The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

Design and Motion Analysis of Tetrahedral Rolling robot

Lige Zhang, Shusheng Bi, Yueri Cai

Abstract—**A novel robot mechanism-tetrahedral rolling robot is introduced in the paper. The robot comprises of six extension struts and four node flats. When the COG of tetrahedron exceeds the stability region, the robot will roll. The structure of the tetrahedral rolling robot is described. Designing method of the robot is given, and it is proved correct and feasible through experiment. Kinematic model in different motion phase is analyzed in the paper, and the rolling critical condition is formulated. The effectiveness of the method is testified through simulation. The study of the paper will provide important reference for the dynamic analysis, optimization design and control of the tetrahedral rolling robot.**

I. Introduction

Tetrahedral robot is a kind of variable geometry truss mechanisms (VGTM), and this conception is originally presented by Hamlin and Sanderson[1][2]. The movement of tetrahedral robot is realized through length change of the truss, and it is a novel mechanism with multi-DOF and multi-loop[3][4]. The motion of extension strut arouses the shape change of tetrahedron, and when the center of gravity (COG) of the tetrahedron exceeds the stable region, the robot will roll. Combination and dismantlement of different tetrahedron constitute fourfold or even twelve-fold tetrahedral robot system. With the increase of robot layer, the degree of freedom (DOF) of robot will increase accordingly, and then more complex motion will be realized [5][6].

Tetrahedral robot has the following advantage comparing with the traditional mobile robot: (1) Motion stability. Symmetrical structure ensures the stability of the robot, and the tumbling problem is avoided; (2) Motion agility. It can adapt to different environment through changing the motion pattern, such as stepping over obstacle, getting across tunnel, striding canal and so on. (3) Simple structure. Modularization is easy to realize, and then polyhedral robot system can be constituted. In a word, the tetrahedral robot has expansive application foreground in daily life, military affairs and outer space exploration.

Presently, little research is about tetrahedral rolling robot.

Manuscript received March 10, 2010. This work was supported in part by Program for New Century Excellent Talents in University (NCET-06-0165).

Lige Zhang is with the Robotics Institute, Beihang University. 100191 China(e-mail: zhanglige@buaa.edu.cn)

Shusheng Bi is with the Robotics Institute, Beihang University. 100191 China (corresponding author , phone: 86-10-82338926; e-mail: ssbi@buaa.edu.cn)

Yueri Cai is with the Robotics Institute, Beihang University. 100191 China(e-mail: cyr_buaa@126.com)

NASA took the lead in the developing of tetrahedral rolling robot, and there are three generations of robot now [5-7]. First generation can realize continuous rolling, but the second and the third generation is so complex that they can not move, and now the control method is in research. Reference[8] describes the design method of a simple tetrahedral rolling robot, and the rolling feasibility is verified. Zhu lei [9] of Beijing Jiaotong University presented a rolling mobile robot based on four-bar mechanism, and the kinematic and dynamic analysis is given. The robot has simple structure, convenient control, strong resist-impact ability and good symmetry. However, this mechanism is far different from tetrahedral robot. The former is an over-constraint six-bar mechanism, and the latter is a kind of variable geometry truss mechanisms. Motion pattern and analysis method is both different.

Since the special motion mode of the tetrahedral rolling robot, the kinematic and dynamic analysis method is different from traditional robot. Although NASA developed the first the tetrahedral rolling robot, theoretical analysis about it is rarely seen. So, a novel tetrahedral rolling robot is designed and the kinematic model is analyzed in the paper. The rationality of the mechanism and kinematic analysis method is verified through simulation and experiment. Dynamic analysis of tetrahedral rolling robot will be discussed in the next work.

II. Mechanism Design of Tetrahedral Rolling Robot

A. *Structure introduction*

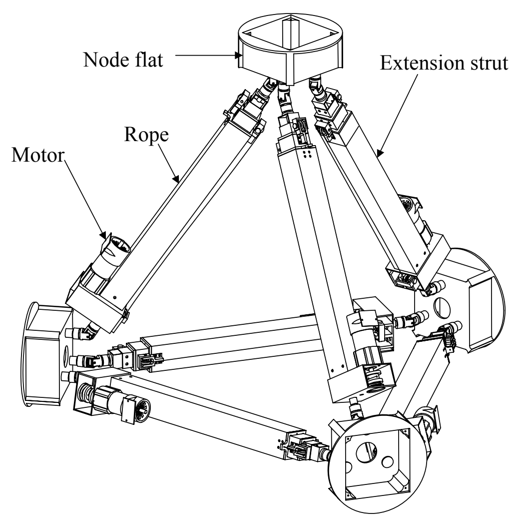


Fig.1. Mechanism sketch map of the tetrahedral rolling robot

The mechanism sketch map of the tetrahedral rolling robot is shown in figure 1. The robot comprises of six extension struts and four node flats, and the initial length of them is the same. Six extension struts and four node flats are connected by hook joint. Different motion pattern of the tetrahedral rolling robot is achieved through adjusting the number and length of the extension strut.

