Pattern Analyses for Semi-Looper Type Robots with Multiple Links

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Abstract: For worm robots applied to pipe inspection and colonoscopy, earthworm-like robots that have a locomotion pattern in backward wave or green caterpillar-like robots that have a locomotion pattern in forward wave have been studied widely. Note however that a method using a single and fixed locomotion pattern is not desirable in the sense of mobility cost, if there are various changes in pipe diameter. In this paper, locomotion patterns are considered for a semi-looper-like robot, which adopts a locomotion pattern of green caterpillars as the basic motion and sometimes can realize a locomotion pattern of looper, whose motion approximately consists of two rhythms or relatively low rhythm.

Keywords: Worm robot, Semi-looper-like robot, Locomotion patterns, Pipe inspection robots, Robots for colonoscopy

1. Introduction

As biomimetic robots [1]–[5], in the study of worm-like robots aiming at the application to an inspection robot in a pipe, or an inspection medical robot in a colonoscopy in the living body, earthworm-like robots that have a locomotion pattern in backward wave or green caterpillar-like robots that have a locomotion pattern in forward wave are studied widely [6], [7], [8], [9].

However, when the environment which differs like the variation of the path in a pipe exists variously, the method of utilizing a single locomotion pattern is not an optimal policy from the viewpoint of mobility efficiency. For example, raising multiple segments simultaneously like a looper (or inchworm) and using a strategy with speedy traveling are better for the environment where the pathway width of a pipe is varying widely, in respect of mobility efficiency. For some research on looper type robots, Takita et al. [10] studied a looper type robot as a kind of rescue robots to check the ability of climbing over a stairway, and Nunobiki et al. [11] verified the ability of locomotion in a narrow space, especially climbing over a vertical narrow path.

In this study, to form a locomotion of the worm type robot which can adapt to the variation of the height in environment, we adopt a green caterpillar (or silkworm) locomotion, which takes forward-wave type locomotion as a basic motion, and study a semi-looper type robot that can realize a looper like locomotion with two or lower rhythms as a special case.

We first consider a worm-like robot consisting of six links, in which the original 13 segments are approximated to one link for representing thoracic legs, four links for representing each abdominal leg pair, and one link for representing one pair of tail legs. Then using the number of links which are completely untouched from the floor, we study the transition pattern generation per one cycle, for three, four, five, and six link models, where we do not take account of the number of actuators and their allocations. However, it is assumed that a singular link regarding two or more links as one link is allowable for a semi-looper like robot, so that the robot can make a speedy motion for more than four links, if the environment has a relatively large height that can do it.

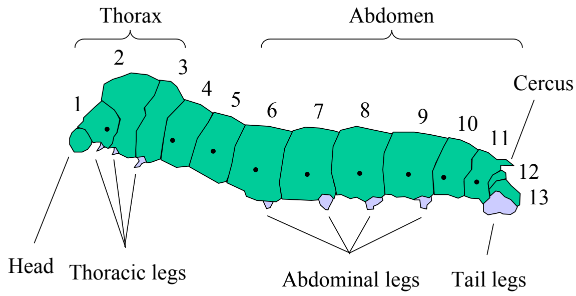


Fig. 1. Silkworm as a representative of caterpillars.

2. Biological Review of Green Caterpillar

2.1. Properties of green caterpillar

Definition 1: The larva of Lepidoptera (associate of butterfly or moth) is called green caterpillar, hairy caterpillar, or simply caterpillar.

Larvae of the Pieridae, Phalaenidae, Geometridae, Tortricidae, etc., in particular, small larvae whose green bodies don't have long hairs, are called green caterpillar. The body consists of thirteen segments, where three-paired thoracic legs (i.e., six legs) are attached on the thorax and five-paired abdominal legs (i.e., ten legs) are also attached on the abdomen. Note here that the thoracic legs are seldom functional and the abdominal legs strictly include one paired tail leg.

