Snake-like Robot Climbs Inside Different Pipes

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***Abstract*—Based on the application of snake-like robot as pipeline robot, this paper presents a compound climbing gait of it. By analyzing the characteristics of existing inside climbing gaits, blend various gait with sensor information, so that the robot can climb in more complex and more extensive inside pipe environment. The experimental results show that the gait is feasible and has good climbing effect.**

***Keywords*—snake-like robot; inside climbing; pipe; gait**

I. Introduction

In the field of robots, ground robots can be roughly divided into wheeled robots, foot robots and limbless robots. The application of wheeled robots and foot robots is more limited by the movement of the environment, such as soft ground or narrow space. In order to make the robot can be applied to more scenes, professor Hirose developed the first generation of snake-like robot prototype ACM-III [1]. The robot has a multi-joint, high-redundancy feature[2] that allows it to move in more complex environments. In the early snake-like robot, it used parallel connection structure to connect each two module, which only to achieve a plane movement[3]. Later, with the appearance of orthogonal structure and the universal joint structure, the snake-like robot can be applied to the three dimensional space movement. For example, the CMU's Uncle Sam [4] and the Norwegian University of Technology's KUKLO [5].

To meet the growing need for robotic application, such as disaster relief[6], seabed detection[7], pipes maintenance [8][9][10] and so on. Especially, with the formation of the 3-D space movement of the snake-like robot, it is gradually excavated as the movement ability of the pipeline robot. Over the past twenty years, there have been a variety of applications used in the pipeline inside the climbing gait, such as peristaltic gait [8], sine-driven gait [9] and rolling gait [10]. These gait ensure that snake-like robots can climb in the inner wall of the straight pipe and can even be applied to a certain extent in complex piping environments, like curved pipe and different diameter pipe. But these gait have a lot of difficulty for complex pipelines,such as the data collection during motion and the adaptation of gait to complex pipe. What's more, it is found that the existing motion gait can pass through the complex pipeline environment within a certain inner diameter range under special control parameters, but it can't be applied to the inside of different diameter complex pipeline environment with the help of same control parameters. This limits the use of snake-like robots as pipeline robots to a certain extent.

In order to solve the limitations of the existing gait in the application of the snake-like robot, the paper explores the characteristics of the existing climbing gait. Combined with the sensor information to enable the snake-like robot to pass through a variety of pipe with help of gait changes. In the straight pipe wall under the premise of normal climbing, to achieve different environments inside the pipeline climbing. The contribution of this paper are

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- Use the robot cycle motion characteristics to provide a data analysis method used in the pipeline changes in order to solve the problem of data acquisition;
- Combined with the characteristics of different gait, designs a composite gait with the rolling gait as the main body, when the need for environmental changes, the auxiliary wave-driven gait and creep gait, so that the robot can meet a variety of complex environmental needs. To a certain extent, reduce the limitations of gait climbing.

For the existing gaits, the rolling gait play badly in variable pipe inside climbing while sine-driven gait don't do greatly in curved pipe inside climbing. And the peristaltic gait can only climb inside straight pipe with small diameter. What's more, compared with the spiral curve smooth motion proposed by Okayama University [11] , the gait in this paper is slightly less in terms of continuity of movement, movement rate and so on when pass the changed pipe connection. However, this paper combines a variety of gait characteristics, in the direction of control, flexibility, adaptability to the pipeline, the number of joints have a greater advantage.

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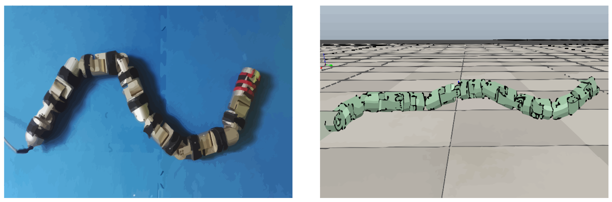
II. BACKGROUND

A. Robot platform

Our existing snake-like robots (Fig. 1(a)) are connected orthogonally. The rotation planes of the adjacent joints of the structure are perpendicular to each other, and the rotation planes of the joints are perpendicular to the axis of the body. According to this robot to build simulation model (Fig. 1(b)), and embedded distance sensor and angle sensor for the realization of the robot feedback control.

