$\omega_x = 5\pi/6$ $\omega_y = 5\pi/6$	$\delta_x = \pi/2$ $\delta_y = \pi/2$	$\phi = \pi/6$
Linear Progression	$A_x = 0^0$ $A_y = 60^0$	$\omega_x = 5\pi/6$ $\omega_y = 5\pi/6$	$\delta_x = 0$ $\delta_y = 2\pi/3$	$\phi = 0$

Fig.4. shows rolling motion on a flat surface (top); sidewinding motion on a flat surface (bottom).

In the sidewinding gait the robot mimics the sidewinding motion performed by desert snakes.

B. Transforming Gait

We have designed the transforming gaits using key-frame interpolation based approach. This approach is commonly used by the animation community. Key-frame consists of a set of joint angle data at a particular timestamp. Fig 5 shows key-frames of the transforming gait which reconfigures the robot from snake configuration into walking configuration. To ensure the stability of the robot, the ground projection of center of mass (CoM) must lie within the support polygon of the robot. Hence, every key-frame must satisfy the stability criteria. Further, the criteria should also be satisfied while transitioning between key-frames.

In key-frame 1, the robot is set into a straight open chain, by setting all the joint angles to zero. In key-frame 2, the robot achieves a pentagon shape by lifting its center part from the ground using the support of the first and last module. These key-frames are in a 2-dimensional plane; hence the inverse kinematics can be easily done using geometric approach and transitions can be achieved using linear interpolation. However to move to key-frame 3, the robot performs 3-dimensional motion and transition cannot be achieved by using linear interpolation.

One solution would be to increase the number of intermediate key-frames and hence essentially approximating the transition curve better. This requires inverse kinematics calculations to find joint angles such that both the feet touch the ground with the required orientation and satisfy the stability criteria. Performing inverse kinematics for 9 DoF will be complicated. To overcome this problem, we came up with an alternate solution in which we set the torque limit of the motor 5 to zero, and using only motors 4 and 6 for transition. These joints are rotated by 90^0 to reach the next key-frame. Setting the torque of motor 5 allows the robot to contort according to the motion of motors 4 and 6. The robot is then moved into successive key-frames 4 and 5 by using linear interpolation.

C. Walking gait

Most of the bipedal walking gaits are designed using zero-moment-point (ZMP) [16] or linear-inverted-pendulum (LIP) approach. In these methods the CoM/ZMP is shifted within the support polygon of one of the legs and then the other leg is moved forward. The configuration of ReBiS, shown in fig.7, is designed in such a way that it inherently satisfies the stability criteria without lateral shifting of the ground projection of the CoM.

To generate gait trajectory, we assumed the foot, in contact with the ground, as the base and the other foot as the manipulator. DH convention [17] is used to obtain the forward kinematics. Frame allocation and DH parameters of the robot are shown in Fig.6 and Table 2 respectively.

The equation for forward kinematics is given by:

$$^{n-1}T_n = \begin{pmatrix} \cos\theta_n & -\sin\theta_n\cos\alpha_n & \sin\theta_n\sin\alpha_n & a_n\cos\theta_n \\ \sin\theta_n & \cos\theta_n\cos\alpha_n & -\cos\theta_n\sin\alpha_n & a_n\sin\theta_n \\ 0 & \sin\alpha_n & \cos\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{2}$$

$$^{0}T_9 = \prod_{i=1}^{9} {}^{i-1}T_i \tag{3}$$

TABLE II. DH Parameters for ReBiS

Parameters			
a_i	***α_i***	***d_i***	**θ_i**
80 mm	*90^0*	*0*	*θ_i*

The table above shows DH parameters for ReBiS. All the links of ReBiS have the same DH-Parameters as shown above.

TABLE III. Ranges of all Possible Joint Angles

Range of Angles	Angles			
	θ_1	**θ_4**	**θ_6**	**θ_9**
Minimum	*-35^0*	*-40^0*	*-40^0*	*-35^0*
Maximum	*-90^0*	*40^0*	*40^0*	*-90^0*

The table above shows the ranges of all possible joint angles as used in database generation.

