ANALYSIS OF TIPOVER STABILITY FOR NOVEL SHAPE SHIFTING MODULAR ROBOT*

LIU Jinguo

WANG Yuechao
Robotics Laboratory,
Shenyang Institute of Automation,
Chinese Academy of Sciences,
Shenyang 110016, China

MA Shugen
Department of Systems Engineering,
Ibaraki University,
Ibaraki 316-8511, Japan

LI Bin
Robotics Laboratory,
Shenyang Institute of Automation,
Chinese Academy of Sciences,
Shenyang 110016, China

Abstract: A novel three-module robot has been introduced. It can change its configuration to adapt to the uneven terrain and to improve its tipover stability. This three-module tracked robot has three kinds of symmetry configuration. They are line type, triangle type, and row type. After the factors and the countermeasures of mobile robot's tipover problem are analyzed, stability pyramid and tipover stability index are proposed to globally determinate the mobile robot's static stability and dynamic stability. The shape shifting robot is tested by this technique under the combined disturbance of pitch, roll and yaw in simulation. The simulation result shows that this technique is effective for the analysis of mobile robot's tipover stability, especially for the reconfigurable or shape shifting modular robot. Experiments on three symmetry configurations are made under unstructured environments. The environment experiment shows the same result as that of the simulation that the triangle type configuration has the best stability. Both simulation and experiment provide a valid reference for the reconfigurable robot's potential application.
Key words: Reconfigurable modular robot   Shape shifting robot   Stability pyramid   Tipover stability index   Unstructured environment

0 INTRODUCTION

In recent years, mobile robots have wide application in unstructured environments such as search and rescue, planetary exploration, military reconnaissance, mine exploration, and so on[1-3]. In such scenarios, the terrain is usually very rough and dangerous for the mobile robots because of its easy leading to the robots's tipover. If a tipover incident happens, it will result in a series of problems: Loss of traction, entrapment, system damage, loss of control, difficulty in overturning back, and even mission failure.

For different tasks and various environments, the traditional designed robots do not have enough flexibility to meet the need. The metamorphic robot or reconfigurable robot has attracted a lot of attention and interesting for their wide potential application. A novel shape shifting modular robot has been introduced. It can change its configuration to adapt to the uneven terrain and to improve its tipover stability. Since it is very difficult and dangerous to test the robot's mobile stability through platform experiment, theoretical research and simulation analysis are effective and necessary. The stability pyramid and tipover stability index are proposed to globally determine the mobile robot's static stability and dynamic stability. The simulation experiment and the environment experiments have shown this technique's validity.

1 SHAPE SHIFTING ROBOT PLATFORM

In unstructured environment missions, mobility and adaptability are important issues for the mobile robot platform. According to literature on mobile mechanisms applied in unstructured environment, the link-type structures, which are also widely used in snake-like robot or serpentine robot and multi-joint robot, have turned out to be effective and reliable for their low barycenter, large contact, continuous driving, and with more degrees of freedom than their workspace.

The link-type structure is hyper-redundant, repeatable, modularized, and available for reconfigurable and shape shifting research. The current link-type structures often have joints with one to three degrees of freedom between adjacent modules. But the joint motion space is usually limited for physical conflict. In this paper, a novel module with offset joints has been proposed as shown in Fig.1. A standard module has three degrees of freedom, the track driving, the pitch joint, and the yaw joint. This type, with offset joints at both sides and with the link arm between adjacent modules, has enough flexibility to metamorphose. A standard module is designed to be mainly composed of a link arm, a track-driven system, an offset pitch joint, an offset yaw joint and so on, as shown in Fig.1. It has three DC motors in which one drives the track, one is for pitch joint, and the third is for yaw joint respectively. Chains are used to drive the wheels forward and backward. The link arm is used to connect and disconnect the adjacent modules. A novel link-type robot is composed of such kind of modules. The key advantage of this type over the other link-type vehicles is its adaptation ability to the environments through various configurations. Most importantly, no matter how many modules it has, this novel link type robot can pose various kinds of symmetry configurations and trim configurations, especially in a line and in a row.