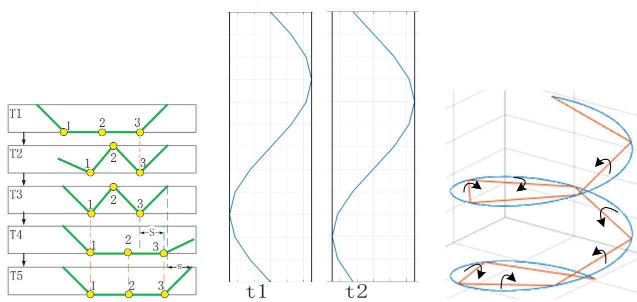


(a) Reality robot (b) Simulate robot

Fig. 1. The Snake-like robot

B. Gaits for in-pipe climbing

The climbing gait inside the pipe of snake-like robot mainly sine-driven gait [9][12], peristaltic gait [8][13] and rolling gait [10][14]. The simple movement principle shown in Fig. 2.



(a) Peristaltic gait (b) Sine-driven gait (c) Rolling gait

Fig. 2. The climbing gait

1) Peristaltic gait basic motion principle shown in Fig. 2(a): It promote the robot forward by maintaining part of the joint fixed, and the release of the central joint deformation[13]. In Fig. 2(a), it exist 3 joints. The joint 1 is the rear joint, the joint 2 is the middle joint, and the joint 3 is the front joint. And then this gait can be divided into several steps:

- Step 1: Reduce the angle of the rear joint, release the rear joint and compress the middle joint until it is fixed.
- Step 2: Increase the angle of the rear joint to make it fixed.
- Step 3: Reduce the angle of the front joint, release the front joint and stretch the middle joint until the level.
- Step 4: Increase the angle of the front joint to make it fixed.
- Step 5: Repeat steps 1-4.

This movement mode only needs to maintain the movement of one end of the other end can be fixed, with various parts of the movement of independent characteristics, but its support points less, uneven force, low power utilization, and the number of joints required.

2) Sine-driven gait basic motion principle shown in Fig. 2(b): It moves the robot forward by maintaining a fixed waveform [12]:

$$T_b = A \cdot \sin(\omega \cdot t + i \cdot \varepsilon) + C \tag{1}$$

The steering angle control value of the i^{th} joint T_i is control by, amplitude A, the angular velocity , the phase and the center value of wave C.

This movement mode is less affected by the environment, when the front end can reach the place, follow-up joints in general can follow up. But to ensure that its normal movement, joint control needs to be continuous, if the front end joints and follow-up joint resistance gap, will lead to abnormal movement, such as part of the variable pipe scene. In addition, it will result more redundant joints in the gait.

3) Rolling gait basic motion principle shown in Fig. 2(c): It is given a consistent amount of change through the function to control, to ensure that the robot joints in the same direction to promote the robot forward[14]:

$$T_i = \begin{cases} A \cdot \sin(\omega \cdot t + i \cdot \varepsilon) & odd \\ A \cdot \sin(\omega \cdot t + i \cdot \varepsilon + \frac{\pi}{2}) & even \end{cases} \tag{2}$$

The parameters of Eq.2 are same as the Eq.1. Combined with the orthogonal structure of the robot, provide the adjacent two joints with $\pi/2$ phase shift, so that the robot rolling forward. Under the gait control, each joint of the robot is a force point, multi-support point, uniform force, high power utilization, but its attitude is fixed. And this gait is difficult to adjust the attitude according to the appropriate needs of the environment.

To climb inside the pipe, there are several gait to achieve it. In those methods, rolling gait and sine-driven gait can pass the change pipe interface with special condition. And rolling gait have great performance in the curved pipe while sine-driven gait play well in variable pipe. In reality world, the pipe environment is combined with both curved pipe and variable pipe. To make the snake-like robot run well inside the pipe environment, this paper design a compound gait to deal with this challenge.

III. COMPLEX PIPELINE INTERNAL CLIMBING

The composite gait designed in this paper needs to sense the external environment through the sensor information. According to the sensor information to determine whether the straight pipe or change the pipeline environment. In straight pipe, the rolling gait is used. when entering the change pipe interface, the rolling gait will embedded the peristaltic gait and the sine-driven gait to push the robot through the pipeline environment change point.

