LOCOMOTION ANALYSIS OF A MODULAR PENTAPEDAL WALKING ROBOT

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ABSTRACT

In this paper, the configuration of a five-limbed modular robot is introduced. A specialised locomotion gait is designed to allow for omni-directional mobility. Due to the large diversity resulting from various gait sequences, a criteria for selecting the best gaits based on their stability characteristics is proposed. A series of simulations is then performed to evaluate the various gaits in different walking directions. A gait arrangement scheme toward omni-directional locomotion is finally derived. Lastly, Experiments are also carried out on our pentapedal robot prototype in order to validate the results of simulation. The experiments confirm the gait analysis and selection is highly accurate in the evaluation of gait stability.

I. INTRODUCTION

Legged locomotion offers great advantages due to its discrete foothold resulting in adaptability to uneven terrain, low energy consumption and less environmental destruction. Furthermore, the articulated limbs of legged robots are able to function in both locomotion and manipulation, thereby achieving better mobility and functionality. Therefore, a robot can either eliminate deadlock by properly manipulating its limbs to regulate the centre of gravity of its body, or improve its stability by using an additional limb as a leg (Zhang et al. 1996).

So far, various kinds of walking machines with two, four, six and eight legs have been developed. Systematic studies have been conducted on gait generation, control realization and algorithm implementation. However, most of these studies were concentrated on models with an even number of legs, as research interests in an odd number of legs is much rarer. Beside the research in (Zhang et al. 1996) and (Zhang et al. 1997), Prihastono et al. proposed a five legged mechanism that was inspired by a starfish (phylum echynodermata). The robot is capable of performing autonomous navigation in cluttered environments (Prihastono et al. 2009). However, these studies, for the most part, considered only fixed-shape robots that were designed based on a predefined and set-up environment.

For locomotion in unknown and hostile environments, modular robot platforms are expected to be more flexible and efficient than traditional fixed-shape robots, since such situations demand on-site locomotion adaption, shape adaption and task planning. Moreover, the modular approach also makes the mobile robotic system versatile, robust, cost-effective and fast to prototype, so that new configurations of different robots can be built quickly and easily for exploration. By differing the system architecture, modularity can be recognised in several approaches. Ohira et al. developed multi-legged modular robots, which can be interconnected to achieve multiple locomotion modes via cooperation and accomplish tasks that cannot be done with a single module (Prihastono et al. 2009). In (Aoi et al. 2006), Aoi et al. presented a multi-legged modular robot, consisting of six homogenous modules, which are connected to each other via a 3-degree-of-freedom (3-DoF) joint. The leg joint is driven in such a way that it follows the desired periodic trajectories, and at the same time, acts as a passive shock absorber. Chen et al. proposed a modular method for formulating the dynamics of multi-legged robots with general leg structures. In this approach, each leg is considered as an individual module, while the whole multi-legged system is treated as a free-floating system with the individual leg module coupled to a main body (Chen et al. 1997).

Even though significant progress has been made in this field, the technology of multi-legged robotics is still a challenging topic to be focused on in robotics research. As mentioned above, previous research work either focused on the classic four and six-limbed modular configurations, or on fixed-shape mobile robots, which offered insufficient flexibility in locomotion. In this paper, by combining the multi-legged locomotion techniques with a modular robotic approach, a pentapedal (five-limbed) modular robotic configuration is proposed. The goal of this research is to develop a versatile robotic mobile platform featuring an easy-to-build mechanical structure, various locomotion capabilities and high manipulation flexibility.

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II. RELATED WORK

A. Modular Robot Research

Modular robotic systems feature extraordinary flexibility, extendibility, robustness and reconfigurability. They are usually composed of multiple building blocks with relatively simple repertoires, together with uniform docking interfaces which enable mechanical junctions and electronic communication throughout the whole system. The last few years have witnessed an increasing interest in modular reconfigurable robotics for education (Daidié et al. 2007), inspired robotic research (Zhang et al. 2007) and space applications (Yim et al. 2007).

Modular robots can be connected in various configurations. Chain-configuration is suitable for locomotion and manipulation since a chain of modules is equivalent to a leg or an arm. Such form is the focus of this paper. In (González-Gómez et al. 2006), 1 dimension (1D), 2D and 3D chain robots are classified according to their topology. A 1D-chain robot, such a snake (Paap et al. 2000), worm (Zimmermann et al. 2004), leg, arm or cord (Kurokawa et al. 2003), can transform its body into different shapes, enabling itself to pass though pipes, grasp objects and move on rough terrain.