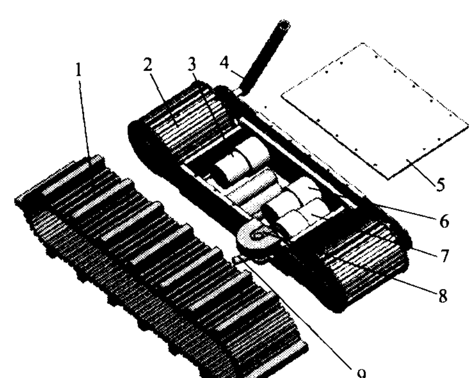

Fig.1 Standard module

1. Track with high gousers 2. Center-hollowed wheel 3. Pitch joint driving motor 4. Link arm 5. Box cover 6. Track driving motor 7. Yaw joint driving motor 8. Yaw joint 9. Link handle

The module robot has been mainly developed for the unstructured environment or the hazardous environment. The wheel type, the leg type and the track type are often used in the mobile robot's driving system. The wheel type system can move with high speed and high efficiency, but it has limited wall-climbing ability and can not overcome the trench. The wheel type mobile robot has very low mobility over rough terrain. The leg type robot can move on almost all kinds of terrain. However, it is difficult to

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design the robot small and hard to control its balance. Both leg type robot's speed and efficiency are very low. The track type is a suitable choice because the track type has good terrain adaptability and full contacting to the ground. Like a tank, the track type robot has good mobility over uneven terrain. In our design, a double-faced timing pulley is used as the track in the mobile system.

Using this kind of module, we develop a three-module shape shifting robot to test the shape shifting technique. The experiment is carried out as shown in Fig.2. It shows that the shape shifting robot changes its configurations from in line type to in row type fluently. The inverse process also works well. The three module robot has three kinds of symmetry configurations, the line type in Fig.2a, the triangle type in Fig.2e, the row type in Fig.2h. The rest ones in Fig.2 are intermediate configurations. Meanwhile, each configuration has various gaits. With combinations of the configurations and the gaits, robot's adaptability and tipover stability can be improved greatly.

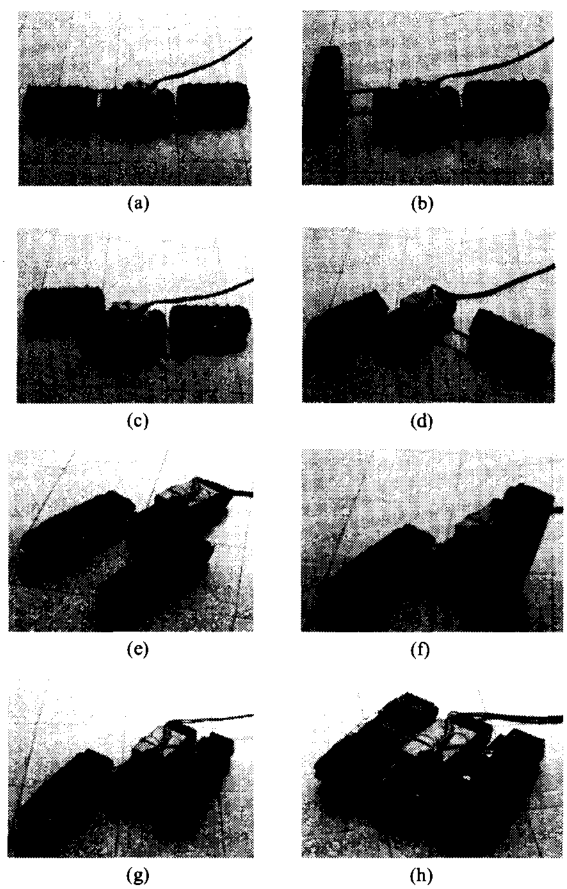


Fig.2 Three-module shape shifting robot

2 TIPOVER STABILITY ANALYSES

The mobile robot's tipover stability is influenced by the terrain condition, the robot system condition, and the extern force. We mainly discuss the terrain condition and the technique to control and improve the robot's tipover stability.

2.1 Terrain condition

The terrain condition decides the robot's mobility and stability to some extent. Terrain condition includes terrain physiognomy and surface topology, which represent the geometry feature and the physical feature respectively. The geometry feature often refers to the natural environment such as hill, knap, plain, etc. The physical feature often refers to the fixed objects such as houses, road, rivers, and forest, the vegetation such as grassland, and shrub, the soil friction factor such as sand, earth, and gravel, the stability of the terrain, and so on.

The mobile robot has disparity mobility and stability in various terrain conditions. Global estimating or mapping of the terrain environment is very important for the design and control of the mobile robot.

2.2 Control and improve the robot's stability

The robot system condition mainly includes the center of mass, the motion velocity, the motion acceleration, and the move format. In the unstructured environment, the terrain condition is unknown, unpredictable, and out of control. We have to control the robot's tipover stability to improve the mobile robot in the following ways.