A. Environment perception

The idea of our work is to use sensing information to detect the change of pipe environment. And the perceptual we need form the environment is the distance between the head module and the inside wall of the pipe. As the rolling gait is chosen as the basic gait, the detection distance of the robot when it run in rolling is necessary. And then it have a detect model like Fig. 3. It shows the cross - section diagram of the rolling gait during climbing.

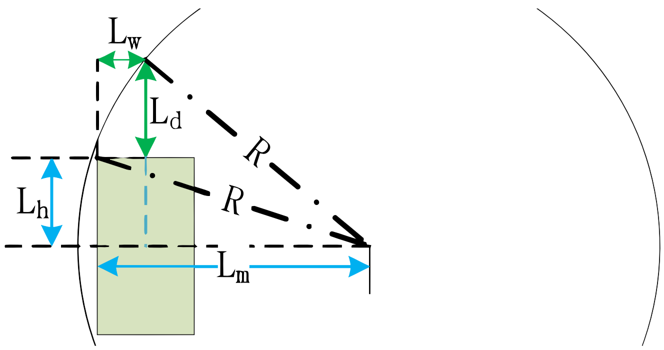


Fig. 3. The schematic diagram of rolling gait inside pipe

The Fig. 3 shows the relationship between the radius of pipe R and detection distance L_d with the help of the half of module height L_h and width L_w. And L_m represents the distance from the center of the circle to the outside of the module. And then, we have:

$$\begin{cases} L_m^2 = R^2 - L_h^2 \\ (L_m - L_w)^2 = R^2 - (L_h + L_d)^2 \end{cases} \tag{3}$$

From Eq.3, it can calculate that:

$$L_d = \sqrt{L_h^2 - L_w^2 + 2L_w\sqrt{R^2 - L_h^2}} - L_h \tag{4}$$

The Eq.4 shows the distance sensor detection value L_d has a positive correlation with the pipe diameter 2R. This result can be applied to complex pipeline environments. In the pipeline environment there is a straight pipe, curved pipe interface, variable diameter pipe interface. The value of L_d in the straight pipe does not change. When entering the curved pipe interface, it is equivalent to entering an area where R is infinitely increased. At this time, the value of L_d is significantly increased. When entering the variable pipe interface, there is a clear trend of shape change, so L_d there will be more obvious trends.

It is worth noting that this result can't be applied directly to rolling gait. Because in the gait in the orthogonal structure of the snake to run, the snake's movement posture is affected by the movement of the snake's body posture. But the rolling gait is cyclical, so the value of L_d will also change periodically, as shown in Fig. 4.

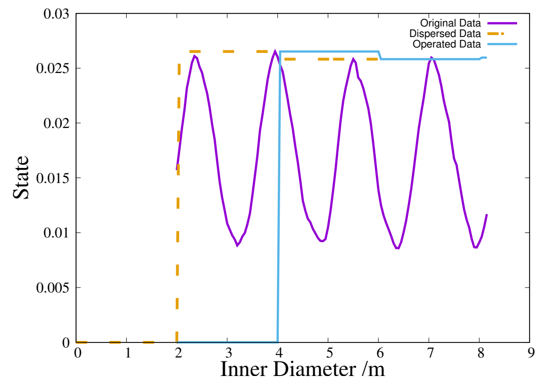


Fig. 4. The detection distance data from the sensor

The L_d value of the project target can be obtained by dispersing the collected data, so as to judge the motion environment of the robot. Discrete processing is:

$$L_d = \max\{L_t, t_{basic} < t < T + t_{basic}\} \tag{5}$$

Where T is the change cycle, t_{basic} is the start time of the discretization period, and L_t is the detection value of the distance sensor at time t. And the result is shown as Fig. 4. After the discretization operation, it will exist a time delay of T between the real-time value and the operated value.

Although there is a time control delay of T, it is possible to detect the distance between the head of the snake-like robot and the inner wall of the pipe in the preceding period. Based on the result, it is possible to determine the current outer wall type of the pipe. With the rolling gait, the snake-like robot will rise in a spiral curve, and then the detection will be a constant when it climb inside straight pipe. Since the variable pipe interface is a round table, the detection will change linearly when the robot inside it. Thus, it can find that, different pipe environment will have different detection distance characteristics:

$$\frac{\Delta L_d}{\Delta t} = \begin{cases} \delta & \textit{straight pipe} \\ C + \delta & \textit{variable diameter pipe} \\ \frac{\Delta f}{\Delta t} + \delta & \textit{curved pipe} \end{cases} \tag{6}$$

In Eq.6, δ is a minimal variation, which is the operating range of the noise of the robot gait movement. In Eq.6, Δf is determined by the distance between the snake head and the center of the pipe and the angle of rotation in the unit time. It is a non-proportional function.