A larva in which long hair or the bunch of hairs grows thick on the surface of the body is called hairy caterpillar. It points out the larva of moths, such as Lymantriidae, Arctiidae, tent caterpillars, and Saturniidae, in many cases. Especially, big-sized one (approximately up to 10 cm), which does not have long hairs, is called caterpillar.

There is also other definition on the caterpillar.

Definition 2: The larva of Lepidoptera is called caterpillar.

Among them, we define one that has green colored body as green caterpillar, one that has hairs as hairy caterpillar, and one that moves with stretching and bending its body as looper. Moreover, the larva of Tenthredinidae is also called caterpillar in classification; for its discrimination, it is the larva of Tenthredinidae, if the abdominal legs including the tail legs consist of seven or more pairs; it is the larva of a butterfly or a moth, if it consists of five or less pairs.

2.2. Characteristics of silkworm

About silkworm which is the larva of a silkworm moth, let us see it in detail here. As shown in Fig. 1, the body of a silkworm is long and slender, which consists of thirteen segments and its length becomes 6 or 7 cm in the peak eclipse period of five age. It is also divided into the head, the thorax (from the first to third segments), and the abdomen (from the sixth to thirteenth segments).

There exist one paired thoracic legs (i.e., true legs on the insectology) for each of the first to third segments and one paired abdominal legs for each of the sixth to ninth segments. There exists a small jag-like cercus on the back of the eleventh segment and there are one paired tail legs in the abdominal part of the thirteenth segment, which is the tail edge of the body. Also, there exist one paired ellipsoidal stigmas for each side of the first and the fourth to eleventh segments,

There are spots in the back side of segments: one in the second segment is called eye-spot; one in the fifth segment is called crescent; and one in the eighth segment is called star-spot. Silkworms that have these spots are called "normal pattern"; otherwise they are called "plain."

In the head part, there are two mouths: the lower small one is called fusula, which is used to vomit thread when making a cocoon; the upper big one has one paired jaws, which is in the form of a saw-like tooth and is used to bite mulberry leaves. It is said that the ocellar eye is useful only to the grade which recognizes light and darkness.

2.3. Characteristics of looper

Since front three pairs among four paired abdominal legs have degenerated, a looper (or inchworm) can perform only a particular locomotion (or walk). The locomotion style is called "looper walk" and it is known that all the larvae of Geometridae have this type of locomotion style. Calling the looper "Looper" in English originates from the fact that the body becomes a loop when having the locomotion. In addition, although the larva of a part of Phalaenidae also has an abdominal leg under degeneration and carries out a looper walk, this worm is called semi-looper because the abdominal legs have not degenerated completely.

3. The Shape and the Locomotion Style of Soft Creatures

3.1. Characteristics of earthworm motion

Muscles of an earthworm consist of traversing one which shortens the body length along the longitudinal-axis direction, and annular one which decreases the diameter of the body. The annular and traversing muscles retain an antagonistic relation according to the effect of a hydroskeleton that coelome liquid (i.e., incompressible fluid) is filled between body-walls. As shown in Fig. 2, in the locomotion style of an earthworm, the part going ahead forms the backward-wave which moves back gradually when the body becomes long and slender by the systole of the annular muscles [12]. In addition, in order to simulate an earthworm motion, Tsuchiya et al. [13] have already approximated about 150 actual segments to the number of 20 segments, and proposed a discrete modeling method using flexible link components.

3.2. Characteristics of green caterpillar motion

A green caterpillar has the annular and traversing muscles for each segment like an earthworm, and performs its locomotive motion by the systole and relaxation. As seen from Fig. 1, the body consists of nodes clearly and has abdominal legs. For example, a silkworm has four paired abdominal legs and one paired tail legs, and one feature is that the body is supported by them. Although it has a tactile sense and thoracic legs, they seldom progress but rather the thoracic legs have achieved a sensory function.

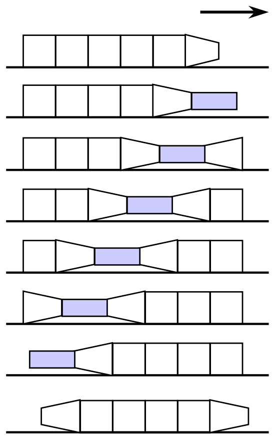


Fig. 2. Earthworm locomotion.