(1) Reasonable stability evaluation criteria are needed to design and control the mobile robot. There are many static and dynamic stability criteria existing. The static stability criteria includes CG projection method[4], static stability margin (SSM)[5], longitudinal stability margin (LSM)[6], crab longitudinal stability margin (CLSM)[7], and energy stability margin[8]. The dynamic stability criteria include center of pressure method (COP)[9], effective mass center (EMC)[10], zero moment point (ZMP)[11], and dynamic stability margin (DSM)[12]. These different stability criteria are needed for different applications. The mobile robot's motion performances should be optimized since if the wrong criteria are applied, and robot's mobility would be limited. The existing stability criteria can be briefly classified into six types[4-13] as follows.

1) Even terrain in the absence of dynamics.

2) Uneven terrain in the absence of dynamics.

3) Even terrain with inertial effects.

4) Uneven terrain with inertial effects.

5) Even terrain with inertial effects and manipulation effects.

6) Uneven terrain with inertial effects and manipulation effects.

As the shape shifting robot designed in this paper has a low motion speed and the missions are mainly under unstructured environments, we propose the stability pyramid technique to globally evaluate the mobile robot's sideline tipover stability and corner point tipover stability.

(2) The mobile robot can change its structure and configuration to adapt its center of gravity and stability. Recently the reconfigurable and shape shifting robot attaches great attentions. They have potential application in unstructured environments because they can change their configuration or structure to adapt to the environment and mission. Such kind of robot can change its configuration to improve its stability too. For instance, the proposed planetary rovers in Ref.[2] and Ref.[3] can adjust their height of the gravity center and support to improve their stability.

As mentioned before, the three-module tracked robot has been designed for unstructured environment missions. The shape shifting robot changes its configuration to adapt to the environment and terrain. The tipover stability various configurations will be analyzed later in the following sections.

3 STABILITY PYRAMID TECHNIQUE

The stability criteria mentioned before, different as they are in description, have the same foundation that the tipover incident is decided by the sign of the gravity moment and the extern force moment acting on the center of the mass from the support polygon. As the track vehicle has two kinds of tipover, the support polygon's sideline tipover and the support polygon's corner point tipover, we have proposed the stability pyramid technique with the consideration of both situations. In practical application, the manipulation force, the momentum, the acceleration, and the terrain disturbance are not clear. So the shape shifting robot has to adopt the right configuration to avoid the mission failure by tipover incident.

3.1 Define the stability pyramid

In solid geometry science, pyramid is defined as a solid figure with a polygonal base and triangular faces that meet at a common point. The polygon is the base face. And the rest triangular faces are side faces. The adjacent side faces' common border is the side edge. The common point is the pyramid's peak. According to the pyramid's geometry features, we define the stability pyramid in a manner similar to the one proposed in Ref.[2] and Ref.[13]. The pyramid's peak denotes the robot's gravity center. The peak's position in the world coordinate is given by

$$x_{com} = \sum_{i=1}^{k}(m_i x_i) \Big/ \sum_{i=1}^{k} m_i \quad (1)$$

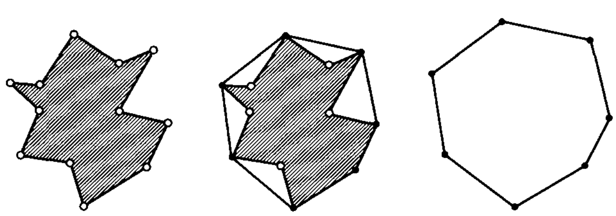
$$y_{com} = \sum_{i=1}^{k}(m_i y_i) \Big/ \sum_{i=1}^{k} m_i \quad (2)$$

$$z_{com} = \sum_{i=1}^{k}(m_i z_i) \Big/ \sum_{i=1}^{k} m_i \quad (3)$$

where x_i , y_i and z_i denote coordinates of the center of mass for the i-module, m_i is the module mass, and k is the number of parts.

While in the modular robot's local coordinate system, the pyramid's peak is set to be the origin. The centers of the modules' mass are given in relative position way. For the wheel type robot and leg type robot, the pyramid's bottom corner points are the outer contact points. For the track type robot, extern track sideline's ends are the corner points. Stability pyramid's convex polygon is jointed by the bottom corner points. Since the shape shifting module robot can change its shape, the bottom corner points change their relative positions and the stability pyramid changes accordingly.

In this approach, Graham algorithm, also called Graham scan, has been used to decide the convex hull of the stability pyramid's bottom side. Given a full set of ground contact points of the mobile robot, Graham algorithm computes their convex hull efficiently as the example in Fig.3.



(a) Simple polygon (b) Convex hull of polygon (c) Convex polygon

Fig.3 Example of Graham algorithm

The algorithm works in three phases is shown as follows[14-15].

(1) Find an extreme point. This point will be the pivot, is guaranteed to be on the hull, and is chosen to be the point with largest y coordinate.

(2) Sort the points in order of increasing angle about the pivot. We end up with a star-shaped polygon (one in which one special point, in this case the pivot can "see" the whole polygon).