B. Transmission mechanism

The design of transmission mechanism need not only consider the input and output form, but also the characteristic of the tetrahedral rolling robot, then the right type of transmission mechanism can be chosen. The extension mechanism of tetrahedral rolling robot has the following characteristic:

(1) Large extension journey and extension ratio. In order to make COG exceed the stability region and then roll, large extension ratio is needed, and it must greater than 2:1.

(2) Small fixing space. Because the nesting structure is adopted in the extension strut, and structure parts need to be set in it, the fixing space is very small whether in the strut or out. This restricts the choosing of transmission mechanism.

(3) Multilevel extension. Two-level extension is far from enough in order to reach the ratio 2:1. Oriented ability of the extension mechanism lies on the length of oriented surface. On the other hand, the fixed base of motor and the joint occupy both ends of the strut. So the extended length of inside bar is limited (about 70%——80% of the full length). In the paper, three-level extension strut is designed, and the first tube is fixed, so there are two relatively motion part.

Synchronous extension is adopted according to the above characteristic. Each extension strut is driven by a motor, and rope transmission mechanism is used. Large and to-and-fro extension journey is obtained through motor's positive and reverse rotation. The second bar is driven directly by the motor, and the third bar is driven by the second bar's movement. Determinate velocity relation and ratio can be educed.

The motor must press close to its extension strut in order to avoid collision with other strut or the floor, so motor axis needs parallel with the axis of the extension strut. After analysis by synthesis, the transmission mechanism is designed, and the sketch map is shown in figure 2.

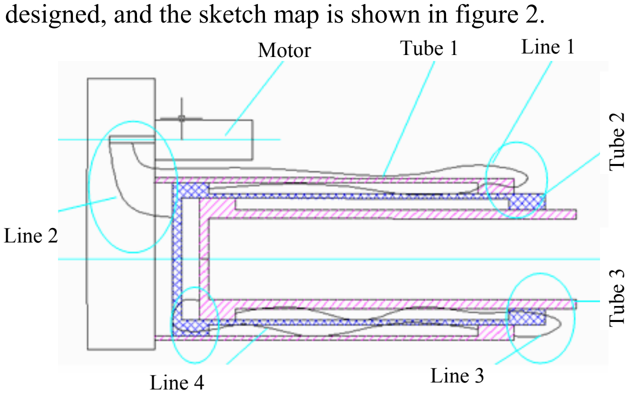


Fig.2. Sketch map of transmission mechanism

C. Oriented mechanism

1) Design of the tube

To-and-fro extension of the mechanism needs only a degree of freedom and other five degrees of freedom must be limited. Over or lack of constraint will affect the right motion of the strut. Tube of large length/diameter ratio can satisfy the demand of nesting structure form. The machining of this type of tube is very difficult and the precision can not be ensured. In the paper, quadrate profiled bar is adopted, and the processing cost is reduced greatly. Quadrate profiled bar avoids the relative rotation between two tubes, and it has great intensity and high wearable ability. On the other hand, the thickness of profiled is very thin, and the weight of the robot is reduced also. The sketch map of the three tube is shown in Fig.3.

2) Design of the oriented mechanism

Oriented sheath is designed to realize the glide between the wall of outside tube and the ektexine of inside tube, as in figure 3. Oriented sheath 1 is fixed on the head of tube 1, and can glide along the ektexine of tube 2, and this is the first oriented point. Oriented sheath 2 is fixed on the end of tube 2, and can glide along the wall of tube 1, and this is the second oriented point. One extension strut has four oriented sheaths aggregately. Similarly, the other two oriented point is obtained. The practical oriented length is the distance between the two points and it is alterable. The least oriented distance lies on the length summation of the two oriented sheath. Nylon is used to machine the oriented sheath, and it is wearable and has lower friction coefficient.

