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A Study of Active-Wheel Snake Robot Locomotion Gaits

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***Abstract*— This research aims to study the locomotion of a wheel snake robot in different environments. The wheel snake robot was developed in the form of Active-Wheel Active-Joint to easily create mobile forms for use in variety of different operating conditions. Using the motion by the force of the wheel, waves are created by the robot to generate friction conditions that can propel the robot in the desired direction. In this work, we experimented with three types of environment: a flat ground, a slope and a tight corner. The experiment shows that the Active-Wheel Sinusoidal (AWS) gait is the best solution for traveling on a flat ground and a slope. For turning in a tight corner, the robot should use the Active-Joint Active-Wheel (AJAW) gait. By adjusting parameters such as motion shape and motor driving speed, the experiment showed that the L-shape gait with varied drive speed required the smallest turning area compared to other gaits that were tested.**

Keywords – Active-Wheel Active-Joint snake robot, locomotion, snake robot gait

I. INTRODUCTION

Hyper-redundant or snake robots have been developed in various forms for different objectives. Hirose [1] developed the snake robots under active-cord mechanism (ACM) concept that uses the relationship between the sinusoidal curve of the robot's body and the friction from the ground to propel the robot forward. The ACM-R3 robot has large wheel and two degree of freedoms joint which increase its ability for climbing on various type of terrains. Howie Choset[3] studied the snake-like locomotion under differentiable and piecewise differentiable gaits which allows the robot to crawl in rugged and uneven terrain. Granosik, Hansen and Borenstein [3] developed the snake robot called OmniTread 4 in which each module has active track on all four sides. This robot is well designed for climbing large obstruction and difficult terrain.

Most snake robots were designed in form of passive – wheel active-joint. The passive wheel allows friction in the direction perpendicular of the robot body which propels the robot forward under the sinusoidal motion. We are interested in the active wheel-active joint robot which allows the robot more climbing ability over various type of terrains.

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II. ACTIVE WHEEL SNAKE ROBOT

A. Mechanical design

We have developed the active wheel snake robot named MoMo which comprises of 6 modules as shown in figure 1. Each robot module is 15 cm x 15 cm (Width x Height) and has 2 degree of freedoms joint. The active wheel is attached module 1, 3 and 5. The digital servo motors (Robotis AX-12) actuate all joints and wheels of the robot (i.e. 15 motors in total).

Fig.1. CAD model of MoMo robot

The motor that control the robot joint can be grouped into two groups: pitch (2,4,6,8,10,12) and yaw(1,3,5,6,9,11). A pair of 15 cm diameter wheels are driven by a motor through a common axle with 3:2 gear ratio. The wheel velocity is between 0.05 to 0.25 m/s. Figure 2 shows the robot mechanical configuration and motor ID assignment.

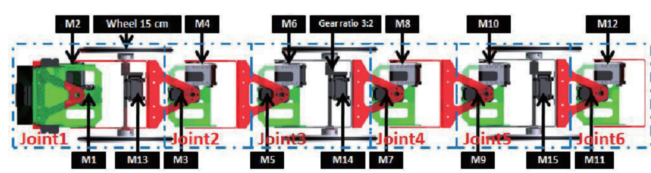

Fig.2. MoMo mechanical configuration

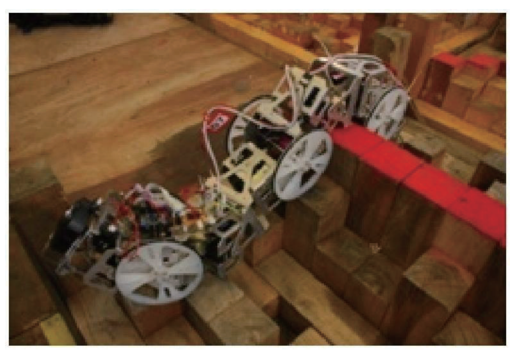

Fig.3. The MoMo robot prototype

The robot is controlled by a computer that sends the motion command via RS232 to an ATMEL ATMEGA128 microcontroller board on the robot. All motors are serially connected to the microcontroller as shown in figure 4.