Since the result of curved is much different to straight and variable, the Δf is not deduced in this paper. From the Eq.6, it can be found that in the straight pipe, the amount of change in the distance is a very small amount. In the variable pipe interface, the distance change is constant. The change of the distance in the curved pipe interfaces is a variable obviously. According to the three types of pipe detection distance change states, it can determine the machine in which the external pipeline environment, so as to make the corresponding operation.

B. Design of compound gait

Among all of the existing gaits, the rolling gait play best in the straight pipe inside climbing. Thus the rolling gait is selected as the basic gait in this paper. But unfortunately, when the rolling gait meet the variable diameter pipe change interface, it play badly. In this way, this paper will embedded sine-driven gait and peristaltic gait in the rolling gait. And then, the ability of the control strategy to adapt to the pipeline will be greatly improved.

When the robot perceives changes in the environment with the help of sensor, the robot start will adjust the gait to suit the environment. Thus the whole process to pass the change pipe environment can be divided into three condition.

- Inside the straight pipe: Use the rolling gait to climb as it can suit more pipe with different value of diameter.
- Meet the change pipe interface: Transmit several joint to pass the interface while other joints keep the rolling gait to climb.
- Inside the change pipe interface: Use the compound gait to pass through the interface. When all of the robot through the interface, it will use rolling gait to continue in the straight pipe.

1) Meet the change interface: As the change of the distance is equal to zero when the robot inside the straight pipe, it can be judged that the robot meet the change interface if the value of the change of the distance is change. And then the processing operation of change interface will be triggered.

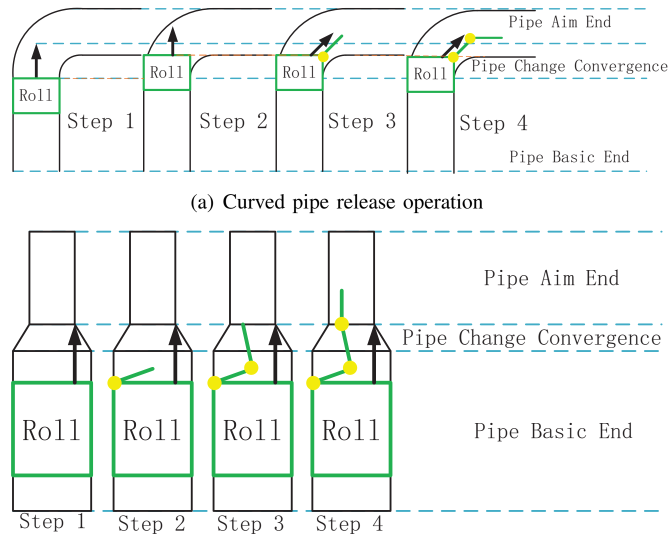
In this processing operation, the rolling gait is the main motion gait, and its control function is same as Eq.2. When the pipeline environment begins to change, part of the joint will be released and then enters the other end of the pipe using the principle of the sine-driven gait at first. The release operation is:

$$T_C = \frac{\Delta T_{last}}{\Delta(i \cdot \varepsilon)} \tag{7}$$

The joint control function value T_{last} of the joint connected to the release joint is subjected to differential processing according to the phase shift $(i{\cdot}\varepsilon)$ corresponding to that joint to obtain the steering control value T_C of the released joint. This operation ensures that the joint is released from the original control curve and approaches the center of the pipe. It means that the released joint will be independent to the other joints. And then it can control in any way.

For different pipe environment, the change pipe interface are different. To make the gait be more suitable, it need different release operation for different environment. Be carefully, if it want to trigger the release operation, the detection distance must be changed obviously.