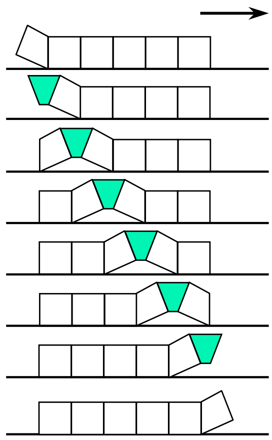


Fig. 3. Caterpillar locomotion.

According to the observations of Ebuchi et al. [12], it is known, in the locomotive motion of green caterpillars, that the tail legs first step forward ahead; then, the step legs move so that a ripple is propagated from the rear abdominal legs to the front abdominal legs; and the thoracic legs finally step forward. That is, contrary to the earthworm, it moves by propagating a forward-wave (refer to Fig. 3). In addition, since the legs cannot hold the ground when the green caterpillar moves on a smooth flat-ground, it moves by a creeping motion like an earthworm.

3.3. Characteristics of looper motion

For the locomotive motion of a certain looper, it is well-known that, after advancing the tail legs first and making the body greatly flexed into a "bridge," the looper then holds the ground, carries the thoracic legs ahead, and finally stretches the body. Since the part which performs the locomotive motion is moved from the tail part to the head part, the looper motion can be categorized into the same forward-wave type motion pattern as a green caterpillar in a wide sense. However, as suggested by Ebuchi et al. [12], the looper motion is here regarded as the 2 rhythm motion pattern which repeats two motions, i.e., the flexion and stretch.

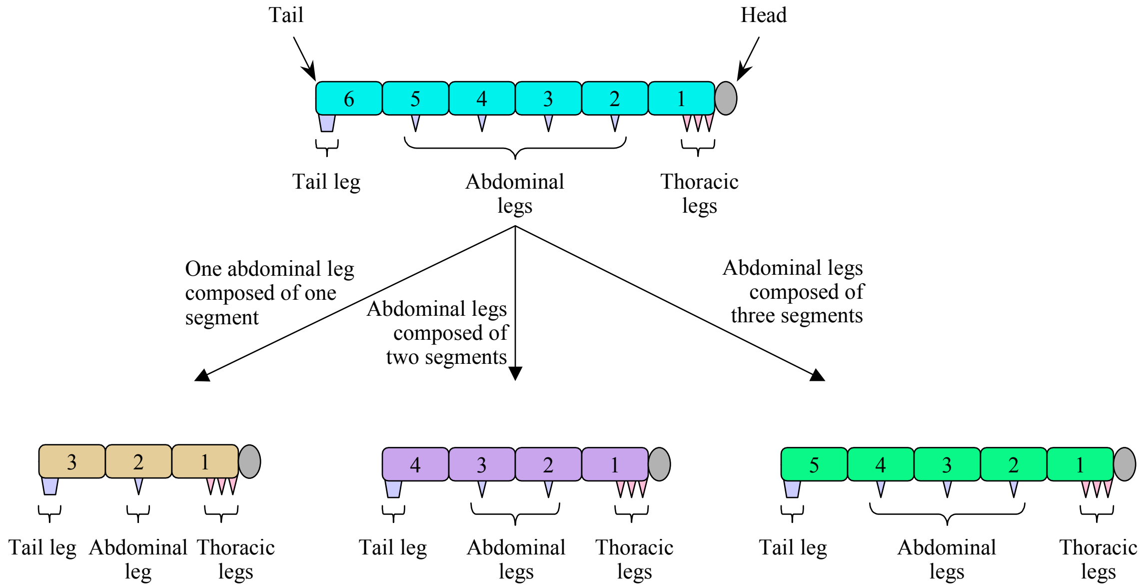


Fig. 4. Segment approximation of a green caterpillar.