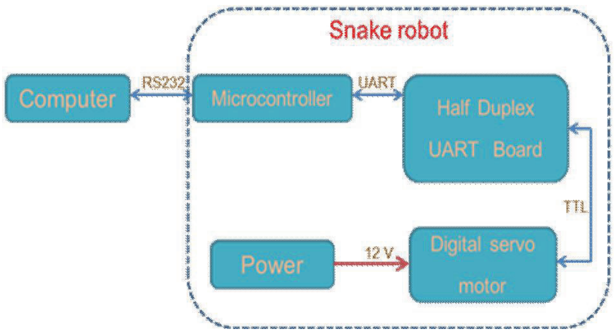

Fig.4 the communication system diagram

III. Locomotion Gaits

A. Moving forward and backward

1. Asynchronous Active-Joint Active-Wheel gait (AAJAW)

In this gait, the joint and the wheel is controlled asynchronously. First, the joint are controlled to the desired configuration. In the forward motion case, all joints are controlled to zero degree position so that the robot assumes a straight line configuration. Then, the wheel motors become active and propel the robot forward or backward.

2. Passive-Wheel Sinusoidal gait (PWS)

In this gait, the wheel is in passive mode in order to create the non-holonomic constraints that resulted in the force which propel the robot forward when the robot body is moving in sinusoidal motion according to serpentine locomotion concept [1]. We used the motion shape code technique [4] to generate the shape and the motion of the robot into a sinusoidal waveform. The sinusoidal shape is generated by selecting the basis angle (α) and the motion shape vector. The angular position of each joint module is specified by θ_i from eq. (1). All joints are controlled to the desired position in one cycle then the cyclic shifting operation is performed at the motion shape vector to generate the motion of the next cycle.

$$\theta_i = C_i * \alpha \tag{1}$$

where θ_i is the desired angle for joint i
C_i is the *ith* component of a motion shape vector
α is the basis angle

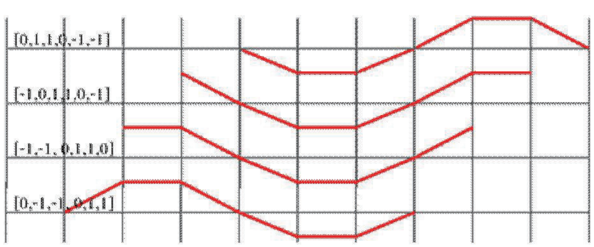

Fig.5. a discretized sinusoidal waveform generated by a motion shape vector

3. Active-wheel Sinusoidal gait (AWS)

The wheel and joint are both active simultaneously in this gait. In the same way that the sinusoidal waveform is generated in the PWS case, in the AWS gait, the wheels are also driven forward as the robot's body is moving. The force from the driven wheel is added to the force created by friction from the robot's body in sinusoidal motion.

B. Turning motion

1. Passive-Joint Active-Wheel Turning (PJAW-T) gait

The simplest turning motion can be achieved from separating the body turning motion and the forward wheel motion into two consecutive operations. At the beginning of this turning gait, the head module is lifted and turned in yaw axis toward the desired direction. Then, the torque on robot's body in pitch and yaw axes are disabled in order to allow the robot's body to be passive. After that, all wheels are powered to move the robot forward toward the direction initialized by the turning of the head module. Figure 6 a. and b. show the robot when the passive-joint active-wheel turning gait is applied.

With this turning gait, after forming its body toward the initial heading direction, the robot's body becomes passive, thus the robot does not constrain its driving force to be on the curve along the robot body. This configuration allows the robot to be naturally curved by the driving force from the wheel. When the robot is moving forward, the body bends more and creates the whole body turning motion. However, the area required for turning becomes large because the robot does not actively hold the torque that keeps it from being within the bound of the curve along its body.

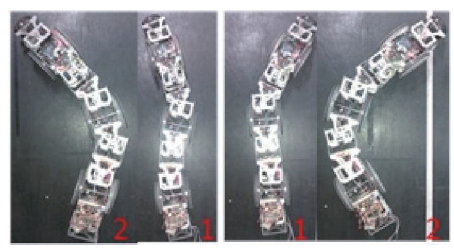

Fig. 6 a) PJAW left turning gait b) PJAW right turning gait

2. Active-Joint Active-Wheel turning gait (AJAW-T)

In the situation where turning area is limited such as a 90 degree corner in a pipe, the robot needs to curve its body within the allowable area while moving forward along that curve. The shape of the robot's body and the forward motion has to be simultaneously adjusted such that the turning can be achieved. We also applied the concept of motion shape vector as mentioned in the earlier section for designing this turning gait. In this case, the motion shape code technique is used to generate the turning gait. Since only yaw rotation is concerned in turning motion, the motion shape vector is only applied to the set of yaw motors. Motion shape vector starts with the turning of the head module. Then the right shift operation is applied until the robot finish the turn (all components in the motion shape vector becomes zero). However, there are three parameters to be selected: the basis angle, the number of active turning joints and the driving speed of each motor. With different parameters, the robot turning gait will behave differently. We designed two turning gaits with different set of parameters for the experiment.

