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Ascending and Descending Snake Robot for Disaster Application

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***Abstract*—This Project is to design a snake-like robot that can provide the locomotion as the real biological snake, and possessed the ability to cross over the obstacles with a certain height's limit, or find another alternative ways instead of climb over it if the height of the obstacles is over the limit. Snake-like robot is a biomorphic hyperredundant robot that resembles a snake. The shape and sizes of the snake-like robot is depend on its own application, different application may required different sizes and shapes, since this project mainly target is to design a snake-like robot that can avoid the obstacles, so the snake-like robot is design to a moderate size with 8 segments, so that the snake-like robot can move flexible in the terrain that have a lot of obstacle. In order to make the snake-like robot function and move like a real biological snake, snake-like robot may construct of multiple joints which enable the snake-like robot to have multiple degree of freedom, which give it the ability to flex, reach and approach a huge volume in its workspace with infinite number of configurations. This mobility can enable the robot to move around in more complex environments. So, the application for this snake-like robot could be very useful in hard to reach places or hazardous environments. For the locomotion of this snake-like robot, it is move in a specific gait, which is a periodic of sine wave motion, just like a lateral undulation motion. Lastly, the special feature such as snake-like locomotion, ability to climb over obstacles or stair, estimate the height, making decisions, and able to remotely control are applied to the design.**

I, INTRODUCTION

Snake-like robot is a biomorphic hyper-redundant robot that resembles a snake. The shape and sizes of the snake-like robot is depend on its own application, different application may required different sizes and shapes, for example, for research and rescue purposed snake-like robot may required as thin as possible to enable it to do the tasks at narrow place. In order to make the snake-like robot function and move like a real biological snake, snake-like robot may construct of multiple joints which enable the snake-like robot to have multiple degree of freedom, which give it the ability to flex, reach and approach a huge volume in its workspace with infinite number of configurations.

For the locomotion of the snake-like robot, there still don't have any snake-like robot can completely mimic the locomotion of real snake, most of the snake-like robot moves by refer to a specific gait, where a gait is a periodic mode of locomotion, for example a gait maybe side winding. There have several type of locomotion for a snake-like robot, which included the movement using the wheels, 'legs', or without both of the wheels and leg but just slide, glide, and slither. Below show the advantages of the serpentine locomotion over the locomotion using wheels or legs:-

A, Stability:

-where the serpentine locomotion have a better stability than wheels and legs, this because the serpentine robot will never fall, even if a free fall occurs, the serpentine robot will survive better than most mobile devices, because the potential failure points like the connections between the body and wheels or leg do not exist.

B, Terrainability:

-means the ability of moving in a rough terrain, if compare the serpentine robot to the robot using wheels or legs, the serpentine robot have better terrainability than the latter, for example, wheels or legs will stuck at a hole but this won't happen to a serpentine robot.

C, Degree of freedom:

-a large number of actuators is required if compare with the wheeled or legged device to help the serpentine robot to subtend the various curves, this means the serpentine robot may have a large number of degree of freedom, where this will introduce reliability problems, that is if failure occur on one of the actuators, then the robot with large

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number of units have a higher chance of having any unit fail.

C, Speed:

The speed for a serpentine locomotion robot is fairly slow if compare to the real snake.In exploration, the snake-like robot is suitable to explore the unpredictable environment, this may due to the ability of snake-like robot.

For the application of the snake-like robot, it may include several fields such as the medical, exploration, routing, and military. For medical, people had applied the snake-like robot technologies into the surgery, for example, the snake-like robot is operating in the narrow throat region, to make incisions and tie sutures with greater dexterity and precision. [1] In exploration, the snake-like robot is suitable to explore the unpredictable environment, this may due to the ability of snake-like robot to distribute its mass over a large area for support so that if the footing is gives way, self-support between secure points enables continued operation.

For routing purpose, such as wiring through passages behind existing walls or through the pipes, these tasks involve long reaches and awkward position through the pipes, so the flexible snake-like robot will be required to make the work easy by maneuver through crowded plenums and pull the initial light weight tapes which will use to pull the actual cables. [1] In military, one of the example maybe the snake-like robot manufacture by Isareal, where the robot can sneak through cracks and into buildings to send back sound and video of enemy movements or even plant explosives.