4. Modeling by Multiple Links

As shown in Fig. 4, the present worm-like robot is approximated by using six links at most, in which the original 13 segments of a green caterpillar (or silkworm) are approximated to one link for representing thoracic legs, four links for representing each abdominal leg pair, and one link for representing one pair of tail legs. For more simplified versions, we also consider three link model in which each link respectively represents the thoracic, abdominal, and tail legs; four link model in which two links are assigned for the abdominal legs; and five link model in which three links are assigned for the abdominal legs.

5. Analysis of Link Motion Patterns

We first define the following definitions.

Definition 3: When a connected link composing of two or more links is regarded as one link, it is called singular link. For example, if any two links are moved just as one link, then we call it two-singular links.

Then, the following assumptions are set to realize a semi-looper motion considered here.

Assumption 1: It is based on the green caterpillar motion which raises the tail link at the motion start time, and raises the thoracic link at the time of one period finalizing. That is, although a singular link motion is permitted, a perfect looper motion with two-link configuration where the tail and thoracic links are not raised from a road (or floor) surface is not considered here. In addition, a two-dimensional motion is assumed in this research.

Assumption 2: It is not taken account of the number of actuators and their allocations.

Assumption 3: Using the number of links which are completely untouched from the floor, the motion pattern is represented by a transition pattern per one cycle. However, it is assumed that a singular link motion is permitted to generate a semi-looper like motion, which can make a speedy motion for more than four links.

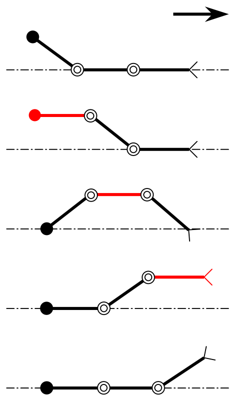


Fig. 5. 1–1–1 motion pattern of 3 link model.

5.1. Three link model

For this case, there exists only 1–1–1 pattern, which is the basic pattern as the green caterpillar motion shown in Fig. 5

5.2. Four link model

The basic pattern is 1–1–1–1 pattern shown in Fig. 6. In addition, as patterns combined with two-singular links and one link, there are 2–1–1, 1–2–1 and 1–1–2 (i.e., the reverse transition of 2–1–1), as shown in Fig. 7.

Here, note that the motion pattern of the reverse transition is defined as one that can obtain the same motion pattern as the original one, if the link transition pattern is moved from the final transition to the start transition after reversing the motion direction.

Moreover, hereafter (i.e., for the following five and six links), the figure of a reverse transition pattern is omitted for the sake of the convenience of space.

5.3. Five link model

The basic pattern is 1–1–1–1–1 pattern as shown in Fig. 8.

For the case when a combinatorial use of two-singular links and one link is considered, there are 2–1–1–1, 1–2–1–1, 1–1–2–1 (i.e., the reverse transition of 1–2–1–1), and 1–1–1–2 (i.e., the reverse transition of 2–1–1–1) patterns as shown in Fig. 9, if two-singular links are only used once.

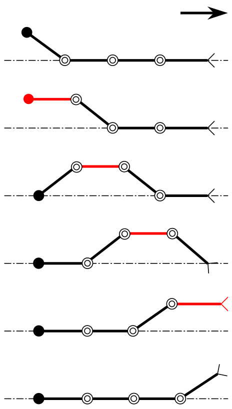
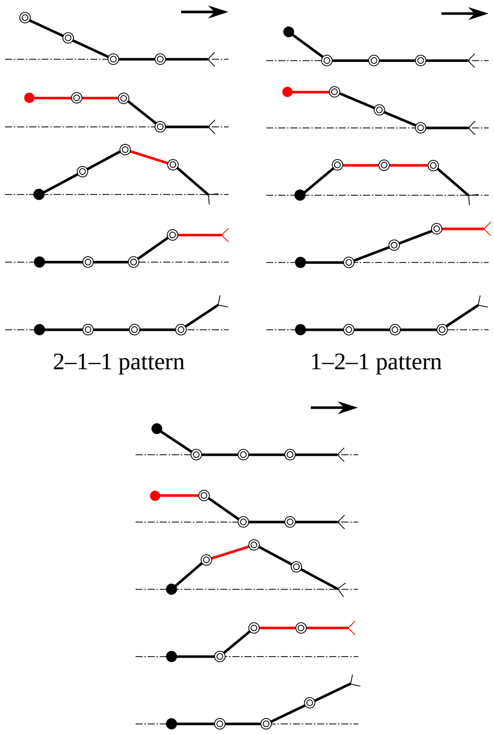


Fig. 6. 1–1–1–1 motion pattern of 4 link model.