2.1. C-shape

In this turning gait, the basis angle is small (+15, -15 degrees) and the number of active turning joint is six. The driving speed of motors during the turn are the same as shown in Table I. Due to the number of active turning joint and the number of robot modules, the total number of steps for this turning gait is 12.

TABLE I
C-SHAPE TURNING STEPS.

Step	Basis angle	Motion Shape Vector	Motor speed
1	15	[1,0,0,0,0,0]	[100,100,100]
2	15	[1,1,0,0,0,0]	[100,100,100]
3	15	[1,1,1,0,0,0]	[100,100,100]
4	15	[1,1,1,1,0,0]	[100,100,100]
5	15	[1,1,1,1,1,0]	[100,100,100]
6	15	[1,1,1,1,1,1]	[100,100,100]
7	15	[0,1,1,1,1,1]	[100,100,100]
8	15	[0,0,1,1,1,1]	[100,100,100]
9	15	[0,0,0,1,1,1]	[100,100,100]
10	15	[0,0,0,0,1,1]	[100,100,100]
11	15	[0,0,0,0,0,1]	[100,100,100]
12	15	[0,0,0,0,0,0]	[100,100,100]

Fig. 7. C-shape turning gait

2.1. L-shape

For the L-shape turning gait. The basis angle is larger (+45, -45 degrees) than in the C-shape. Thus, the shape of the robot when two consecutive joints are bending is closer to an L-shape as shown in figure 8. The number of active turning joint is two. The total number of steps for this turning gait is 8. The driving speed of motors can be either the same or can be varied as shown in Table II. The different speed on three driving wheels helps to reduce the slippage at the bending part of the robot's body.

TABLE II
L-SHAPE TURNING STEPS.

Step	Basis angle	Motion Shape Vector	Motor speed
1	45	[1,0,0,0,0,0]	[100,100,100]
2	45	[1,1,0,0,0,0]	[100, 50, 50]
3	45	[0,1,1,0,0,0]	[100, 50, 50]
4	45	[0,0,1,1,0,0]	[100, 100, 50]
5	45	[0,0,0,1,1,0]	[100, 100, 50]
6	45	[0,0,0,0,1,1]	[100, 100, 0]
7	45	[0,0,0,0,0,1]	[100, 100, 0]
8	45	[0,0,0,0,0,0]	[100,100,100]

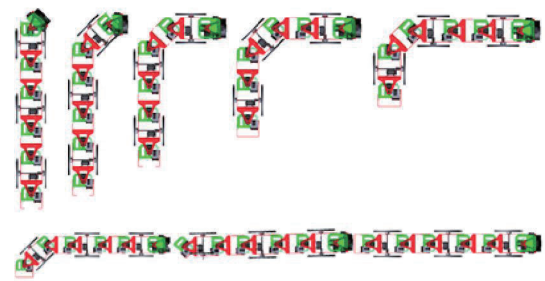

Fig. 8. L-shape turning gait

IV. EXPERIMENT

MoMo robot was tested with various gaits, which were discussed in the previous section, on three different environments: flat ground, slope and tight corner. The robot was controlled to move forward ten times for each gait in each experiment.

A. Moving forward on flat ground

Three different gaits: AAJAW, PWS and AWS were tested on a flat ground. The result is shown in Table III. AWS gait has the highest velocity on flat ground. PWS has the lowest velocity compared to other gaits.

TABLE III
FORWARD VELOCITY FOR DIFFERENT GAITS ON FLAT GROUND

Forward gaits	Vavg (m/s)	Vmin (m/s)	Vmax (m/s)
AAJAW	0.127	0.123	0.130
PWS	0.051	0.049	0.046
AWS	0.132	0.130	0.136