The objective of this project is to design a snake-like robot, which can either move by making decision itself in an unknown terrain (inspection) or move remotely with the assist of camera. Besides that, we are also required to program the snake-like robot so that it can move similar as the biological snake.

Snake-like robots are multi-segmented devices. Based on their physical structure and design, these robots could have great mobility in their movements. This mobility can enable the robot to move around in more complex environments. [2] The application of these kind of robots could be very useful in hard to reach places or hazardous environments, this is one of the reason that make the snake-like robots playing important role in our life and had been utilized in many fields like research and rescue, military, inspection and others.

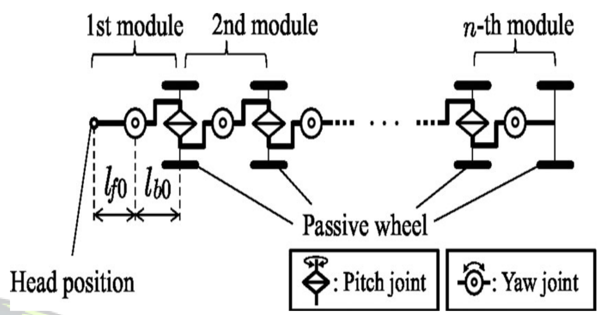

Fig 1 : N-Module Snake Robot

II, MODELLING

We consider an n-module snake robot as shown in Fig. 1. The module of this robot has a yaw rotational joint, and is connected in series via a pitch rotational joint. The passive wheel is coaxially placed with the pitch joint and velocity constraint, preventing side slip from occurring if the wheel touches the ground. The snake robot can perform the same locomotion as a living snake by bending its joints appropriately considering the velocity constraint. l_{f0} is the length from the anterior end of the link to the axis of the yaw joint, l_{b0} is the length from the posterior end of the link to the axis of the yaw joint, and $L = l_{f0} + l_{b0}$. [1] Let $\varphi_i$be the yaw joint angle of the ith module, $\psi_i$be the pitch joint angle between the ith and $i + 1$th module, and let us define$\boldsymbol{\psi} = [\psi_1, . . . , \psi_{n-1}]^T$, and $\boldsymbol{\varphi} = [\varphi_1, . . . , \varphi_n]^T$.

A, Step Environment:

Fig. 2 shows the step environment and the snake robot discussed in this paper.

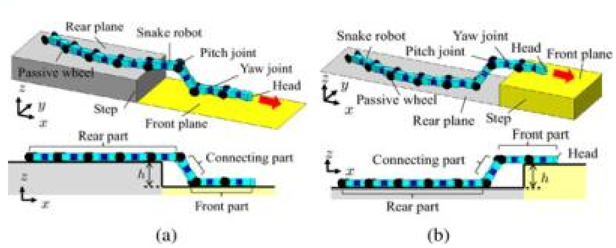

Fig. 2. Step environment and a snake robot. (a) Descending case. (b) Ascending case.

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We can break down the ascending and descending motion on a step into four phases. Fig. 3 shows the ascending phase of the snake robot. Realizing the movement in (a) and (d) can be accomplished by the methods in, and, while that in (b) can be accomplished by the method proposed in and . Thus, this paper focuses on locomotion, while shifting between two planes as shown in (c).

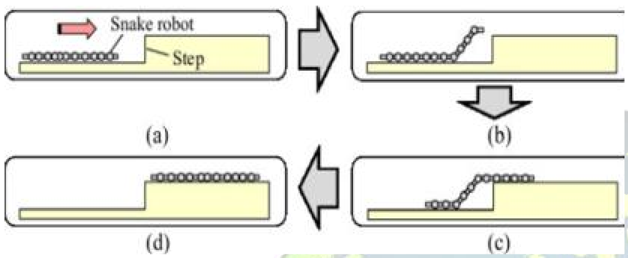

Fig. 3.Ascending phase of the snake robot. The snake robot (a) locomotes on the rear plane, (b) raises its head when approaching the front plane, (c) locomotes, while shifting between the two planes, and (d) locomotes on the front plane.