(3) Build the hull, by marching around the star-shaped poly, adding edges when we make a left turn, and back-tracking when we make a right turn.

As shown in Fig.4, contact points p_i (i=1~n) in the convex hull are numbered in ascending order in a clockwise manner when viewed from above. The vector $\boldsymbol{p}_i$ begins from the pyramid's peak and ends at contact point p_i. The lines joining the corner points are referred to as tipover sidelines. They are given by

$$\boldsymbol{a}_i = \boldsymbol{p}_{i+1} - \boldsymbol{p}_i \quad i = 1, 2, \cdots, n-1 \quad (4)$$

$$\boldsymbol{a}_n = \boldsymbol{p}_1 - \boldsymbol{p}_n \quad (5)$$

The tipover sideline normals that intersecting the center of mass can be described as

$$\boldsymbol{l}_i = (1 - \hat{\boldsymbol{a}}_i \hat{\boldsymbol{a}}_i^{\mathrm{T}})\boldsymbol{p}_{i+1} \quad (6)$$

where $\hat{\boldsymbol{a}}_i = \boldsymbol{a}_i / \|\boldsymbol{a}_i\|$

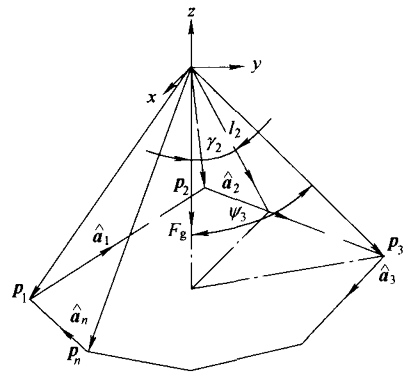


Fig.4 Stability pyramid

Sideline tipover stability angles can then be computed for each tipover sideline as the angle between the gravitational force vector $\boldsymbol{F}_g$ and the axis normal l_i

$$\gamma_i = \sigma_i \arccos(\hat{\boldsymbol{F}}_g \cdot \hat{\boldsymbol{l}}_i) \quad i = 1, 2, \cdots, n \quad (7)$$

with

$$\sigma_i = \begin{cases} +1 & (\hat{\boldsymbol{l}}_i \times \hat{\boldsymbol{F}}_g) \cdot \hat{\boldsymbol{a}}_i < 0 \\ -1 & \text{Otherwise} \end{cases} \quad (8)$$

where $\hat{\boldsymbol{l}}_i = \boldsymbol{l}_i / \|\boldsymbol{l}_i\|$ and $\hat{\boldsymbol{F}}_g = \boldsymbol{F}_g / \|\boldsymbol{F}_g\|$.

For the corner point tipover incident, corner point tipover stability angles can be computed in the same manner as

$$\psi_i = \varepsilon_i \arccos(\hat{\boldsymbol{F}}_g \cdot \hat{\boldsymbol{p}}_i) \quad i = 1, 2, \cdots, n \quad (9)$$

with

$$15\, \varepsilon_i = \begin{cases} +1 & (\hat{\boldsymbol{l}}_i \times \hat{\boldsymbol{F}}_g) \cdot \hat{\boldsymbol{a}}_i < 0 \text{ or } (\hat{\boldsymbol{l}}_{i+1} \times \hat{\boldsymbol{F}}_g) \cdot \hat{\boldsymbol{a}}_{i+1} < 0 \\ -1 & \text{Otherwise} \end{cases} \quad (10)$$

where $\hat{\boldsymbol{p}}_i = \boldsymbol{p}_i / \|\boldsymbol{p}_i\|$

When we globally consider the tipover stability, stability angle is given by

$$\theta_i = \min(\gamma_{i-1}, \psi_i, \gamma_i) \quad i = 2, \cdots, n \quad (11)$$

where $\theta_1 = \min(\gamma_n, \psi_1, \gamma_1)$

The overall vehicle stability angle is defined as the minimum of stability angles

$$\alpha = \min \theta_i \quad i = 1, 2, \cdots, n \quad (12)$$

When $\alpha < 0$, tipover instability will occur. Thus, the goal of stability-based kinematics reconfigurability is to maintain a large value of α .