2–1–1 pattern   1–2–1 pattern

1–1–2 pattern

Fig. 7. Motion patterns of 4 link model, as a combination of two-singular links and one link.

If two-singular links are used twice, then there are 2–2–1, 1–2–2 (i.e., the reverse transition of 2–2–1), and 2–1–2 patterns as shown in Fig. 10.

Furthermore, as patterns of combining three-singular links and one link, there exist 3–1–1, 1–1–3 (i.e., the reverse transition of 3–1–1), and 1–3–1 patterns, as shown in Fig. 11.

5.4. Six link model

The basic pattern is 1–1–1–1–1–1 as shown in Fig. 12.

For patterns of combining two-singular links and one link, using only once two-singular links yields 2–1–1–1–1, 1–1–1–1–2 (i.e., the reverse transition of 2–1–1–1–1), 1–2–1–1–1, 1–1–1–2–1 (i.e., the reverse transition of 1–2–1–1–1), and 1–1–2–1–1 patterns as shown in Fig. 13.

For the case when two-singular links are used twice, it yields 2–2–1–1, 1–1–2–2 (i.e., the reverse transition of 2–2–1–1), 2–1–2–1, 1–2–1–2 (i.e., the reverse transition of 2–1–2–1), and 2–1–1–2 patterns as shown in Fig. 14.

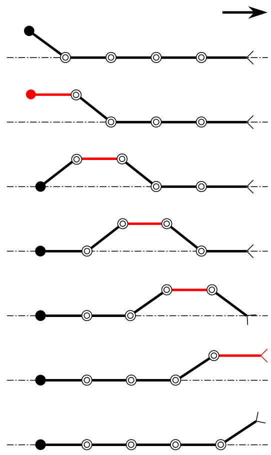
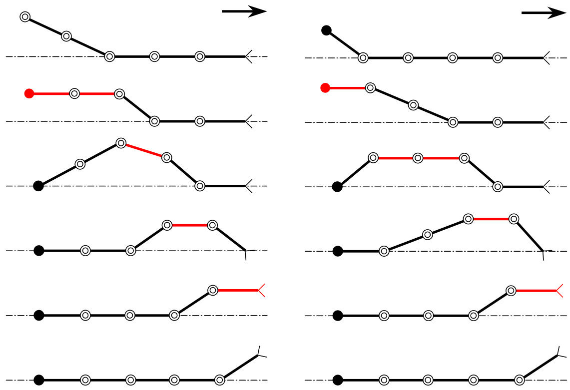


Fig. 8. 1–1–1–1–1 motion pattern of 5 link model.



2–1–1–1 pattern   1–2–1–1 pattern

Fig. 9. Motion patterns of 5 link model as a combination of two-singular links and one link, where two-singular links motion is used only once.

Furthermore, as a pattern of combining only two-singular links, there exists 2–2–2 pattern as shown in Fig. 15.

On the other hand, for patterns in which three-singular links and one link are combined, there are 3–1–1–1, 1–1–1–3 (i.e., the reverse transition of 3–1–1–1), 1–3–1–1, and 1–1–3–1 (i.e., the reverse transition of 1–3–1–1) patterns as shown in Fig. 16.

In addition, for patterns in which two-singular links, three-singular links, and one link are combined each other, there exist, as shown in 17, the following patterns: 2–3–1, 1–3–2 (i.e., the reverse transition of 2–3–1), 2–1–3, 3–1–2 (i.e., the reverse transition of 2–1–3), 3–2–1, 1–2–3 (i.e., the reverse transition of 3–2–1), 3–1–2, and 2–1–3 (i.e., the reverse transition of 3–1–2).

