Spider-Robot 8-Leg Cooperative Walking Velocity Control Strategy Based on Environmental Information

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This paper aims at realization of the walk of a spider as an organism, and intends to construct a robot that can walk with its 8 legs in cooperation with each other by adapting itself to various types of environmental information. A spider as an organism can walk on a variety of places by corresponding to a variety of environment. With the aid of neural networks and fuzzy control, decision-making or realization of the environment-adaptive walk is done. Utilizing the distance to the destination or fear information as surrounding environmental information, a report is hereby released with respect to the computer simulation and experimental result of walks ambiguously expressed in such a manner as “gradually accelerate speed” or “walk so as not to be tired.”

Key Words: Moving Robot, Adaptive Control, Fuzzy Set Theory, Neural Network, 8-Leg Cooperative Walking, Decision Making, Environmental Information

1. Introduction

Spiders, which have evolved from arthropod of Chelicerata, have lived for almost more than 300 million years(1). Spiders, which have continued to live by allowing their bodies to be made smaller to evolve their feeding habits and convert their residential environment into 3-dimensional space. In the world at present, almost 30 000 species of spiders live. In Japan as well, approximately 1 200 species of spiders live(2). Spiders live in such a variety of environment as of tropical rain forests, cold belts, deserts, high mountains, etc(2). Meanwhile spiders have accomplished their evolvement as users of strained string, but the number of their legs still remain 8 from their advent to the world. Utilizing their 8 legs skillfully makes it possible for spiders to walk on a variety of irregular surfaces of land, to climb twigs or leaves, or furthermore to crawl on cobwebs strained by themselves leaving the impression looking as if they were attempting their own space walk. From this it might be imagined that 8 legs will provide them with the most adequate gait. Then it remains to be seen in what manner spiders are able to use their 8 legs for their walk. To solve this problem from a point of view of technology, construction is intended with an organism-type 8-leg robot standardizing a spider into a specific model. Furthermore realization is planned with a robot that can walk along allowing itself to adapt to various types of environmental information mutually in collaboration with their 8 legs. In this paper, a report is released in relation to the process where walking experiments were conducted after construction of a prototype of the spider-shaped robot capable of 8-leg walking. Moreover it is explained in what a manner the walking speed of the robot should be continuously be changed, allowing the robot to collaborate with the surrounding environmental information and bodily information, and furthermore allowing these kinds of information to be in collaboration with the 8 legs.

In recent years, study on robots referring to the walk of the spiders that are adaptable enough for a variety of environment and are in possession of capability of walking on various types of place is much reported(3)–(6). However a very few types are available with the study on the robot walking on its 8 legs or a spider-shaped robot allowing itself to be adapted to the natural environments. It remains to be seen in what a manner a spider uses its legs in walking or what kind of decision-making a spider does to do walking adaptable enough for the environment. To explain such doubtfulness from a point of view of technology, it is indispensable to accomplish realization of a spider as a robot. In future such a posture of technolog-
ical accomplishment will, it is believed, make it possible for a walk with taking on a human being on various road surfaces but also on a net in a shape similar to a style of space walk. For example, it becomes the change of the wheelchair. It is applicable as a movement vehicle which can be moved even to the place where it can’t walk in the human foot. And, when no one can walk on the quagmire or wreckage brought about by disaster, a robot is allowed to walk on the nets or ropes strained over such quagmire or wreckage to find out the people who are buried alive under such debris. Thus a rescue robot becomes available with us. With such situations as a background, observation is made with the usefulness of 8-leg walking as is to be done by adapting the machine to the surrounding environment through the study on the mutual collaboration control with the information in question and bodily information of oneself.

In this paper, a report is first of all released with the result of the investigation of a gait of a spider as an organism and the process where a prototype of a spider-shaped robot (Fig. 1) with which 8-leg walk is possible was constructed to conduct experiments for walking. Secondly another report is released in connection with the walking speed control allowing the robot to realize the decision-making to explain whether the machine spider should walk rapidly or slowly, or the spider should run away from the spot together with collaboration with the surrounding environmental information and bodily information. At the final stage, the result of the simulation concerning the environment-adaptive collaboration walking speed control is reported. Meanwhile although no attempt is made this time to allow the machine spider to directly walk on the debris, it is necessary to think of slightly gradual irregular land. Therefore to allow the machine to be adapted to the road shape, it is necessary to allow the machine to walk by collaborating with its 8 legs. Keeping such a situation in mind, observation is hereby made to explain in what a manner the 8 legs should be cooperated with the machine to walk. As the surrounding environment to be taken up, the target information reaching the preys or residences of the worm, and fear information from natural enemies and humans are used. Meanwhile as to the humans, biorhythm such as mentality, physical, emotional rhythm, etc. is with them. Likewise with this, biorhythm close enough to these matters is in existence with a spider. Such being the case, fatigue information exercising greatly on the bodily rhythm is utilized as in-body information. With the help of these kinds of environmental information, a neural network is used for the decision-making explaining whether the worm-shaped machine should walk slowly, should walk as mildly as possible in order not to be tired or should run away. Furthermore to allow the machine to take an ambiguous walk in a manner to walk as easily as possible in order not to be tired by taking up as a criterion for judgment natural information having in itself ambiguity such as distance or fatigue as an original, fuzzy is used for controlling walking speed.