According this, we have different release operation in variable pipe interface and curved pipe interface step by step, just like Fig. 5:



(a) Curved pipe release operation

(b) Variable diameter pipe release operation

Fig. 5. Release operation when pipe change

In Fig. 5(a), it shows the release operation in curved pipe. The first joint will be released at Step 3. At Step 4, the second joint is released first, and then transmit the front end to the aim end of the pipe with the help of sine-driven gait and the control of the released joint will be empty.

In Fig. 5(b), it shows the release operation in variable diameter pipe. The first joint will be released at Step 2. At Step 3, release the second joint and then release the first joint again, but this time it shall according to the release result of the second joint. At Step 4, release the third joint first, and then the second joint should do the second release. After all at Step 4, use the sine-driven gait to transmit the front end to the other end of pipeline while the second released joint should be in empty control. And then the second released joint will be passive joint.

In the operation of release, the sine-driven gait is control by the Eq.1. In order to ensure gait consistency, the center value of wave C, also the initial state value, should be same as the control value before sine-wave transmit. And combine the characteristics of the sine-driven gait that are less environmental barrier to pass the front end joints into the other side of the pipe.

When there is a partial joint at the other end of the pipe, the robot joint at the other end of the pipe gives the new rolling gait control:

$$T_i = \begin{cases} P_a \cdot A \cdot \sin(\omega \cdot t + i \cdot \varepsilon) & odd \\ P_a \cdot A \cdot \sin(\omega \cdot t + i \cdot \varepsilon + \frac{\pi}{2}) & even \end{cases} \tag{8}$$

$$P_a = \frac{D_{old}}{D_{new}} \tag{9}$$

The parameters T_i, A, $\omega \cdot t$, i, ε are same as the Eq.2. And the parameter Pa is the ratio of the diameter of the original end to the diameter of the target end of the pipe, as shown in Eq.9. Since the amplitude A in the rolling gait determines the inner diameter of the single-ring of the robot's attitude, the smaller the value of A is, the smaller the diameter of the robot's attitude is. Thus, directly applied the ratio Pa to the amplitude A can be adapted to the variation of the pipe diameter. For straight pipe and curved pipe, it have $D_{old} = D_{new}$. When in different diameter pipe $D_{old} \neq D_{new}$.

2) Inside the change interface: When the joints number in both two end are the same or the joints in the aim end are enough to form a single ring, it means that the robot inside the change interface.

From the experiments, it can find that when the robot inside the interface, the robot will be able to keep its body not to fall. And in this way, the robot moves at both ends of the pipe.When the robot moves at both ends of the pipe at the same time, the robot joint control distribution shown as Fig. 6:

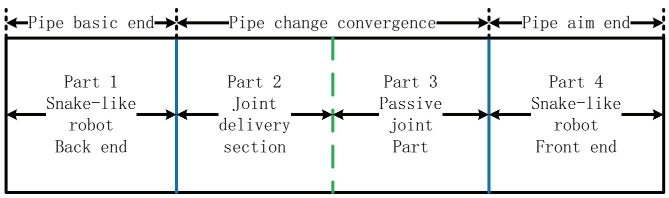


Fig. 6. Module control distribution of snake-like robot

In this way, the idea of peristaltic gait is used. The rolling control of robot front end is independent, which is discontinuous with the release control of the Part 2. In order to solve the problem of the discontinuous of the gait, this article adds a passive joint part between the front end and the joint delivery section. The passive joint does not give control and will rotate as the robot's attitude changes. At this point, the introduction of the peristaltic model of the mind to control the robot gait:

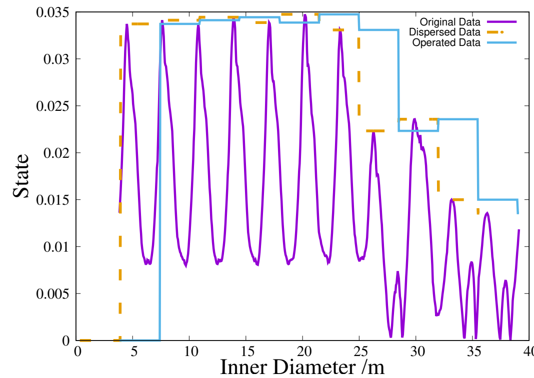
- Step 1: Make the front end to be fixed, and keep the back end movement. And then, release the first joint of back end.
- Step 2: The front end and the back joint are fixed. Set the first joint of the release site the passive joint. Finally, the rest of the joint in delivery section should be further released.
- Step 3: Fix the back end, and incorporate the first joint of passive part into the front end. And then move the front end.