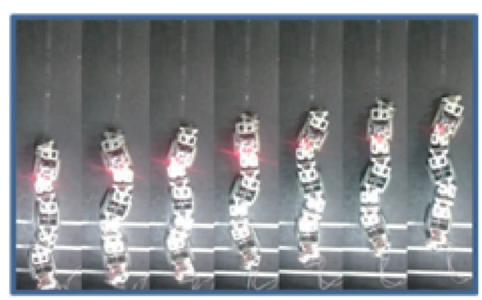

Fig. 9. Passive-Wheel Serpentine gait on flat ground

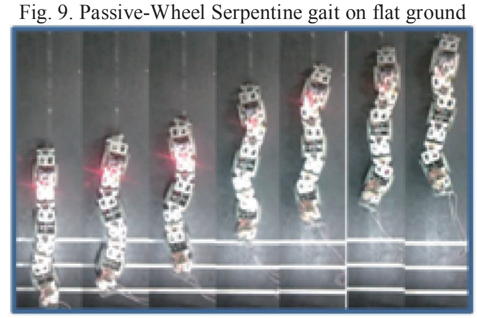

Fig. 10. Active-Wheel Serpentine gait on flat ground

B. Moving forward on slope

In order to move forward on the slope, the wheel configuration can add the constraint that helps the robot to be affected less by the gravitational load. In the Active-Wheel Serpentine (AWS) gait, when the basis angle of the Serpentine gait increases, the robot should increase its climbing ability. We tested the robot by controlling it to move up a slope using AWS gait with different basis angles at 1 meter distance. The slope is varied from 0 to 27 degrees (at 5 degrees incremental until it reaches 25 degrees).The maximum basis angle that the robot can perform is 55 degrees due to its physical limitation.

Case 1 : basis angle =0 (AAJAW)
Case 2 : basis angle =9
Case 3 : basis angle =18
Case 4 : basis angle =27
Case 5 : basis angle =36
Case 6 : basis angle =45
Case 7 : basis angle =54

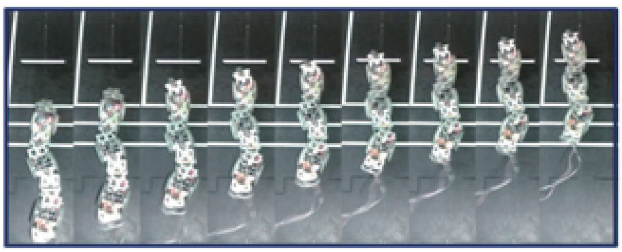
Fig.11. Moving up a slope with AWS gait

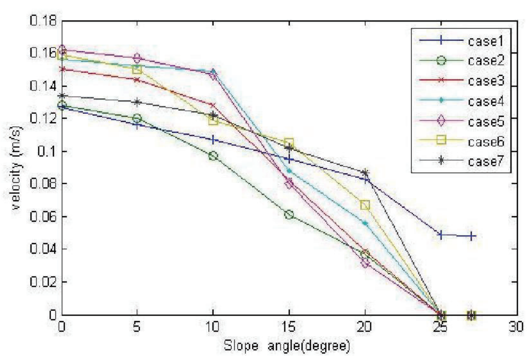

Fig. 12. Graph between the robot velocity and the slope angle for AWS gait with different basis angle.

From the result shown in Figure 12, case 5 (α=36 degrees) has the highest velocity when the slope angle is between 0 and 10 degrees. When the slope angle becomes larger (15 and 20 degrees), case 7 (α = 54 degrees) has highest velocity.

In case 1 which the basis angle is zero (i.e. AWS and AAJAW are the same), the robot climbed the slope with lower velocity compared to other cases at the lower slope angle. However, when the slope angle is larger than 25 degrees, the robot can climb without slipping only under this case.

C. Turning in tight corner

In this experiment, The Active-Joint Active-Wheel turning gait (AJAW-T) under three different configurations : C-shape, L-shape with constant speed, L-shape with varied speed (as described in section 3) were tested. The testbed for the experiment is a 30 cm width path with a 90 degrees turning corner. We measured the distance between the middle of the path and the center of the joint for all 6 modules of the robot. Figure 13-15 shows the average of the measured distance for each joint over 10 trials under each configuration of AJAW-T. Figure 16-18 shows the snapshot of the 3 tested configurations.