2. Spider’s Gait Characteristics

In order first of all to probe gait of a spider as an organism, a Neoscona nautica living under eaves near here was captured and was allowed to walk on the floor. The spider, who keeps its life by straining a cobweb, also is able to wander about with great ease. While he was walking about, he was photographed by a digital still camera and was surveyed in his gait. The individual pieces of the photographed image was displayed onto the screen, and the time spans while the individual legs of the spider were coming into contact with the ground and were afloat in air was measured. As a result support by more than 4 legs of its own was noticed with the spider. The standardized gait of the spider is listed in Table 1 (the legs supporting the body are indicated by ●, the ones being idle are indicated by ○). With this, the same result is obtained from other kind of study. With the gait of Neoscona nautica, 2 patterns are shown, i.e. the pattern of the Step 1 (Fig. 2(a)) with the legs of L1-L3-R2-R4 as supporting legs and the pattern of the Step 2 (Fig. 2(b)) with L2-L4-R1-R3 as supporting legs. Thus it is explained that with the spider’s

Fig. 1 Spider-robot

Table 1 Walking step patterns

<table>
<thead>
<tr>
<th>Leg No</th>
<th>Left</th>
<th>Right</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L1</td>
<td>R1</td>
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<tr>
<td></td>
<td>L2</td>
<td>R2</td>
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<td></td>
<td>L3</td>
<td>R3</td>
</tr>
<tr>
<td></td>
<td>L4</td>
<td>R4</td>
</tr>
</tbody>
</table>

(F● Support ○ Return)

Fig. 2 Walking of Neoscona nautica
normal movement, periodical walking with which 2 types of the step by means of 4-legged support are mutually repeated is being made. Based on this result, walking by repetition of 4-legged support of the Step 1 and the Step 2 is to be realized in this paper.

3. Walking Experiment of the Spider-Robot

3.1 Construction of a prototype robot

Design was made this time keeping in mind that the robot should be light enough and compact enough as far as possible. As a reality, each leg of a spider has 7 articulations on it. It appears that the spider bends its legs by means of flexing, and extends them by the change of the internal pressure caused by just a slight amount of flexing and flow of the blood. However it is difficult to create its structure in a straightforward concrete style. Therefore as actuators, a servo meter is to be used so that numerical control will be possible. Furthermore in the hope that yawning of the body during walk will be the minimum, the degree of freedom per a leg shall be 3. Thus as the total, the robot is of 24 degrees of freedom. The drawing for design is shown in Fig. 3, whereas the total spectacles are shown in Fig. 1. Meanwhile with a view to allowing the body to be as compact as possible, the motors are all installed onto the top of the body and the 1st articulation of the leg joint is linked with a gear. On the other hand, the 2nd and 3rd articulations are of the structure in combination of pulleys connected by belts. To lose weight, the body and legs are made of aluminum. The individual dimensions are: the body width is 0.14 m and the body length is 0.28 m. The body height is 0.12 m and the whole length of the leg is 0.19 m. Finally the whole weight is 2.5 kg.

3.2 Spider-robot control and walking experiments

With the 8-leg spider-shaped robot constructed this time, a walking experiment to explain whether repetition of the 4-legged support shown in Fig. 2 will make it possible to do all the types of walking or not. To accomplish the control of the robot, Raibert’s idea of virtual legs was adapted based on his insistence that the step of an animal having 4 legs can be expressed as a 2-leg walk. First of all, a virtual 2-leg walk taking up as a single pair every 2 legs of the right and left sides among 8 legs (Fig. 4 (a)). On the other hand, the movement of an organism exhibiting autonomous adaptation in a real world is formed mainly by combination of the Central Pattern Generator (CPG) with the reflection generated by the sensitivity deriving from periphery. This is widely accepted as the fact. On the other hand, reports are retained at hand stating to the effect that CPG was utilized with the walk of a cockroach-shaped robot or lobster-shaped robot. From these it is deduced that the CPG generating the fixed pattern should be, as shown in Fig. 4, adapted also to the spider-shaped robot. Thanks to the control mechanism referred to above, all the types of walk can be made on artificial lawn making use of just frequency-fixed numerical control without sensor feedback. As the types of walk, forward/rearward movement, walk depicting a rotational radius R in a longitudinal direction (R forward progress), rotation, and diagonal walk are considered. Let the walk speed be 3 types, i.e. high speed 0.15 m/s, middle speed 0.075 m/s, and low speed 0.005 m/s (3 types are available with the rotating speed, i.e. 0.52 rad/s, 0.26 rad/s, and 0.09 rad/s in rotating speed). During walk, constant speed is maintained. These

![Fig. 3 Design of spider robot](image)

![Fig. 4 Imaginary walking combination](image)

![Fig. 5 Walking experiments](image)
are shown in Fig. 5. Meanwhile with the control pattern where legs are driven, trapezoid driving is used.