Note that those applied forces, such as those exerted by impact, acceleration or deceleration, and obstacle interference, can be accounted in the stability computation. Given an applied force $\boldsymbol{F}_a$ by the manipulator on its environment, the resultant force along a tipover sideline is computed as

$$\boldsymbol{F}_i = (1 - \hat{\boldsymbol{a}}_i \hat{\boldsymbol{a}}_i^{\mathrm{T}})(\boldsymbol{F}_g + \boldsymbol{F}_a) \quad (13)$$

If there is a moment $\boldsymbol{M}_a$ associated with $\boldsymbol{F}_a$, the net force about a tipover sideline is computed by

$$\boldsymbol{F}_i^* = \boldsymbol{F}_i + \frac{\hat{\boldsymbol{l}}_i \times (\hat{\boldsymbol{a}}_i \hat{\boldsymbol{a}}_i^{\mathrm{T}})\boldsymbol{M}_a}{\|\boldsymbol{l}_i\|} \quad (14)$$

The minimum stability angle in static or dynamic case can be computed in the above way. For a mobile system, the minimum tipover energy is also needed to be considered in dynamic case.

That is, the minimum energy $E_{\min}$ needed for sideline tipover or corner point tipover can be given by

$$E_{\min} = F_{\mathrm{eq}} h(1-\cos\alpha)/\cos\alpha \qquad (15)$$

while h is the stability pyramid height, F_{eq} denotes the equivalent force on the center of mass. Eq.(15) can be simplified by the non-dimension representation

$$e = (1-\cos\alpha)/\cos\alpha \qquad (16)$$

3.2 Tipover index

We propose a comprehensive stability index, tipover index, to optimize the robot's configuration for maximum stability by using the technique mentioned above. The tipover index can be computed by

$$\phi = \max\left(\frac{\lambda_i}{\gamma_i} + \frac{\rho_i}{\psi_i} + \zeta_i\sqrt{\frac{\cos\theta_i}{1-\cos\theta_i}}\right) \quad i = 1,\ 2,\ \cdots,\ n \qquad (17)$$

where θ_i ——Nominal stability angle given by Eq.(11)

λ_i ——Sideline tipover index weight decided by the static or dynamic influence and the angle between the sideline and motion direction. If the sideline is close to the motion direction, the weight increases, otherwise it decreases accordingly. The reason is that when the robot is in motion, it will be more available to tipover in the motion direction for extern influence such as obstacle and the terrain change

ρ_i —— Corner point tipover index weight decided by the distance between the center of mass and the corner point. When the robot is moving over uneven terrain or under extern force action, the robot is easily to get tipover at the closest corner point. This weight should increase in such a case

ζ_i —— Energy weight of tipover index defined for safety under dynamic case and the minimum tipover energy. This branch globally considers the motion direction, the inertia, the terrain condition, and extern force. It is decided by the practical situation

Usually, values of λ, ρ and ζ are chosen from 0 to 1.0 according to the situation. In the same manner, the mean tipover index can be given by

$$\bar{\phi} = \frac{1}{n}\sum_{i=1}^{n}\left(\frac{\lambda_i}{\gamma_i} + \frac{\rho_i}{\psi_i} + \zeta_i\sqrt{\frac{\cos\theta_i}{1-\cos\theta_i}}\right) \qquad (18)$$

In general, both the tipover index ϕ and the mean tipover index $\bar{\phi}$ represent mobile robot's tipover dangerous degree in motion. The former relates to the most dangerous situation and the later relates to the system dangerous situation respectively. The larger the values are, the more dangerous the system will be, otherwise, the system will be more stable and safe.

3.3 Equivalent representation of the stability disturbance

From the stability pyramid's definition, the influence of the terrain condition and the extern force on the robot are generalized as the equivalent force's value and direction. It can be seen from Eq.(17) that force direction is the key factor.

The mobile robot in motion is influenced by the instability factors such as terrain change, the unbalanced ground force, and the extern force. It will change its configuration unavoidably such as in pitch, roll and yaw ways. To a certain configuration, the mobile robot's stability pyramid size is fixed but the pyramid's space position and the equivalent force F_g^*'s direction is changeable. Variable F_g' is defined to comprehensively consider the F_g^*'s direction and the terrain condition. As shown in Fig.5, comprehensive force's direction is consistent with the negative direction of z axis. So all the disturbance factors can be reflected by stability pyramid's pitch, roll and yaw accordingly.