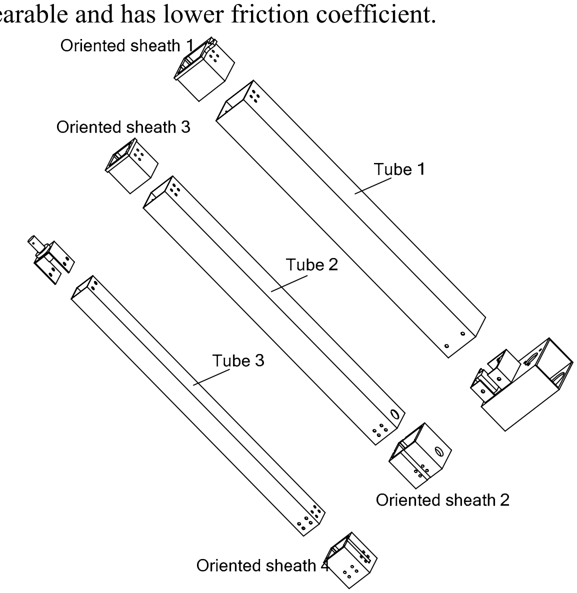


Fig.3. Sketch map of oriented mechanism

D. Exchange-direction mechanism

The drive of the rope is unilateral, so it can only produce the pull toward the motor. For generating the pull err from the motor, exchange-direction mechanism is needed. As shown in figure 4, two reverse driven force of the second extension strut will be generated if the direction of deferent rope is changed by 270° and 90° after the motor. Similarly, two reverse driven force of the third extension strut will be generated if the direction of deferent rope is changed by 180° after the motor. So, the exchange-direction mechanism is classified into two types: 180° and 90° exchange-direction. The combination of the two types can satisfy the exchange-direction demand.

The exchange-direction mechanism is designed according to the above characteristic. The left is the 180° exchange-direction mechanism, and it is fixed on the head and end of the second tube, and the head of the third tube. The right is the 180° exchange-direction mechanism, and it is fixed on the fan-out of the motor.

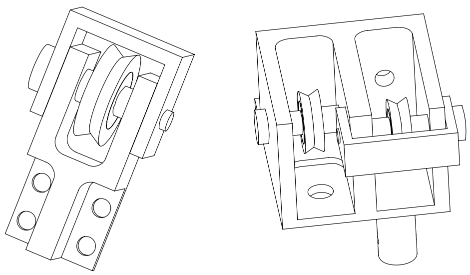


Fig.4. Sketch map of exchange-direction mechanism

E. Joint and node flat mechanism

Joint is the mechanism connected the extension strut and nod flat. The node's pose is changing with the motion of the strut, and the relative pose between joint and node is changing too. So, the node and strut should be connected by some kind of joint with some flexibility. Though analysis on the connecting part, it can be seen that extension strut can not rotate around its axis for the exist of oriented mechanism, so gimbal with two DOF is chosen as the joint in order to satisfy the demands of strut's position and pose changes. The node with gimbal joint mechanism is shown in figure 5.

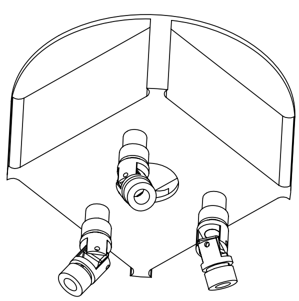


Fig.5. Sketch map of node mechanism

III. KINEMATIC ANALYSIS

A. Kinematic analysis before falling

1) Rolling critical condition

The tetrahedral rolling robot has different kinds of motion pattern, and one pattern is chosen to analyze: DB and DC retain the original length, $l_{DC} = l_{DB} = l_0$; the length of AD after extension is $l_{AD} = l_1$; the length of BC after extension is $l_{BC} = l_2$; AB and AC extend at the same speed, length after extension is $l_{AB} = l_{AC} = l_3$. The shape of tetrahedron will transform symmetrically taking the △ADM as the mirror, and to some degree, the COG of tetrahedron exceeds the stability region and roll around roll axis BC. The process of movement is shown in figure 6.

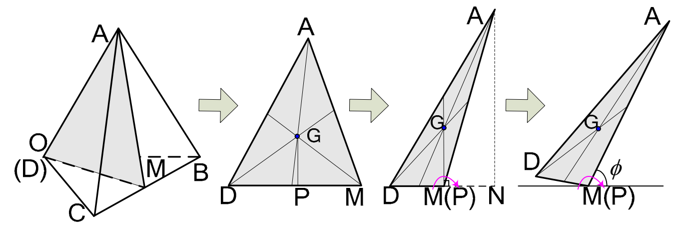


Fig.6. Falling process of tetrahedron

Supposing each component' mass of the tetrahedral rolling robot is distributed equably, then the contacting surface between the tetrahedron and the floor is the stability region. It can be sure that when the next condition is satisfied, the tetrahedron will fall, and that is: The projection of the center of △ADM (COG of tetrahedron) is superposed on M or fall on the prolongable line of DM ($GP \perp DM$). M is the center of BC. Here the length of different strut should satisfy the following condition:

$$\begin{cases} l_1^2 + l_2^2 - l_3^2 \geq 3l_0^2 \\ l_1, l_2, l_3 \leq 2l_0 \end{cases} \tag{1}$$

Equation (1) is the rolling critical condition.