At the next stage, remodeling is made so that the machine spider will be able to walk on the irregular land having several mild undulations such as a ground level in a school or park. As shown in Fig. 4(b), let the movement be virtual 4-leg walk taking up 2 pieces each of the legs as a pair. Furthermore let the individual pairs be provided with CPG, and let the paired 2 legs be moved reciprocally. As with the case of the virtual 2-leg walk, the machine spider is enabled to walk on a relatively smooth irregular land in a variety of gaits.

4. Environment-Adaptive Speed Control

As the first step to allow the movement of the machine to approach the behavior of a spider, speed control adaptable to the environment should first of all be considered. A spider as an organism, which is placed on a floor and is at first perplexed with the surrounding environment unfamiliar to him, starts to run fervently toward a target such as a wall chosen by him. After repetition of such a conduct several times, his running speed comes to be decelerated supposedly from fatigue. He sometimes ceases to walk and remains motionless for a while. When a spider who continues to remain motionless is frightened by clapping of human hands, he instantly runs away at a high speed. As described above, a spider does not always do constant walking. His walking speed is subject to change owing to his physical situations including fatigue, feelings, and fear given from his natural enemies or humans. To reproduce the spider’s natural walk, distance information and fear information extended to a target are used as external natural environment information. Meanwhile as internal environment information, fatigue information is considered instead of bodily and emotional biorhythm. By using the 3 types of the environmental information, simulation is conducted under the supposed condition with a view to explaining in what a manner the walking speed is being changed. Based on the information shown in Fig. 6, it was decided by using a fuzzy model and a neural network whether a spider robot walks slowly or walks to preserve its strength, or runs away. A flowchart is shown in Fig. 7. First of all, let the speed to start walking be determined from the state of the fatigue at that time. Secondly by calculating the fatigue, let it be determined what kind of gait should be taken for the spider. Finally by determining the walking speed complying with the individual gaits, let the worm walk. Furthermore let the procedure be repeated until the organism reaches the target. On the other hand, the concept of fatigue, fear, etc. is the information hard to be quantified. In the meantime, the walking speed is not the factor sensitively subject to change for the inputted information. Therefore for the determination of the walk-starting speed and walking speed, let fuzzy theory be adapted. From the fact that inferior animals’ movement project level function is scantly, let inference as simple as possible be used. Furthermore let the inference be used commonly through any of the cases. For determination of the speed complying with the walking styles, let a method to allow the weighted parameter of the THEN part to be continuously changed be taken. The IF part of the fuzzy membership function is depicted in Fig. 8(a), whereas the THEN part is depicted in Fig. 8(b). First of all, the adaptability degree $w$ is obtained from two IF parts by means of the expression shown below.

\[ w = \mu_1 \cdot \mu_2. \]  

Secondly the speed coefficient $\delta$ expressing the changing ratio of the speed is obtained from the expression shown below.

![Fig. 6 Environmental information](image)

![Fig. 7 Control flowchart](image)
Furthermore on the supposition that the speed at present singleton of the THEN part in coincidence with each other. Where

\( \mu \)

fatigue information. In the meantime, 

\( d \)

individual functions. In this experiment, let it be understood spectively the constants operating the gradient of the individual functions. During continuously walking. In both the cases as well, from the speed during walking at present and the time

\( t \)

\( \alpha \)

\( \beta \)

\( \Delta f_{\text{max}} \)

\( v(t) = v_0 + \delta \cdot \Delta f_{\text{max}}. \)    \hspace{1cm} (3)

4.1 Walk-starting speed

In starting a walk, the individual types of the speed equivalent to the 3 cases shown below are obtained from the fatigue remaining in the body.

(1) Since not so much fatigued, the spider starts to walk at a rather rapid speed.

(2) Since fatigue is normal, the spider starts to walk at an intermediate speed.

(3) Since considerably fatigued, the spider starts to walk at a rather slow speed.