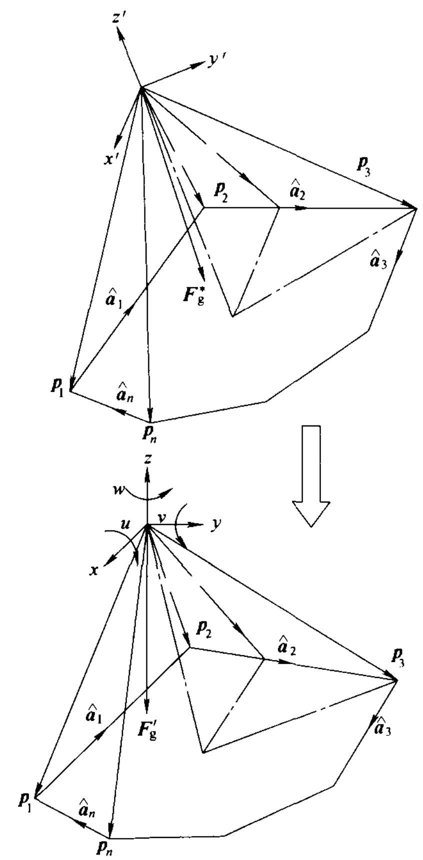


Fig.5　Equivalent representation of the stability disturbance

During disturbance, we assume that the robot has configuration changes such as roll of x axis with angle u, pitch of y axis with angle v, and yaw of z axis with angle w in sequence. Then the stability pyramid's corner points change accordingly. The position transformation matrix is given by

$$\boldsymbol{T}_{\mathrm{RPY}} = \begin{bmatrix} \boldsymbol{Q}_{\mathrm{RPY}} & \boldsymbol{P}_0' \\ 0 & 1 \end{bmatrix} \qquad (19)$$

where $\boldsymbol{R}_0' = [0\ 0\ 0]^{\mathrm{T}}$ and $\boldsymbol{Q}_{\mathrm{RPY}} = \boldsymbol{Q}_z(w)\boldsymbol{Q}_y(v)\boldsymbol{Q}_x(u)$, so

$$\boldsymbol{Q}_{\mathrm{RPY}} = \begin{bmatrix} cw\cdot cv & cw\cdot sv\cdot su - sw\cdot cu & cw\cdot sv\cdot cu + sw\cdot su \\ sw\cdot cv & sw\cdot sv\cdot su + cw\cdot cu & sw\cdot sv\cdot cu - cw\cdot cu \\ -sv & cv\cdot su & cv\cdot cu \end{bmatrix} \qquad (20)$$

where $cv = \cos v$ and $su = \sin u$. They are presented in a simplified way, and so do the rest ones.

Thus, the robot stability can be analyzed by recalculating the stability corner points of the stability pyramid.

4 ANALYZE TIPOVER STABILITY OF THREE SYMMETRY CONFIGURATIONS

4.1 Three configurations' static stability pyramid

The symmetry configurations in Fig.2 have been paid special attention for their controllability and stability. We define that x positive direction is the track moving direction, z positive direction denotes the height direction, and y positive direction represents the right side of moving direction. The three-module shape shifting robot has three symmetry configurations, line type in

Fig.2a, triangle type in Fig.2e, and row type in Fig.2h. The line type is approximately symmetric. We assume that each module has the same mass and the density is uniform. Let the coordinate zero denote the center of the mass. According to the robot's physical dimension in Fig.2, the corner point positions of the static stability pyramid are given in following Table.

Table Specifications of three static stability pyramids

Cofiguration	Corner point				Tipover index weight		
	p	x/mm	y/mm	z/mm	λ	ρ	ζ
Line type	1	524	32.67	-50	1.0	1.0	1.0
	2	-524	-49.33	-50	0.5	1.0	0.5
	3	524	-49.33	-50	1.0	1.0	1.0
	4	524	32.67	-50	0.5	1.0	0.5
	5	138	59.17	-50	0.5	0.5	0.5
	6	-138	59.17	-50	0.5	0.5	0.5
Triangle type	1	-230	186.5	-50	1.0	1.0	1.0
	2	-230	-186.5	-50	0.5	1.0	0.5
	3	46	-186.5	-50	0.5	0.5	0.5
	4	322	-41.0	-50	1.0	1.0	1.0
	5	322	41.0	-50	0.5	1.0	0.5
	6	46	186.5	-50	0.5	0.5	0.5
Row type	1	-138	190	-50	1.0	1.0	1.0
	2	-138	-190	-50	0.5	1.0	0.5
	3	138	-190	-50	1.0	1.0	1.0
	4	138	190	-50	0.5	1.0	0.5

4.2 Simulation of the tipover stability disturbance

It is assumed that the terrain slope degree is lower than $\pi/4$ and the yaw angle is less than $\pi/4$.The three stability disturbances, as mentioned before, can be defined as follows respectively

$$u(t)=\pi/2[\delta_u(t)-0.5] \tag{21}$$

$$v(t)=\pi/2[\delta_v(t)-0.5] \tag{22}$$

$$w(t)=\pi/2[\delta_w(t)-0.5] \tag{23}$$

where $\delta_u(t)$, $\delta_v(t)$ and $\delta_w(t)$, though being different, are random number from zero to one.