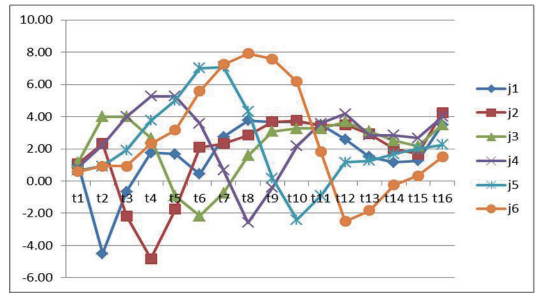

Fig.13. Error of C-shape turning gait

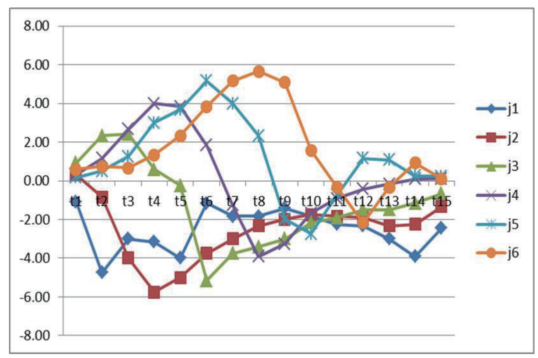

Fig.14. Error of L-shape turning gait with constant driving speed

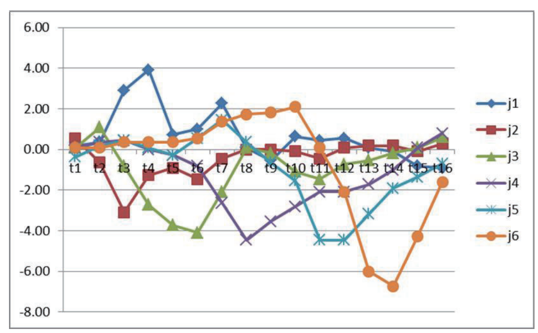

Fig.15. Error of L-shape turning gait with varied driving speed

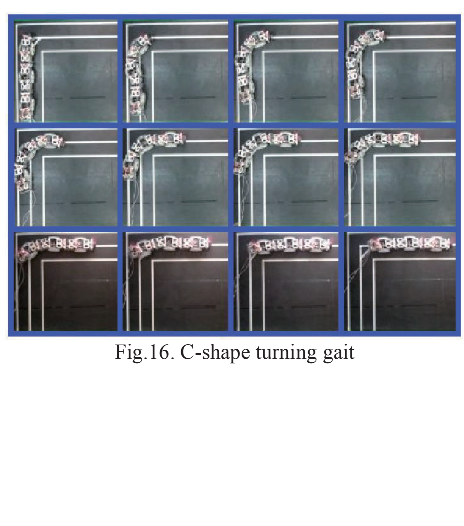
Fig.16. C-shape turning gait


Fig.17. L-shape turning gait with constant driving speed


Fig.18. L-shape turning gait with varied driving speed

V. DISCUSSIONS

From experimental results in section 4, the first experiment shows that the AWS gait resulted the highest velocity for forward motion on a flat ground. The AWS gait combined the advantage of the Active Wheel drive and the sinusoidal serpentine locomotion together, thus the resulting propelling force for the robot is the combination of the wheel driving force and the force created from the sinusoidal body motion (i.e. from the constraint of the wheel orientation).

In the second experiment, the AWS gait with 36 degrees basis angle has the highest climbing velocity on a small slope (slope angle is 0, 5 and 10). When the slope is steeper, the larger basis angle of the robot will increase its climbing ability. Thus, the AWS with 54 degrees basis angle outperform other cases when the slope angle is 15 and 20. However, when the slope is at 25 degree, the AWS gait can no longer climb up the slope and slip down. From visual observation, we found that as the slope became steeper, the AWS gait caused the wheel of the robot to lift off the ground. The wheel was also slipping noticeably on one side, because the two wheels on each module were driven through a common axle without a differential gear mechanism. The AAJAW gait did not require the robot body (pitch-yaw joint) to move at all in the forward motion case. Thus, this gait was still able to propel the robot upward on a steep slope even at a lower velocity.

In the last experiment, the L-shape turning gait with varied speed required the minimum turning area compared to the other two cases. During turning, the motion shape and the change of driving speed is important for adjusting the turning gait to be able to turn in a tight area. When the turning area is not restricted, the Passive-Joint Active-wheel Turning gait which is less precise but easier to be implemented can be used. In the task where the precision of turning is required, the Active-Joint Active-Wheel Turning gait should be used with the motion shape and the driving speed that are designed for the specific requirements of the task such as the curvature and the width of the path.

VI. CONCLUSIONS

The Active Wheel snake robot can be useful for various type of exploration task. We designed and tested various locomotion gaits that can be implemented on the Active Wheel snake robot for different environments. On the flat ground, the Asynchronous Active-Joint Active-Wheel (AAJAW) is the simplest gait to be implemented and used the least amount of power. However, the Active-Wheel Sinusoidal (AWS) gait has the highest moving speed because it uses the combination of driving force from the wheel and the body. When slope climbing is concerned, the AWS with large basis angle will provide better climbing ability. However, with the current design of our robot, we had the problem of wheel slippage in the AWS gait which caused problem when the slope angle is larger than 20 degrees. In the task that needs the robot to turn in the tight area such as a 90 degree corner of a pipe, the AJAW L-shape turning gait with varying speed is best fit for the task. However, when turning in open area, the PJAW turning gait is simpler and requires less parameter to be adjusted. In order to design a turning gait for a specific task, parameters such as the basis angle, the number of active joint and the driving motor speed are needed to be selected for the optimal performance.

ACKNOWLEDGMENT

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