In 2004, our group designed a series of low-cost passive modular robots and modular robot locomotion. In cooperation with Dr. Juan González-Gómez, the Y1 modular robot with 1 DoF was designed in 2004 as the first prototype (Gonzalez-Gomez et al. 2007). By using this prototype, the minimal configurations for movement of snake-like robots were studied (Zhang et al. 2008). Then the new modular robot Cube-M with one DoF, an improved version of the Y1 modular robot, was presented (Zhang et al. 2009). It features an easy-to-build mechanical structure, four connecting faces, an onboard micro controller and a friendly programming environment.

B. The Pentapedal Configuration

To the best of the authors' knowledge, limited literature has been found focusing on the pentapedal configuration which has considerable redundancy in locomotion and control. However, the robot could gain auxiliary competence in mobility and functionality if a certain proper control strategy enables the reuse of one or two limbs as manipulator. Our goal is to develop a pentapedal robot platform capable of moving on rough terrain and accomplishing tasks with redundant limbs.

The pentapedal configuration has no corresponding prototype existing in nature, though some quadrupedal animals have certain auxiliary features to enhance their locomotion. For example, primates utilise their tail to keep their balance and improve climbing performance. In addition, it is advisable to implement radial symmetry in the robot's general configuration, inspired by pentamerism in nature. Therefore, the pentapedal robot has the characteristics of omni-directional locomotion. However in special cases, it is able to transform into quadrupedalism while operating one limb as a manipulator.

The design of such a robotic configuration is also inspired by existing multi-legged robots. The omni-directional configuration calls for high equivalence among the legs, in order to satisfy the accessibility of locomotion in various directions. On each leg of the robot, the distribution of articulations adopts the classic layout of insect-mimicking robots. The three Dof are provided by three articulation at the hip, knee and heel.

The control of a pentapedal robot also suggests a novel gait to enable the robot to move in a fluent and efficient manner. Therefore a rational gait should evenly utilise all the legs while maintaining sufficient stability. This paper discusses mainly gait generation and selection towards walking stability and fluency.

Firstly in Section III, this paper outlines the sequential 3+2 gait, which is specifically designed for pentapedal configuration. Due to the large diversity of gait sequences, a series of selections according to locomotion stability criteria is proposed in Section IV. In Section V, simulations are implemented to select the best gait sequences. Finally, the gaits are tested by experiments on our robot prototype.

III. DEFINITION OF PENTAPEDAL LOCOMOTION GAIT

Due to the absence of similar five-limbed creatures in nature, our research aims to introduce a fully artificial gait to be adopted to the robot.

Considering the static stability of the pentapedal configuration, the robot must have a minimum of three supporting feet in order to sustain the body. The remaining two limbs are utilised as striding legs in order to achieve better efficiency. Therefore, the sequential "3+2" gait for the pentapedal robot is defined as follows:

a) The gait cycle is divided into 5 phases. During each phase, a pair of feet stride one pace's length in the walking direction of the robot.

b) The striding foot-pair sequence is indicated by the gait sequence.

c) In every stride phase, the striding foot-pair should not be two adjacent feet.

d) The of robot's torso movement is evenly distributed along the walking direction during each phase. The speed is therefore at 0.4 time of pace length during each stride, in order to follow the movement of feet.

The robot walks with a specified sequence, length and direction. As such, the trajectories of the feet are determined. In Figure 1, the position of robot's torso and feet are illustrated from left to right. The robot starts the gait cycle from a neutral stance, as shown in the left-most picture, and then strides one pair of feet during each state. After a gait cycle, each foot has been involved in striding twice. The robot moves twice the pace length after a whole gait cycle finishes.

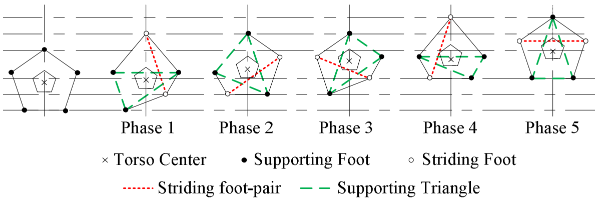


Figure 1: The five phases during a Sequential "3+2" Gait example. The robot strides its legs in pairs according to a certain sequence while the torso moves towards the corresponding direction in fixed speed.

