Experimental investigation of turning maneuverability of a multilegged robot using pitchfork bifurcation

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1 Introduction

For the mobility of robots, using many legs has advantages, such as the ability to avoid falling and to tolerate leg malfunction. However, many intrinsic degrees of freedom make the motion planning and control difficult. In addition, many contact legs can impede the maneuverability during locomotion. The underlying mechanism for agile locomotion using many legs remains largely unclear from biological and engineering viewpoints.

In our previous works [1, 2], we showed that straight walking of a multilegged robot, which consists of many body segments connected by yaw joints with torsional springs, becomes unstable through Hopf bifurcation by changing the spring stiffness uniformly among the joints. Moreover, the instability contributed to high turning maneuverability [3]. In this study, we showed that the straight walking becomes unstable through pitchfork bifurcation by changing the spring stiffness in a different way. Furthermore, we investigated the turning maneuverability using the pitchfork bifurcation by robot experiments.

2 Method

2.1 Robot

Figure 1 shows our multilegged robot, which consists of six body segment modules (Modules 1-6) and was developed in our previous works [2, 3]. Each module is composed of a single body and one pair of legs. Each leg has two links connected by pitch joints, while that in the first module (Module 1) has an additional link connected by a yaw joint to control the walking direction. Each leg joint is manipulated by a motor. The body segments are passively connected by yaw joints (Yaw joints 1-5) installed with torsional springs. Module 1 has a laser range scanner to find the relative position of a target for the turning task.

2.2 Leg control for straight walk

First, we performed robot experiments of straight walking to investigate the stability. We controlled the leg movement by using the two pitch joints in each leg to follow the desired movement, which consists of two parts: half of an elliptical curve that starts from the posterior extreme position (PEP) and ends at the anterior extreme position (AEP), and a straight line from the AEP to the PEP (Fig. 1B). In the straight line section, the leg tips moved from the AEP to the PEP in the opposite walking direction at a constant speed parallel to the body. The contralateral legs in each module were manipulated to move in antiphase, and the relative phase between the ipsilateral legs was set to $2\pi/3$ rad. We fixed the leg yaw joint angles of Module 1 so that the leg tip trajectories were parallel to the body segment. Because torsional springs were installed on the body-segment yaw joints and the leg tips moved parallel to the body segments at an identical speed for all legs, our robot was expected to walk in a straight line while keeping the body segments parallel to each other. Although our previous works [1, 2] changed the torsional spring constants uniformly among the Yaw joints 1 to 5, this study changed only that of the Yaw joint 1.

2.3 Turning control

To investigate the contribution of straight walk stability to turning maneuverability, we performed robot experiments for a quick turn to approach a target located on the floor using the leg yaw joints of Module 1 and laser range scanner in a similar way to our previous work [3]. More specifically, the leg yaw joints were controlled based on the relative angle between Module 1 and the target monitored by the laser range scanner to direct Module 1 to the target. This experiment was designed so that Module 1 determined the walking direction and the other modules followed Module 1 through
passive connections of the body-segment yaw joints, where we set a limited range of the leg yaw joints to prevent the robot from completing the turning task only by this control irrespective of the straight walk stability. We used 45° relative angle and 0.9 m distance between Module 1 and the target and set all body segments parallel to each other as the initial condition.

3 Result

3.1 Destabilization of straight walk through pitchfork bifurcation

When the torsional spring constant of Yaw joint 1 was large, the robot performed straight walking as expected (Fig. 2A). However, when the spring constant was small, straight walking transitioned to curved walking, where all body-segment yaw joints converged to different values from zero with the same sign (Fig. 2B).

To clarify the mechanism for this gait change, we used different torsional spring constants for Yaw joint 1. Figure 3 shows the average and standard deviation of the converged angles of Yaw joint 3 for different spring constants. When the spring constant was less than a critical value, the converged angle was almost zero and the robot showed straight walking. In contrast, when the spring constant was larger than the critical value, the robot showed curved walking. Furthermore, the angle increased as the spring constant decreased (the joint compliance increased). These results suggest that straight walking transitioned to curved walking through pitchfork bifurcation.

3.2 Turning maneuverability

Figure 4 compares the results of the turning task using three cases of torsional spring constants in Yaw joint 1: close to the bifurcation point (critical) and smaller (soft) and larger (hard) than the bifurcation point. For the hard case, the robot was difficult to change the walking direction and failed the turning task with a large overshoot in the floor trajectory. In the soft case, the robot showed a too sharp turn to approach the target. In contrast, when the spring constant was close to the bifurcation point, the robot approached the target and succeeded the turning task.

4 Discussion

Stability and maneuverability are important factors for evaluating locomotor performance and they have a strong connection [4]. Our robot experiments showed that straight walking becomes unstable through pitchfork bifurcation and transitions to curved walking. Furthermore, the instability does contribute to turning performance. In particular, we have to determine adequate torsional spring constant depending on the turning condition. We would like to investigate the relationship between the physical, control, and turning conditions in the future.

Acknowledgements

This study was supported in part by JSPS KAKENHI JP17H04914.

References