We mainly discuss three kinds of symmetry configuration's tipover stability under five disturbance of the stability pyramid: ①Roll disturbance. ②Pitch disturbance. ③Roll and yaw disturbance. ④Pitch and yaw disturbance. ⑤Row, pitch and yaw disturbance.

In the above situations, the tipover index weights λ, ρ and ζ are chosen to be 0.5 or 1.0 according to their definitions as shown in Table. The simulation time is 2 s and in which 11 sampling data are selected. The tipover index and the mean tipover index are calculated from Eq.(4) to Eq.(23), and especially from Eq.(17) and Eq.(18). The combine disturbance simulation results are shown in Fig.6.

It can be seen from the simulations that the triangle type has the best tipover stability, the second one is the row type and the line type is the last one when under various stability disturbance.

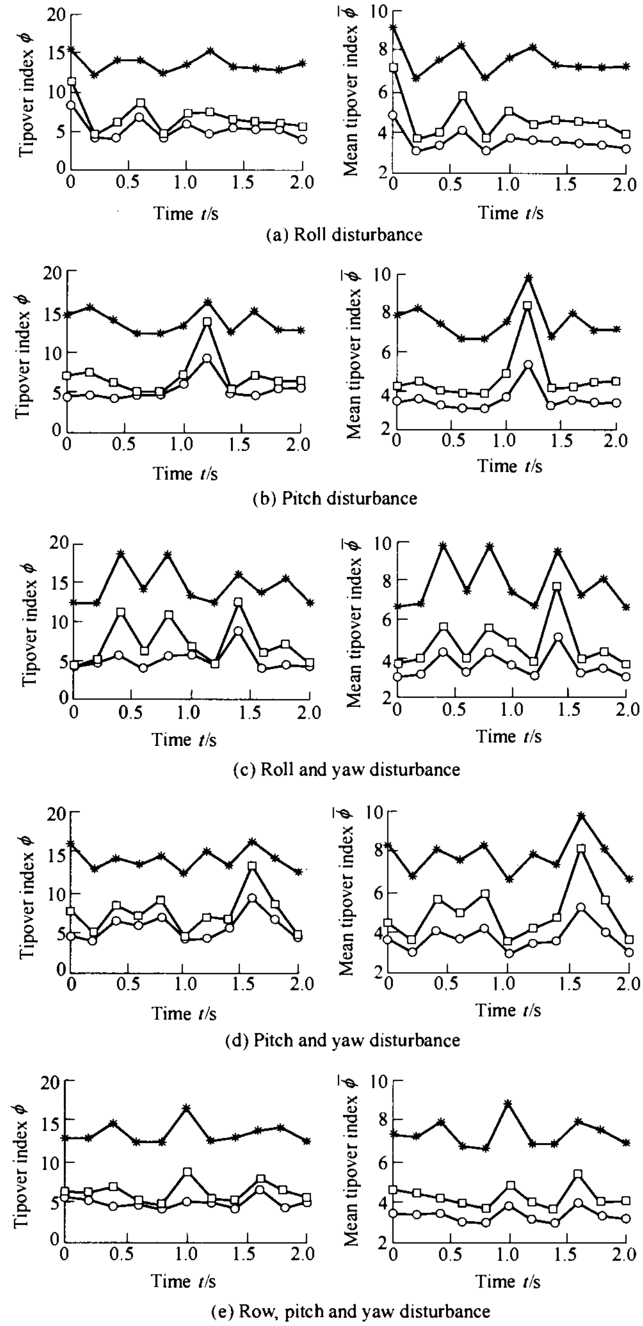


Fig.6 Stability disturbance simulation

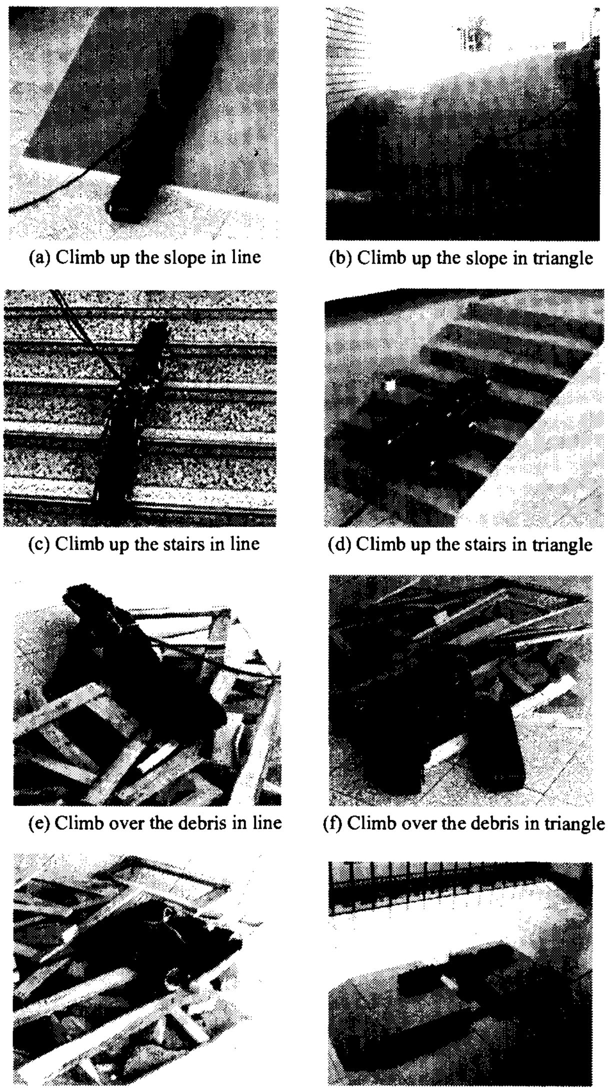
—*— Line type —○— Triangle type —□— Row type