Repeat steps 1-3 until the robot all passes through the pipe change junction. What's more, the release operation is same as the operation proposed before.

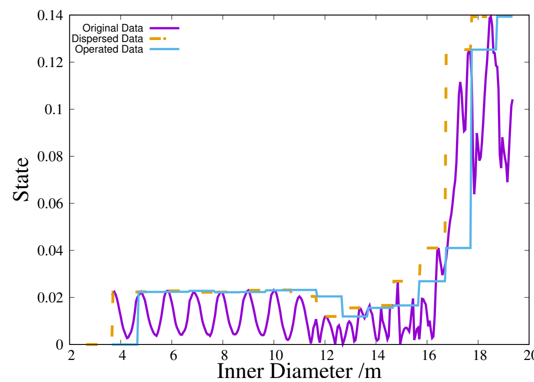
IV. Experiments

A common gait study of complex piping environments is a challenge. In this paper, by combining the distance information, combining a variety of gait, to solve the limitations of a single gait. After that, the composite gait can be applied to a wider complex pipeline environment.

A. Identify pipe type identification based on distance detection



(a) Variable diameter pipe distance detect



(b) Curved piped distance detect

Fig. 7. Detection distance data image

From the Fig. 7(a), it can find that the distance detection results of variable diameter pipe connections can be discretized so that the amount of change is a stable value. Fig. 7(b) shows that the curved pipe distance detection results through the discretization show a change in the value of the ever-changing. From the front section of Fig. 7, it can be found that the change in distance detection results is almost zero for straight pipes. Therefore, it is feasible to classify the pipeline type by distance detection.

B. Climbing inside the pipe

Fig. 8 show the gait during the climbing process of the curved pipe. And the climbing inside the different diameter pipe is mostly similar.

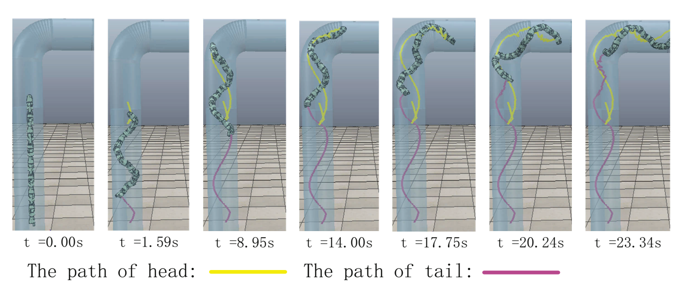


Fig. 8. Climb inside curved pipe

During the course of 0s to 14.05s, the robot climbed in a rolling gait, and at 17.35 seconds it was perceived that the presence of a curved pipe. And then the sine-driven was used to drive the gait to pass two joints into the narrow duct end. At 23.84s and 29.64s can be found at the two ends of the pipe robot with different control gait movement. In the pipe changed interface has a slave joint, it is irregular and it is not consistent with the movement of other joints. At 38.79s, the robot has been successfully passed reduced pipe interface.

This paper not only experimented with different diameter elbows, but also validated the variable pipe environments of different proportions. For a brief description, use the path to shows movement of the robot, shows as Fig. 9.

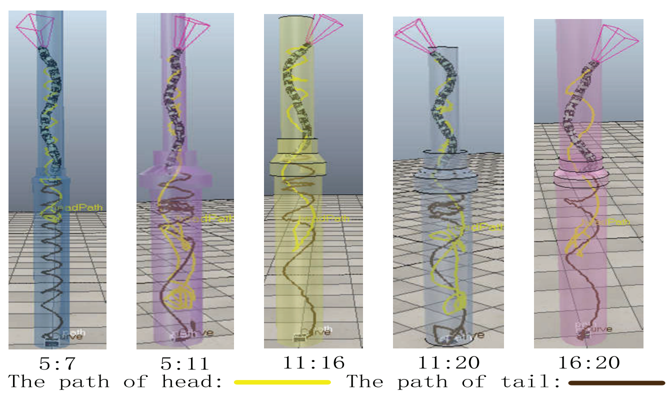


Fig. 9. Climb inside different ratio pipe of variable diameter

From Fig. 9, it can get an interesting result. For most of the Chinese national standard diverted pipe, the gait can control the snake-like robot in a rolling gesture through different proportions of variable diameter pipe interface.