B, Kinematic Model:

The robot can be treated as a 2-D snake robot by projection onto the *xy*plane as shown in Fig. 4. Note that ungrounded wheels are not shown in Fig. 4 (e.g., the $i-1$th wheel). On the *xy*plane, let $w = [x_h, y_h, \theta_h]^T$ be the position and attitude of the robot's head and $\psi_h$be the absolute pitch attitude of the robot's head, and let us define $\Psi_i = \psi_h + \Sigma_{j=1}^{i-1} \psi_j$ and $|\Psi_i| \leq \pi 2$. l_{fi} and $l_{bi}$are the projections of l_{f0} and l_{b0} on the *xy*plane, respectively. [3] Note that l_{fi} and l_{bi}change with the pitch joint angle because they are projections on the *xy*plane and the state of whether each wheel touches the ground is switched dynamically by the position and body shape of the robot. l_{fI} and $l_{bi}$are expressed as

$$l_{fi} = l_{f0} \cos\Psi_i, \quad l_{bi} = l_{b0} \cos\Psi_i.$$

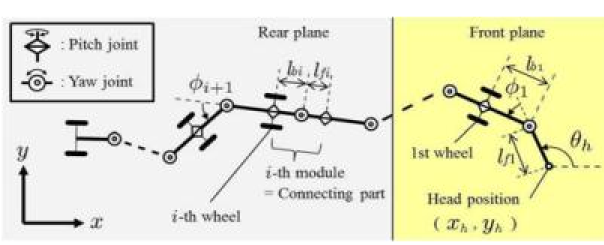

Fig. 4.*xy*projection model of the snake robot.

The yaw angle of the connecting part is zero: By assumption 1, the direction of the wheel axis of the connecting part is the same as those of the anterior and posterior wheels as shown in Fig. 4, and the connecting part can connect the front and rear parts, such that each wheel touches each plane. In this case, planning of the connecting part only requiresappropriately controlling the angles of the pitch joints. [3]

By introducing this assumption, the shift in the connecting part can be planned based only on the pitch joint angles. Therefore, it is possible to deal with 3-D motion by breaking it down into motion parallel to the *xy*plane and that parallel to the *z*-axis. In this paper, we consider the case, where the connecting part consists of one module and $|h| < l_{f0} + l_{b0}$. However, the model and controller presented in this paper can be applied to higher steps by increasing the number of links in the connectingpart. [4]

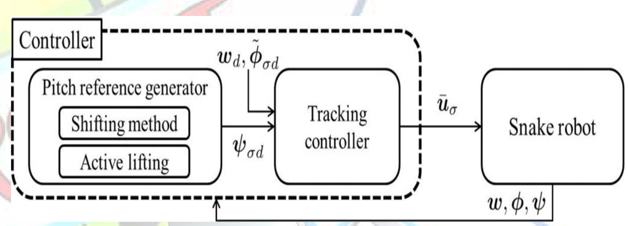

Fig. 5. Structure of the proposed controller

III. CONTROLLER DESIGN

The control input related to locomotion in the direction of the *xy*-axis is determined based on the kinematic model (6). Moreover, the connecting part is shifted in the posterior direction by determining the desired value of the pitch joints so that the ungrounded module sequentially touches the ground in the descending case and the grounded module is sequentially lifted up in the ascending case. [2]

The motion of the robot is determined by the motion of the yaw and pitch angles, with a vector consisting of the angular velocity of the yaw and pitch joints used as the control input. The robot is propelled via serpentine motion using the yaw angle to move forward and the pitch angle to shift back the

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connecting part. The pitch angle is also used to raise certain wheels (referred to as active lifting). [4] We also propose a controller, consisting of a pitch reference generator, which sets the pitch angle, and the tracking controller, which controls the input to the robot. Fig. 6 shows the structure of the proposed controller. The pitch reference generator determines the desired value of the pitch joint angles based on the shifting method and active lifting, and the tracking controller calculates the input velocity, by which the controlled variable converges to the desired value.

A, Tracking Controller:

We set the desired vector of the controlled variable $.w\ \sigma$ as $.w\sigma d= [wTd,\psi Td,\tilde{}\varphi T\sigma d]T$, where $wd= [xhd,\ yhd,\ \theta hd]T$ is the desired vector of the position and attitude of the robot's head.