6. Conclusion

In this research, in order to generate the motion of worm-like robots adaptable to the change of height, locomotion patterns for a semi-looper type robot have been considered, where the basic motion was assumed to be a green caterpillar motion consisting of a forward-wave and a looper-like motion was sometimes included on the way of the one cycle pattern. In particular, several motion patterns in two-dimensional space were considered by modeling the original 13 segments of a green caterpillar (or silkworm) with six links at most, or with three links at least.

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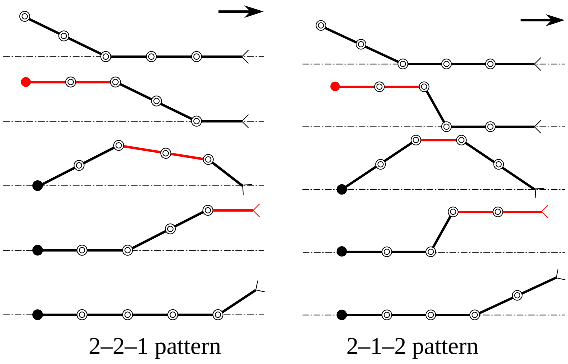


Fig. 10. Motion patterns of 5 link model as a combination of two-singular links and one link, where two-singular links motion is used twice.

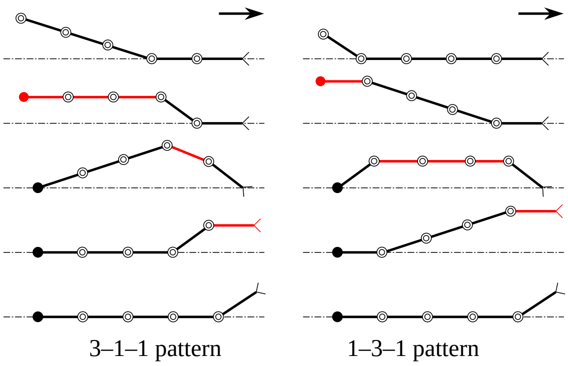


Fig. 11. Motion patterns of 5 link model as a combination of three-singular links and one link.

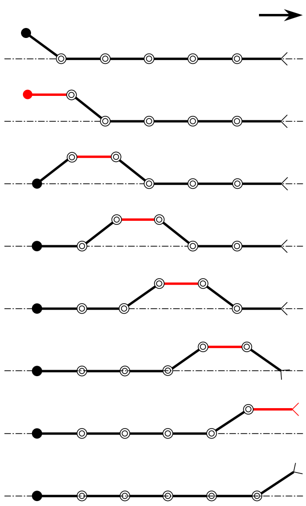
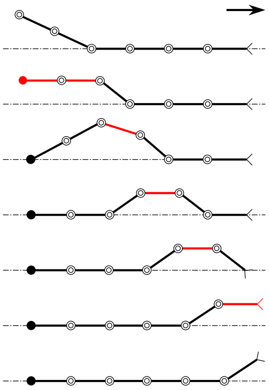
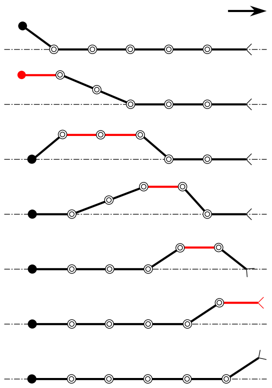


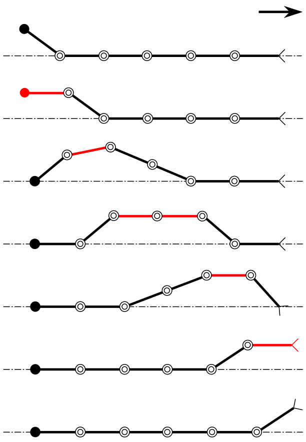
Fig. 12. 1–1–1–1–1–1 motion pattern of 6 link model.