The above experiments show that this complex gait can be used not only for the inside of variable diameter ducts but also for the inside of the curved pipe.Thus it can be applied to most of the pipeline environment.

C. Compare with other gaits

In this paper, the existing gait and the proposed compound gait under different amplitude, different diameter of the pipeline inside curved pipe and variable pipe were compared experiments.

1) The Experimental preparation: In this paper, we use the snake-like robot with 17 joint, which contain head. Its inner diameter of each joint is 6.5cm, height is 11.5cm. The experimental environment is a 90 degree corner curved pipe, and 7 : 5 ratio of variable diameter pipe. And all pipes are vertical.

For each gait, the amplitude of the gait will influence the expanding form of the snake robot, which will affect the robot's pressure on the pipe internal. So the amplitude determines the degree of adaptability of the gait to the inner diameter of the pipeline, while other parameters play a aiding role. Thus, in this paper, the performances of among gaits under the same amplitude inside the same pipe environment was cared. And the performances of them can be divided into four states:

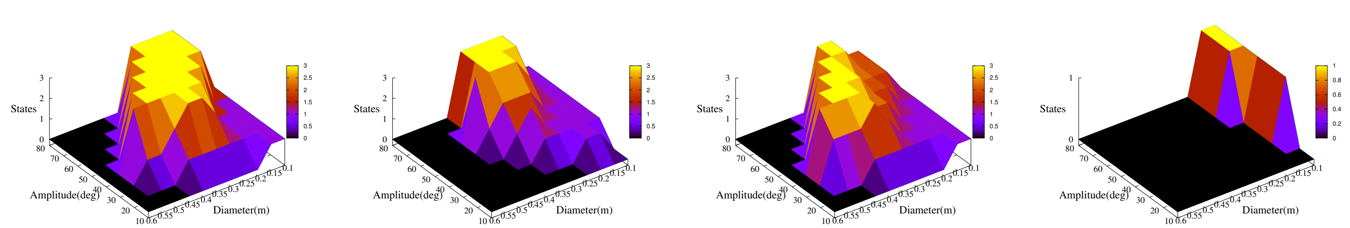
- 0: It is unable to climb inside the straight pipe.
- 1: It can only climb inside the straight pipe.
- 2: It can pass several joints to the pipe change interface under some specially parameters.
- 3: There is exists a set of parameters that satisfy the condition so that it can pass through the pipe change interface successfully.

2) The results of compare experimental: After a large number of experiments, the status distribution of different gaits under the control of different parameters are shown in Fig. 10 and Fig. 11. It shows the different performance inside the complex pipe environment of different gaits.

Since the peristaltic can only climb the small diameter straight pipe, it's unnecessary to be cared.compare with sine-gait, the compound gait and rolling gait can climb in wider pipe environment. When the diameter is too small, none gait can pass the change pipe interface. Especially, only the compound gait can pass through change pipe interface with special parameter when the diameter is 0.20m. To pass through the change pipe environment, the compound gait have best performance. It can pass a majority of complex pipe environment under the experiment condition. And sine-driven gait play better than rolling gait when the diameter is not large.

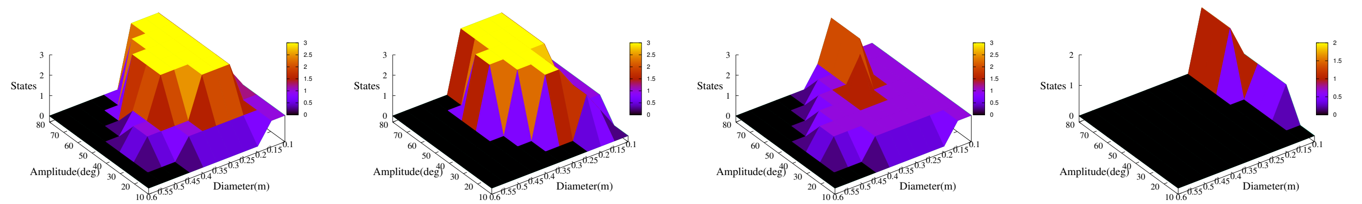
To analysis the detail performance of the gaits, the states of the gaits inside different diameter in 50deg or 60deg are cared. There are shown inFig. 10 and Fig. 11.