In order to clarify the sequence of the striding feet, the foot-pairs are numbered 1, 2, 3, 4 and 5, as shown in Figure 2. The pole is set at the centre of the body, while the polar axis is defined as 0°. Due to the radial symmetric characteristic of the robot, the characteristics in the range of [54°,126°), [126°,198°), [198°,270°), [270°,342°) and [342°,54°) are identical. In addition, these ranges are axially symmetric with respect to the 90°, 162°, 234°, 306° and 18° axes, which divide their own corresponding range into two symmetric parts. This paper only focuses on the direction between 54° and 90°, which can also represent situations in other ranges by using an appropriate transformation.

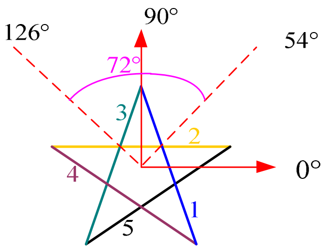


Figure 2: The Numbering of Feet and Foot-pairs

IV. LOCOMOTION GAIT ANALYSIS AND SIMULATION

The Sequential "3+2" Gait can secure at least three supporting feet during the gait cycle, but the robot may eventually fall when some gaits are implemented. The goal of the gait analysis is to select best gaits to apply to the robot.

Since the stride frequency never exceeds 3 Hz due to the speed of the actuator, dynamic effects are not taken into account in the analysis. Hence the analysis of the Sequential "3+2" Gait is based on each state during a gait cycle. Besides the 5 phases during a whole gait cycle, each phase is divided into a pre-stride state and a post-stride state by the stride movement. Each state indicates a situation, recording the positions of all of the feet as well as robot's centre of gravity. Therefore, in 10 states during a gait cycle, the analysis evaluates each gait sequence in terms of its stability, as shown in Figure 3.

The Sequential "3+2" Gait provides an even utilization of striding legs while maintaining the basic stability in locomotion. However, by presenting a sequence permutation between five striding foot-pairs, the number of various gaits reaches the factorial of 5, equals to 120.

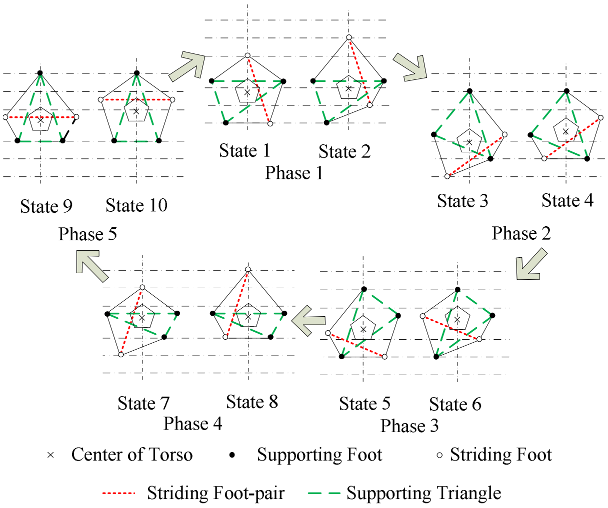


Figure 3: In each phase of a gait cycle, the pre-stride state is numbered with odd numbers while the post-stride state with even numbers. These ten states are sufficient for demonstrating interaction between the centre of gravity and supporting triangle.

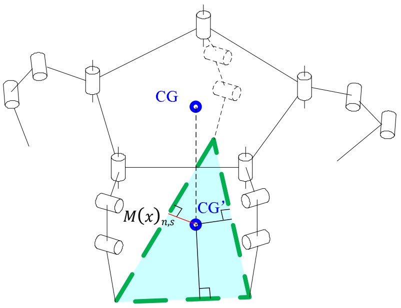
Stability Analysis

The stability margin is defined as the minimum distance from the projection of the centre of gravity to one of the edges of the supporting triangle. When the projection of the centre of gravity falls out of the supporting triangle, the robot will be no longer stable to stand on the supporting legs.

The stability margin is investigated as a key value in evaluating the stability of a gait. When the walking direction x is given, a 120×10 matrix $M(x)_{n,s}$ can be derived, where $M(x)_{n,s}$ indicates the stability margin of s^{th} state in No. n gait.

Two indicies are designated as the reference of the stability of a gait. The first is the minimum stability margin $M(x)_{n_{min}}$, which evaluates the most vulnerable situation to disturbances during the whole period. The summed stability margin $M(x)_{n_{total}}$ is used to investigate the overall stability of a gait.