5 EXPERIMENT UNDER UNSTRUCTURED ENVIRONMENT

Experiment has been made on the shape shifting robot to test its mobility and stability under unstructured environments. Experimental result shows that three symmetry configurations have their peculiar advantages and shortages respectively. The line type has the best mobility as shown in Fig.7a, Fig.7c, Fig.7e, and Fig.7h, while it has the worst stability for its easily lateral tipover as shown in Fig.7c. In the wood and brick piled debris, the row type has limited mobility but excellent stability for its compact structure as shown in Fig.7g. The triangle type has the best tipover stability as shown in Fig.7f and excellent mobility as shown in Fig.7b and in Fig.7d.

6 CONCLUSIONS

The novel shape shifting modular robot can change its configuration to adapt the environment and improve its tipover stability. After the factors and the countermeasures of mobile robot's tipover problem have been analyzed in detail, stability pyramid and tipover stability index have been proposed to globally determinate the mobile robot's static stability and dynamic stability. And the shape shifting modular robot's stability has been tested by this technique under the combined disturbance of pitch, roll, and yaw in simulation. At last, experiments on these three symmetry configurations have been made under unstructured environments. The environment experiment has the same result as that of the simulation that the triangle type has the best stability. Both simulation and experiment have provided a valid reference for the reconfigurable robot's practical mission. Since the current platform has only limited utilities for its simple control technique, it is important to improve its control system, sensor system and communicating system in the near future.



(a) Climb up the slope in line (b) Climb up the slope in triangle

(c) Climb up the stairs in line (d) Climb up the stairs in triangle

(e) Climb over the debris in line (f) Climb over the debris in triangle

(g) Climb over the debris in row (h) Pass the ditch in line

Fig.7 Experiment under unstructured environment

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Biographical notes

LIU Jinguo was born in 1978. He received his BS degree and MS degree in School of Mechanical Engineering, Anshan University of Science and Technology, China, in 2000 and in 2003, respectively. He is currently a PhD candidate and an assistant professor in Robotics Laboratory, Shenyang Institute of Automation, Chinese Academy of Sciences, China. His research interests include novel robot design and theory, reconfigurable modular robot, search and rescue robot, planetary rover, and biomimetics. He has published over ten papers and was awarded the Best Paper Award from the 2005 IEEE International Conference on Robotics and Biomimetics and the Excellent Paper Award from the 2005 SIA May 4th Youth Scientific Conference.
Tel: +86-24-23970079; Fax: +86-24-23970021; E-mail: liujinguo@sia.cn.

WANG Yuechao was born in 1960. He received his PhD degree in School of Mechatronic Engineering, Harbin Institute of Technology, China, in 1999. Since 1987, he has been in Shenyang Institute of Automation, Chinese Academy of Sciences. He is currently a professor and the director in Shenyang Institute of Automation, Chinese Academy of Sciences, China. His current research interests include robot control, multi-robot systems, and micro-nano manipulations.

MA Shugen was born in 1963. He received his PhD degree in School of Mechanical Engineering Science, Tokyo Institute of Technology, Japan, in 1991. Now he is an associate professor in Department of Systems Engineering, Ibaraki University, Japan. And he is also a professor in Shenyang Institute of Automation, Chinese Academy of Sciences, China. His research interest is in the design and control theory of new types of robots, the mechanism and control of redundant manipulators, and biomimetics.

LI Bin was born in 1963. He received his MS degree in School of Medical Science, China Medical University, China, in 1988. He is currently a professor in Shenyang Institute of Automation, Chinese Academy of Sciences, China. His current research interests include robot control, biomimetics, and reconfigurable robot.