From Fig. 10 and Fig. 11, it can find that when the amplitude is 50 degree, the rolling gait can pass the curved pipe with large diameter. Even more, it can pass through both curved



(a) Compound gait (b) Sine-driven gait (c) Rolling gait (d) Peristaltic gait

Fig. 10. The different gait states of curved pipe climb result



(a) Compound gait (b) Sine-driven gait (c) Rolling gait (d) Peristaltic gait

Fig. 11. The different gait states of variable pipe climb result

pipe and variable pipe when the diameter is 0.3m. And in this way, the sine-driven gait can only variable pipe in suitable pipe. When the amplitude is 60 deg, it can find that the sine-driven gait can pass both curved pipes and variable pipes in a great measure with 60 degree. And the rolling gait can only run in curved pipe with special condition. In those to experiment, the compound gait play best while peristaltic do bad.

According to previous, it can find that rolling play great in the curved pipe while sine-driven do well in the variable diameter pipe. Luckily, the compound gait do best in both curved pipe and variable diameter. In addition, the compound gait combined the advantage of other gait and it perform better than the superposition of other gait results. What's more, when the diameter become larger, the sine-driven is unable to climb the straight, while complex gait and rolling can achieve. This says that the number of redundant joints of sine-gait more than other two gaits.

In addition to make sure which gait play better in different proportion variable pipe, the more experiments are done. Since the peristaltic play worst, it is not cared. The previous experiment shows that all of gait do well with 0.3m and 0.35m diameter variable under 50deg of amplitude. The experiments of these two condition are cared and the results are shown in table I and table II.

TABLE I
RESULT OF DIFFERENT PROPORTION VARIABLE PIPE N 0.3M

Proportion / Gaits	5:7	5:11	11:16	11:20	16:20
roll	1	0	1	0	1
sine	1	0	1	1	1
compound	1	0	1	1	1

TABLE II
RESULT OF DIFFERENT PROPORTION VARIABLE PIPE IN 0.35M

Proportion / Gaits	5:7	5:11	11:16	11:20	16:20
roll	0	0	1	0	1
sine-driven	1	0	1	1	1
compound	1	1	1	1	1

The meaning of the values of two table is similar. '0' represent the robot can not pass the variable pipe change interface while '1' present it can. And the result of two table is obvious. Compare with other two gaits, the rolling gait do worst in this pipe environment. And the sine-driven gait and compound gait are not much different inside variable pipe climbing. But when the diameter become larger, the compound will do better.

All of the experimental results show that, if other gait can be achieved, the composite gait proposed in this paper will be able to pass through complex pipelines unless it can not climb in a straight pipe. When other gaits can't pass through complex pipelines, the composite gait is very likely pass through the pipeline.Compare with existing gait, this suggests that it is more adaptable to complex pipelines.

For the horizontal state of the pipeline, in addition to peristaltic gait, the rest of the gait as long as the normal crawl can pass through the pipeline changes. In this article is not described one by one.

The experimental results show that the composite gait proposed in this paper can be applied to all kinds of complicated pipeline environments better than the other gait.

V. Conclusion and Future Work

In view of the complex pipeline environment, this paper analyzes the characteristics of the existing climbing gait of snake-like robot in the pipeline. Analyze their limitations and advantages. Use the distance sensor information to identify the pipe environment in which the robot is located. The introduction of passive joints, according to a variety of gait characteristics blend of a variety of gait to form a new composite gait.

Experiments show that this composite gait can be applied to a wider range of complex pipeline environments. In the premise of maintaining the normal movement of robot this gait can through the corresponding changes in the pipeline. Because the gait not only can pass through various proportions of variable diameter tubing, but also can through different diameters curved tubing and variable diameter tubing with different diameters, it satisfies most of the climbing requirements of snake-like robots as a pipe robot application. But the gait can't guarantee that the robot can pass the changed pipe when it can climb in straight pipe.

In the follow-up stage, we will be introduced outside the perception, so that the robot can adjust the control parameters, to maintain normal posture, to ensure its normal movement. And then the snake-like robot will be able to pass through any of the inside of the pipe.

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