When the projection of the centre of gravity falls out of the supporting triangle, we deem that $M(x)_{n,s}$ does not exist. Thus the value of $M(x)_{n_{min}}$ and $M(x)_{n_{total}}$ will not be calculated due to its instability.



CG- Center of Gravity;
$M(x)_{n,s}$ - Minimum Distance from Projection of Centre of Gravity to Edge of the Supporting Triangle

Figure 4: The Definition of Stability Margin

By investigating the stability margin in each state, any gaits with unstable states are eliminated.

Simulation

A series of parameters derived from the model of our modular pentapedal robot prototype is adopted correspondingly in the simulation.

The robot's five hips are placed at the five corners of a pentagon with a diameter of 188mm, while the feet are set similarly on a pentagon with a diameter of 340mm. The torso is set horizontally at a height of 90mm. The pace length for each stride is 100mm, as shown in Figure 5. Due to the evenness of leg placement, the robot's centre of gravity is supposed to coincide with the centre of the torso.

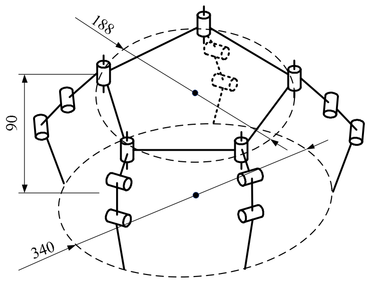


Figure 5: General Set-up of Simulation Model of Pentapedal Robot

The model has five identical legs equally distributed around the torso. Each leg consists of three identical modules, providing three degrees of freedom for transition movement. The kinematic geometry of each leg is shown as Figure 6.

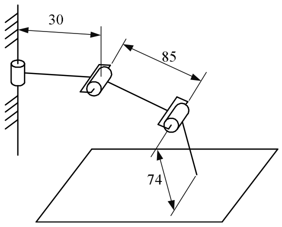


Figure 6: The Kinematic Model of the Robot's Leg

The stability margins of all states are calculated among 120 gaits. The calculation is performed when the walking direction is set at 90°, 84°, 78°, 72°, 66°, 60° and 54°. These 7 directions are selected evenly between 54° and 90° with an interval of 6°, sufficiently showing the distribution of superior gaits in this range of directions.

Stability in the 90° Walking Direction

When the robot moves in the direction of 90°, 52 gaits keep their stability margins above 0 during all the states. The minimum stability margin during the 10 states is calculated as described in (1).

$$M(90)_{n_{min}} = \mathrm{Min}\left\{M(90)_{n,s}\right\} \qquad (1)$$

Table 1: List of Stable Gaits in 90° Walking Direction

Gaits with Specified Sequences	$M(90)_{n_{min}}$ (mm)
No.79(2-3-4-5-1); No.94(2-1-5-4-3) No.80(2-3-4-1-5); No.93(2-1-5-3-4) No.83(2-3-1-5-4); No.92(2-1-3-4-5) No.84(2-3-1-4-5); No.91(2-1-3-5-4)	20.21
No.49(3-4-5-2-1); No.119(1-5-4-2-3) No.51(3-4-2-5-1); No.118(1-5-2-4-3) No.52(3-4-2-1-5); No.117(1-5-2-3-4) No.63(3-2-4-5-1); No.113(1-2-5-4-3) No.64(3-2-4-1-5); No.114(1-2-5-3-4) No.65(3-2-1-4-5); No.110(1-2-3-5-4) No.66(3-2-1-5-4); No.109(1-2-3-4-5)	12.58
No.15(5-2-4-3-1); No.40(4-2-5-1-3) No.16(5-2-4-1-3); No.39(4-2-5-3-1) No.17(5-2-1-4-3); No.37(4-2-3-5-1) No.18(5-2-1-3-4); No.38(4-2-3-1-5) No.73(2-4-3-5-1); No.89(2-5-1-4-3) No.74(2-4-3-1-5); No.90(2-5-1-3-4) No.75(2-4-5-3-1); No.88(2-5-4-1-3) No.76(2-4-5-1-3); No.87(2-5-4-3-1)	4.54
No.1(5-4-3-2-1); No.29(4-5-1-2-3) No.3(5-4-2-3-1); No.28(4-5-2-1-3) No.4(5-4-2-1-3); No.27(4-5-2-3-1) No.5(5-4-1-2-3); No.25(4-5-3-2-1) No.21(5-1-2-3-4); No.34(4-3-2-1-5) No.22(5-1-2-4-3); No.33(4-3-2-5-1) No.23(5-1-4-2-3); No.31(4-3-5-2-1)	4.03

Secondly, the sum of stability margins in 10 states is also calculated as an alternative reference to evaluate the stability of gaits as described in (2).

$$M(90)_{n_{total}} = \sum_{s=1}^{10} M(90)_{n,s} \qquad (2)$$

Table I shows that the minimum stability margins of gaits. All the stable gaits only appear to have 4 values as 20.21, 12.58, 4.54 and 4.03. At the same time, gaits that are symmetric with respect to the 90° axis appear to have the same result since the direction of 90° coincides with the symmetry axis.