4.2 Calculation of the fatigue

Let it be understood that the fatigue will be calculated from the speed during walking at present and the time during continuously walking. In both the cases as well, let an exponential function be used to express natural increase and decrease of the information. At this stage, let a monotonously increasing function as shown below that takes the values ranging from 0 to 1 be considered for the speed fatigue coefficient \( f_v \) and continuous walk fatigue coefficient \( f_w \).

\[
\delta = \frac{\sum w \cdot d}{\sum w}.
\]    \hspace{1cm} (2)

Where \( \mu_1 \cdot f_2 \) is the membership value by the distance and fatigue information. In the meantime, \( d \) is the value of the singleton of the THEN part in coincidence with each other. Furthermore on the supposition that the speed at present is \( v_0 \) and the maximum rectification speed is \( \Delta f_{\text{max}} \), the speed \( v(t) \) to allow the spider to walk is obtained from the expression shown below.

\[
v(t) = v_0 + \delta \cdot \Delta f_{\text{max}}.
\]

4.3 Walking form decision

A spider as an organism, which has accomplished evolution by dexterously adapting itself to the environment on earth, is not excellent enough to be in possession of a memory function or learning function as a vertebrate animal whose sensitive systems are highly developed does. In addition to the above, it is imagined that the information as seen in the factors including natural enemies is derived from the long-evolved gene information\(^9\). From these it can safely be affirmed that simple control might be sufficient for decision-making of the walking style. Also it can safely be said that the information to run away from fear should be learned off-line. Thus a neural network is hereby used. 3-layer structure, i.e. the structure of 4 units of input layer, 1 unit of output layer, and 25 units of hidden layer is taken, and a back propagation method is used for learning. The structure of neural network is shown in Fig. 9. The walking style to be chosen is as shown below.

(1) Form-a: accelerates speed gradually.

(2) Form-b: walks mildly not to be tired so much.

(3) Form-c: walks continuously at an initial speed.

(4) Form-d: runs away for fear of being injured.

(5) Form-e: takes a rest owing to having reached limitation of fatigue.

Form-a is a walking style to accelerate the speed gradually to the extent that fatigue becomes heavier. Form-b is a walking style preventing the fatigue from becoming heavier. Form-c is a walking style where speed is gradually lowered accompanied with accumulation of fatigue, although the walk is continued at an initial speed. Form-d is a walking style to run away as soon as fear is felt. Form-e is a walking style to take a rest until the fatigue is recovered to a certain level. For the calculation of the walking speed complying with the individual walking styles, a

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method to tune fuzzy rules is to be taken.

4.4 8-Leg cooperative control

The 8-leg-cooperated control of this time is done on the assumption that touch sensors are attached onto the tips of the individual legs. The 4 CPGs, which are in a pair and are reciprocally grounded, are allowed to do an 8-Leg cooperating walk that can comply with even the slightest amount of irregularities or undulations by taking synchronlessness based on the information inputted from the leg tip. The structure of 8-legs cooperative control is shown in Fig. 10. We also used a neural network for these controls. The unit number of input layers is 8, the unit number of the output layer is 2 and the unit number of hidden layer is 38. Its neural network (NN) structure is shown in Fig. 11. A walk is made to start at the moment when four and more support to walk is completed. And, a robot can walk corresponding to undulation roads.

4.5 Walking speed control results

In accordance with the flow shown in Fig. 7, computer simulation is made in the 5 walking styles described above. Furthermore it is shown respectively in Figs. 12 and 13 how the walking speed and fatigue were changed with the walk Form-a and Form-b. The walk controlled experiment is done continuously each three time. It is made known in Fig. 12 that the spider walks at first in a low speed, but the speed is gradually accelerated. In Fig. 13, it is understood that when the fatigue is developed, the speed is lowered so that the fatigue will not be developed than the degree referred to. Meanwhile in Fig. 14, it is shown that the spider runs away at a high speed be-
cause he is aware of fear. However it is understood that the speed is lowered as the spider comes to be liberated from fear (Form-d).

5. Conclusions

We intended to realize a robot that can walk by mutually collaborating with the 8 legs, environmental information, and individual legs with adaptation to various types of environmental information by craving for realization of the walk of a spider as an organism. The walk of a spider as an organism was first of all examined, and a prototype of a spider-shaped robot was constructed. By using the robot with the help of a concept of the virtual legs and CPG peculiar to arthropod, forward proceeding and rearward moving at a low and high speed together with rotating and diagonal walk were allowed to be done. Thus it is shown that spider’s free walk can be realized. At the next stage using neural networks and fuzzy by collaborating with the surrounding environments such as distance, fear, etc. and by collaborating mutually with the individual legs, it is shown that walking speed can be controlled. Setting a fuzzy membership function onto such an inferior organism as of a spider and operating parameters of the rule corresponding to the walking style with which decision-making is made have made it possible for an environment-adaptive walk to be realized. Furthermore allowing the leg tip sensor information to do feedback and enabling the 8 legs to cooperate with each other makes it possible for a walk on smooth but unjust land to be realized.

References