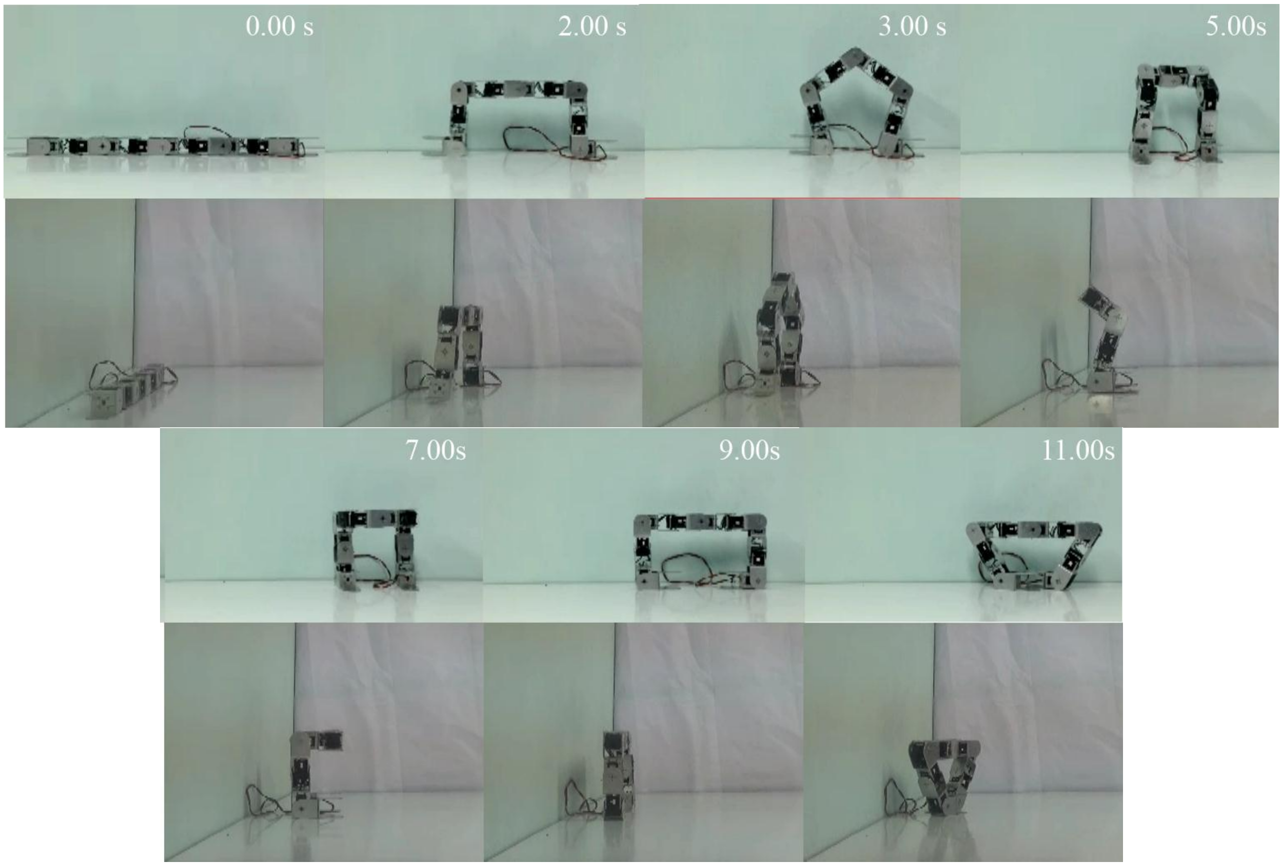

Fig.5. shows the Key-frames used for walking gait. The front and side views as well as the time for each key-frame is shown here.

Performing inverse kinematics for 9 DoF is complicated. It also requires many constraints to obtain unique solutions. Hence, we set the angles of 5 joints to be fixed and performed inverse kinematics on just 4 joints. 5 joint angles are fixed such that the robot should inherently satisfy the stability criteria. Angle of joint 5 is set to 0^0 so that the top of the robot remains horizontal. Angles of joint 3 and 7 are set to its lock angle of 120^0. At the lock angle, the load of the robot is directly transferred to the links and there is no load on the motor. This reduces the power consumption.

With these angles, the CoM of the robot is within the feet of the robot. In this walking configuration, we have assumed the front foot as the base and the rear feet as the manipulator. The front foot is kept on the ground and rear foot is moved forward. Hence, the CoM must lie within the contact area of the front foot. To achieve this, we set the angles of joint 2 and 8 to -20 and 20 respectively.

$$\theta = [\theta_1 \ -20 \ 120 \ \theta_4 \ 0 \ \theta_6 \ 120 \ 20 \ \theta_9]^T$$

To obtain the inverse kinematics, we have used a forward kinematics based approach. Firstly, we generated a database by performing forward kinematics on all combinations of possible joint angles and calculated the location and orientation of the manipulator. The ranges of joint angles, used for the generation of the database, are shown in table 3.