Gaits whose first two striding foot-pairs are identical appear to have the same minimum stability margins. In other words, the selection of striding foot-pairs in the first two phases is critical to the total stability of the whole cycle.

Figure 7 shows the total stability margin of 10 states for the 52 gaits in the blue column, together with the minimum stability margins from Table I represented by the red column. The gaits with a higher minimum stability margin also dominate in total stability margin.

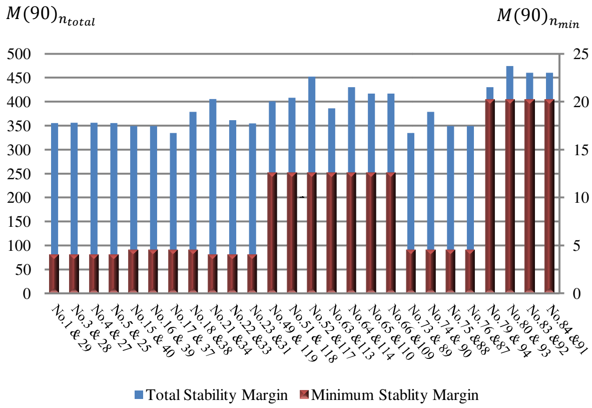


Figure 7: Total and Minimum Stability Margin of All the Stable Gaits in the 90° Walking Direction

Stability in the Range between 54° and 90°

Similar simulations are repeatedly carried out while the walking direction is set to 84°, 78°, 72°, 66°, 60° and 54°.

28 gaits are able to keep their stability margin above zero in these directions. The sets of top-ranking gaits in these walking directions still show great similarity due to the change of direction.

The calculation of the stability margin is performed in a widened range. Equations (3) and (4) show the minimum and total stability margin of a gait in the 7 walking directions.

$$M_{n_{min}} = Min\left\{\begin{matrix} M(90)_{n_{min}}, M(84)_{n_{min}}, M(78)_{n_{min}}, \\ M(72)_{n_{min}}, M(66)_{n_{min}}, M(60)_{n_{min}}, \\ M(54)_{n_{min}} \end{matrix}\right\} \tag{3}$$

$$M_{n,total} = M(90)_{n_{total}} + M(84)_{n_{total}} + M(78)_{n_{total}} + M(72)_{n_{total}} + M(66)_{n_{total}} + M(60)_{n_{total}} + M(54)_{n_{total}} \tag{4}$$

Figure 8 shows the gaits with dominant minimum stability margins and total stability margins.

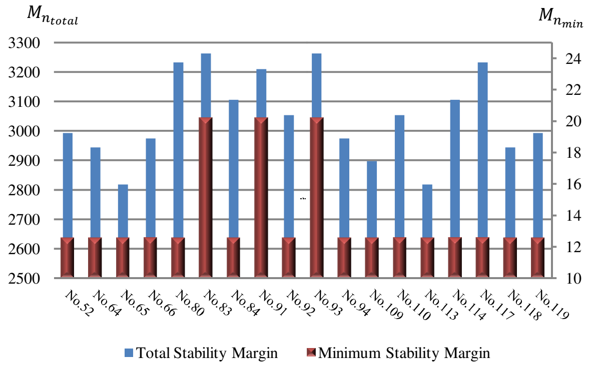


Figure 8: Total and Minimum Stability Margin of Dominant Stable Gaits in 7 Walking Directions

No.83(2-3-1-5-4), No.91(2-1-3-5-4) and No.93(2-1-5-3-4) gaits keep their minimum stability margin above 20mm, and also keep high total stability margins among all the situations.

Gait Transformation for Omni-directional Locomotion

After investigating the stability of the 120 gaits in the range between 54° and 90°, three superior gaits with extraordinary stability emerged from the 120 gaits. By analyzing the axial and radial symmetric characteristics, these three gaits can be transformed appropriately to fit locomotion in directions other than the range between 54° to 90°.