In addition to resolution, conversion time is another major factor in judging anADC. Conversion time is defined as the time it takes the ADC to convert theanalog input to a digital (binary) number. For the ADC in PIC18Fmicrocontroller, the conversion time is dictated by the internal clock source(crystal frequency)The step size for ADC with 10-bit resolution and used 5V as reference voltage.

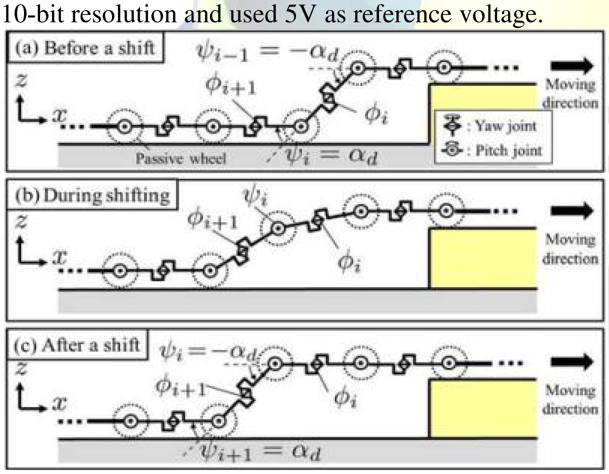

Fig. 6. Shift of the connecting part.

B. Pitch Reference Generator:

Assume that the connecting part is the *i*th module. The pitchreference generator, which is designed to shift the connectingpart, consists of the shifting method and active lifting. [3] The shiftingmethod determines the reference to shift the connecting partfrom forward to backward depending on the motion, while theactive lifting determines the reference to change the shape ofthe body of the robot and to prepare for the shift.

In this paper, we assume the connecting part is shifted as shown in Fig. 6. This figure depicts the robot (a) before the shift, (b) during the shift, and (c) after the shift of the connecting part in the ascending case, and is described for the case, in which all yaw angles are zero for readability.

C. Active Lifting for the Additional SCP:

We consider lifting up arbitrary wheels actively as shown in Fig. 7. If one wheel is lifted up, the corresponding velocity constraint disappears. The number of SCPs increases as the number of velocity constraints decreases. [4] These additional SCPs can affect the shape of the robot through direct control. If the lifting height is small, the lifting angle of the pitch joint does not affect the motion of the yaw angles.

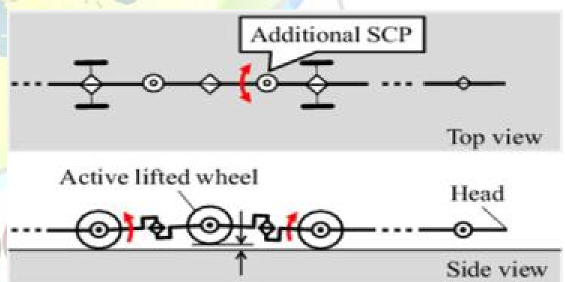

Fig. 7. Active lifting of the wheel

D. Shifting Method:

In the shifting method, the reference of pitch joints is generated by transiting two states: (S1) preparation for shifting, and (S2) shift of the connecting part

*1) Preparation for Shifting:*The yaw angle φi+1 becomes the connecting part at the next shift because the *i*th module is the connecting part. From assumption 1, it is necessary for φi+1 to converge to zero before shifting the connecting part. In the descending case, the *i*th wheel becomes ungrounded, and φi+1 becomes one of the SCPs by forward motion of the robot. In the ascending case, φi+1 becomes an additional SCP by active lifting. As the SCP can be controlled directly, we set the desired

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value of φ_{i+1} to $\varphi_{(i+1)d} = 0$, in preparation of shifting.

2) Shifting Condition: If the robot satisfies the shifting condition, the state of the robot transits from (S1) to (S2). Let the border of the step be on the line $x = x_{step}$and the direction of motion be the positive direction of$x$.The pitch angles $\psi_{i-1}, . . . , \psi_{i+j-1}$ satisfying Conditions 1–3are not unique and can be set as desired. However, these shouldnot be set; therefore, to cause a collision between the connecting part and the two planes during shifting. shows anexample of shifting on a high step.