2–1–1–1–1 pattern

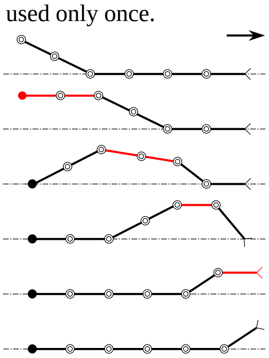


1–2–1–1–1 pattern

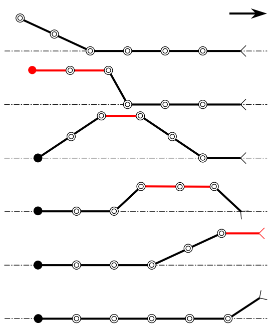


1–1–2–1–1 pattern

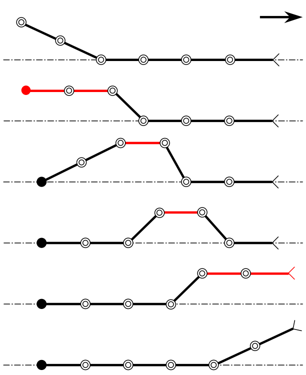
Fig. 13. Motion patterns of 6 link model as a combination of two-singular links and one link, where two-singular links motion is used only once.



2–2–1–1 pattern



2–1–2–1 pattern



2–1–1–2 pattern

Fig. 14. Motion patterns of 6 link model as a combination of two-singular links and one link, where two-singular links motion is used twice.

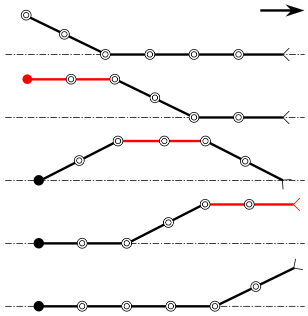
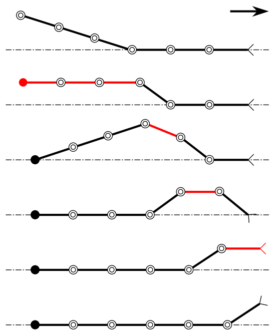
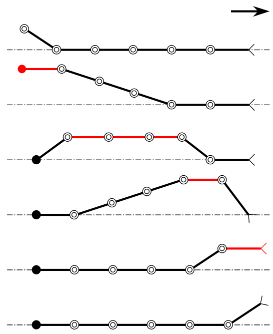


Fig. 15. 2–2–2 motion pattern of 6 link model as a combination of only two-singular links.

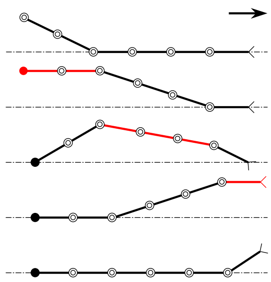


3–1–1–1 pattern

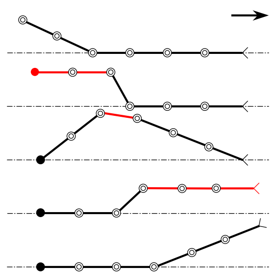


1–3–1–1 pattern

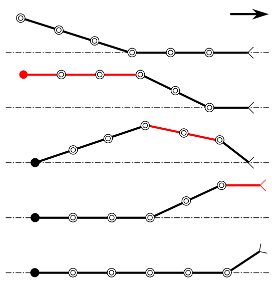
Fig. 16. Motion patterns of 6 link model as a combination of three-singular links and one link.



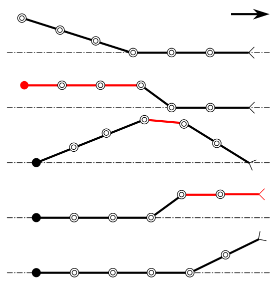
2–3–1 pattern



2–1–3 pattern



3–2–1 pattern



3–1–2 pattern

Fig. 17. Motion patterns of 6 link model as a combination of two-singular links, three-singular links, and one link.