According to the numbering in Figure 2, Foot-pair 1 and 4 is respectively symmetric to Foot-pair 3 and 5 with respect of 90° axis. Therefore, the three best gaits in the range between 90° and 126° are derived as 2-1-3-4-5, 2-3-1-4-5 and 2-3-4-1-5.

Table 2: Optimised Gaits in All Walking Directions

Walking Direction	Selected Gaits
[54°,90°)	2-3-1-5-4; 2-1-3-5-4; 2-1-5-3-4
[90°,126°)	2-1-3-4-5; 2-3-1-4-5; 2-3-4-1-5
[126°,162°)	3-4-2-1-5; 3-2-4-1-5; 3-2-1-4-5
[162°,198°)	3-2-4-5-1; 3-4-2-5-1;3-4-5-2-1
[198°,234°)	4-5-3-2-1; 4-3-5-2-1; 4-3-2-5-1
[234°,270°)	4-3-5-1-2; 4-5-3-1-2; 4-5-1-3-2
[270°,306°)	5-1-4-3-2; 5-4-1-3-2; 5-4-3-1-2
[306°,342°)	5-4-1-2-3; 5-1-4-2-3; 5-1-2-4-3
[342°,18°)	1-2-5-4-3; 1-5-2-4-3; 1-5-4-2-3
[18°,54°)	1-5-2-3-4; 1-2-5-3-4; 1-2-3-5-4

Considering the radial symmetric characteristics, the corresponding gaits in other directions can also be derived by shifting the foot-pairs, as shown in Table 2.

V. EXPERIMENT

The experiment evaluating the sequential “3+2” gait is performed on our pentapedal robot. In fact, all of the geometric parameters and initial set-up in our simulation are inherited from this robot prototype.

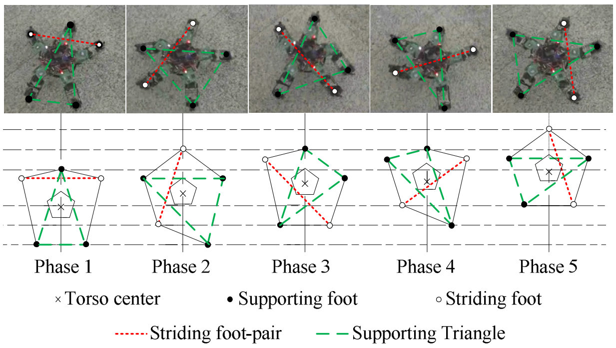


Figure 9: The pentapedal robot succeeds in walking in a stable manner. The picture below shows gait No.79(2-3-4-5-1) in comparison with the snapshots above.

During the experiments, the robot walks on a horizontal even plane, while it performs all of the 120 gaits. The gait parameters are also set identical to the simulation. The walking direction is set to 90°.

Gait stability is judged based on observation. When the robot does not stand on the supporting legs as planned, or any clash of legs appears, the current gait will be deemed instable.

The experimental result shows the 22 gaits which have their minimum stability margin equals to 20.21 and 12.58 in Table I to have satisfying performance. Other gaits, including the ones with minimum stability margins below 10, show the instability in some phases during a gait cycle.

The experiments also show that all these 22 stable gaits do not appear to have any clash between legs. In other words, maintaining sufficient stability margin can, at the same time, guarantee a sparse lay-out of legs, and thus prevent the clash from occurring.

VI. CONCLUSION

The modeling and simulation has greatly reduced the work of testing various gaits, and provided helpful reference to judge the stability of gaits.

The greatest achievement of our research is a locomotion control strategy toward a modular pentapedal robot. First, the modular configuration of an omni-directional pentapedal robot was introduced. A large group of gaits was derived after the Sequential “3+2” Gait had been defined. Following this, a series of analysis and simulation were performed to select the most stable gaits, by calculating and comparing the minimum and total stability margins in various conditions. Lastly, experiments were carried out on our robot prototype, giving evidence that high-ranking gaits provide the robot with sufficient stability in locomotion.

Thus, the research on pentapedal robot is only confined in the locomotion on horizontal and even surface. It is desirable to expand this method to accommodate more complicated environment in future. In addition, the highly pre-defined gaits deprive the possibility which enables the robot to decide the striding strategy according to the current situation. An intelligent algorithm with reversed mechanism will be appreciated to accomplish the gait generation.

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