IV. EXPERIMENTS

Experiments were performed to confirm the effectiveness of the proposed control method. The experimental system is shown in Fig. 8. The snake robot has active joints and passive wheels with $l_{f0} = l_{b0} = 0.088$ m and $n = 8$. The pitch and yaw joints use Dynamixel MX-64R and MX-106R (ROBOTIS) actuators. The real-time position and attitude of the robot were measured by OptiTrack (NaturalPoint, Inc.), which is optical motion capture and tracking software. The joint angles were measured by the absolute encoder in the Dynamixel MX-64R and MX-106R. A PC was used to calculate the input and control the actuators with the PC and actuators connected in a daisy chain via an RS485 interface. We set the parameters of the controller to K_w = diag(0.5, 0.5, 1), $K_\psi = 0.1 I_{n-1}$, $\tilde{K}_{\varphi\sigma} = 0.5 I_{n\sigma}$, t_ψ= 5 s, and _ = 0.05. [4]

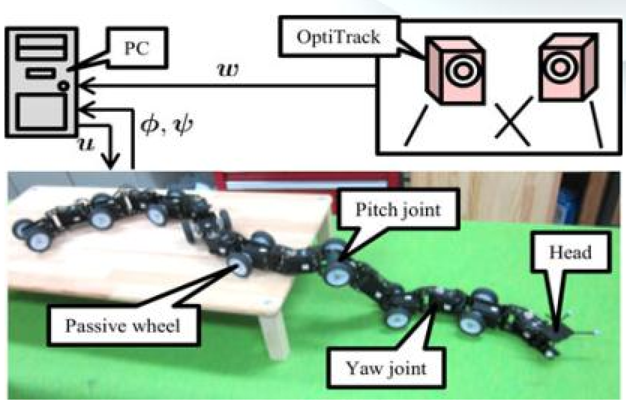

Fig. 8.Experimental system.

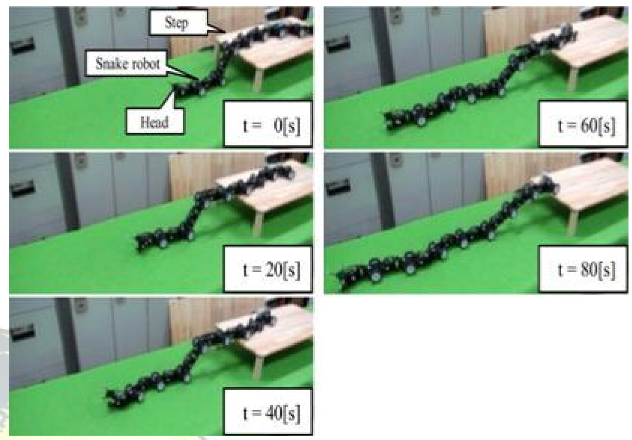

Fig. 9.Descending motion of the snake robot.

V. CONCLUSION

In this paper, we proposed a control method to realize trajectory tracking of a robot's head and ascending and descending locomotion in a step environment consisting of two parallel planes. We focused on locomotion with shifting between two planes, and introduced an assumption related to the connecting part and yaw angle to simplify the model and Controller. We decomposed 3-D motion into motion parallel to the *xy*plane and that parallel to the *z*-axis. In addition, we derived a model of the robot as a hybrid system with switching on the *xy*plane. We also proposed a controller consisting of a tracking controller and pitch reference generator based on the shifting method for the connecting part and active lifting to control the shape of the robot. Experimental results demonstrated the effectiveness of the proposed control method.

An advantage of the proposed method is that the method can accomplish trajectory tracking of a robot's head and ascending And descending a step without collision. Moreover, it can be implemented using a microcomputer and contributes to downsizing the robot because the computational overhead is smaller than that of a controller based on a dynamic model. However, a limitation of the method is that it is a kinematic controller, which assumes that the wheels do not slip sideways. It is not suitable if the dynamic effect of the motion of the robot is large or in the case of a slippery floor owing to the increased model error. Moreover, the steps considered in this research are the simplest in discrete 3-D environments, and the controller cannot be applied to nonparallel planes. Furthermore, it is necessary to observe the position and attitude of both the robot and step when using the proposed controller. These are the limitations of the proposed method. In future studies, we intend considering a control method for ascending and descending stairs in a more complicated environment, incorporating environmental recognition using only internal sensors, and modeling and control without velocity constraints, e.g., based on dynamics considering anisotropic friction.

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