Each entry in this database consists of the values of the 4 joint angles and their corresponding mapping to the x, y, z displacement and roll, pitch, yaw orientation of the manipulator. After generating the database, we obtain the joint angles for our key-frames by selecting the entry with minimum least square error.

A total of 7 key-frames were used to form the walk cycle. Fig. 7 shows the key-frames for the walk. Initial position of ReBiS walking gait is shown in Fig. 7 on the left. In the next

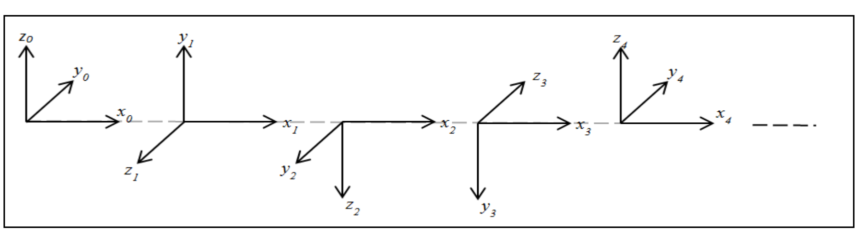

Fig.6. Frame Allocation of ReBiS

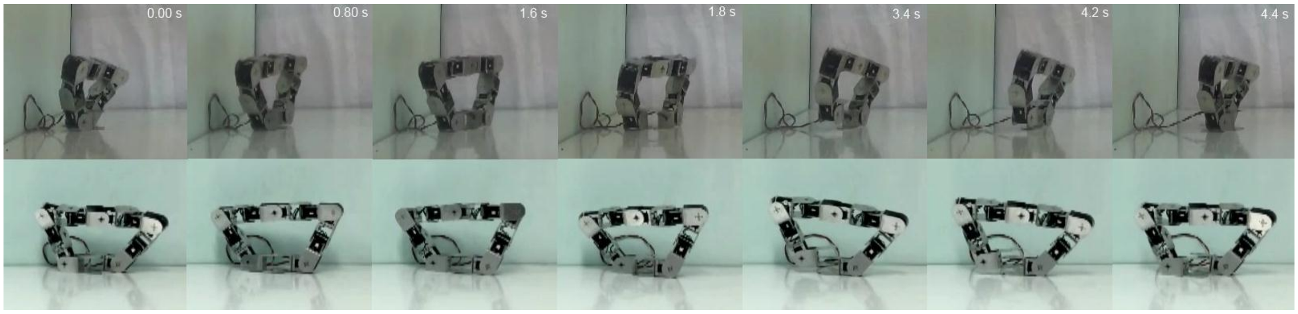

Fig.7. shows the key-frames used for walking gait. The front and side views as well as the time for each key-frame is shown here.

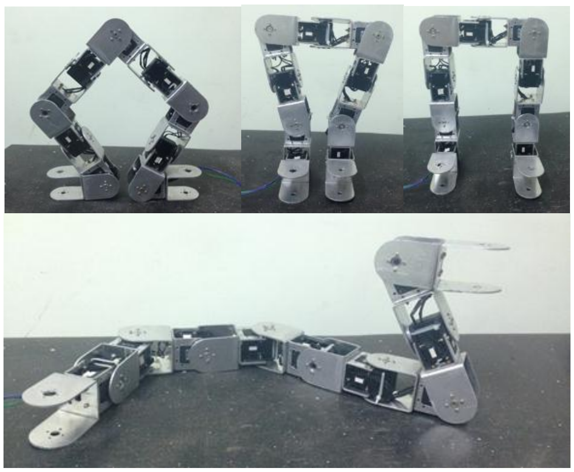

Fig. 8.shows some of the possible configurations of ReBiS.

key-frame the rear feet is lifted. This configuration is stable as the robot is bent in the forward direction and the CoM is located in the forward foot. The third key-frame involves moving the second manipulator to another stable position. 4. Now the foot is placed on the ground. The transition between key-frame 3 and 4 is unstable hence we have increased the speed of the transition. The walking cycle is completed by repeating the same process for the other leg.

IV. Conclusion

This paper introduced a novel design of a reconfigurable robot without attachment or detachment of modules. A prototype of ReBiS has been fabricated and one or more gait(s) of each category has been implemented and shown in the video attachment with this paper. Different images show ReBiS performing sidewinding, rolling, transforming and walking gaits. A novel method of walking is also presented where lateral shifting of CoM is not required. The implemented model confirms to the inverse kinematic analysis.

Future work on this system will be on exploring various configurations possible with the ReBiS Robot. Images show a few more configurations possible by using 9 modules. Our goal is to design optimal gaits to achieve efficient walking along with ability to walk on rough and uneven terrains.

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