If the four struts (AB, AC, AD, BC) extend at the same speed, that is a special case, and the rolling critical condition is:

$$2l_0 \geq l \geq \sqrt{3} l_0 \tag{2}$$

Note：l is the strut length after extension.

2) Jacobi Matrix

According to the mechanism characteristic and motion pattern of the tetrahedral rolling robot, the coordinates is established as fig.7.

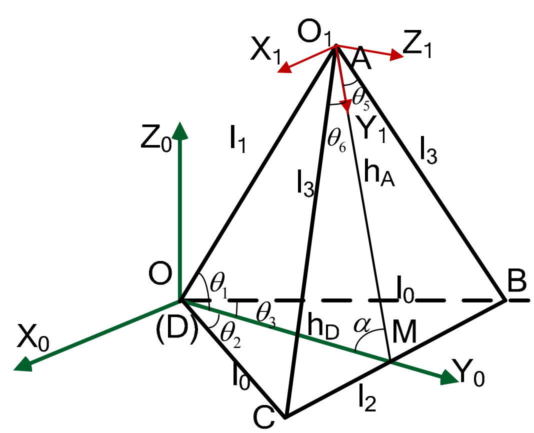


Fig.7. Coordinates of the tetrahedral rolling robot

Inertial frame {O_0} and peak coordinates {O_1} is shown. Axis Z_1 of peak coordinates {O_1} is perpendicular with △ABC, and Axis Y_1 is superposed on midline AM. Axis X_1 can be deduced by the right hand rule. Thus it can be seen, angle α between Z_1 and Z_0 is the dihedral angle between plane ABC and plane BCD.

The transform matrix from peak coordinates{ O_1 }to inertial frame { O_0 } is

$$ {}^{0}_{1}T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha & \Delta y \\ 0 & -\sin\alpha & \cos\alpha & \Delta z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{3} $$

Where

$$ \Delta y = \frac{l_1^2 + h_D^{\ 2} - h_A^{\ 2}}{2h_D} $$

$$ \Delta z = \frac{\sqrt{2l_1^2 h_D^{\ 2} + 2l_1^2 h_A^{\ 2} + 2h_D^{\ 2} h_A^{\ 2} - l_1^4 - h_D^{\ 4} - h_A^{\ 4}}}{2h_D} $$

$$ \cos\alpha = \frac{h_A^{\ 2} + h_D^{\ 2} - l_1^2}{2h_A h_D} $$

$$ h_A = \sqrt{l_3^{\ 2} - \frac{1}{4} l_2^{\ 2}}, \quad h_D = \sqrt{l_0^{\ 2} - \frac{1}{4} l_2^{\ 2}} $$

Supposing that the position and the pose of component i 's center of the tetrahedral rolling robot is expressed as Ω_i, Φ_i, and Ω_i, Φ_i is the non-linear function of joint variable l, $l = (l_1, l_2, l_3)^T$. The equation is

$$ \Omega_i = f_\Omega(l_1, l_2, l_3) \tag{4} $$

$$ \Phi_i = f_\Phi(l_1, l_2, l_3) \tag{5} $$

The first differential coefficient of them is the velocity v_i and angle velocity ω_i of component i . The equation is

$$ v_i = \dot{\Omega}_i = \begin{bmatrix} \frac{\partial f_\Omega}{\partial l_1} & \frac{\partial f_\Omega}{\partial l_2} & \frac{\partial f_\Omega}{\partial l_3} \end{bmatrix} \begin{bmatrix} \dot{l}_1 & \dot{l}_2 & \dot{l}_3 \end{bmatrix}^T = J_{T,i}(l,t)\dot{l}(t) \tag{6} $$

$$ \omega_i = \dot{\Phi}_i = \begin{bmatrix} \frac{\partial f_\Phi}{\partial l_1} & \frac{\partial f_\Phi}{\partial l_2} & \frac{\partial f_\Phi}{\partial l_3} \end{bmatrix} \begin{bmatrix} \dot{l}_1 & \dot{l}_2 & \dot{l}_3 \end{bmatrix}^T = J_{R,i}(l,t)\dot{l}(t) \tag{7} $$

The second differential coefficient of them is the acceleration a_i and angle acceleration ε_i of component i . The equation is

$$ a_A = \dot{J}_{T,i}\dot{l}(t) + J_{T,i}\ddot{l}(t) \tag{8} $$

$$ \varepsilon_i = \dot{J}_{R,i}\dot{l}(t) + J_{R,i}\ddot{l}(t) \tag{9} $$

$J_{T,i}$ $J_{T,I}$ is the translational Jacobi matrix, and $J_{R,i}$ is the rotational matrix.

The kinematic analysis method of the restoring phase can refer to the phase before falling.

B. Falling phase

The process of beginning fall of the tetrahedral robot is shown in fig.6. Supposing that the vector of BC is

$$ t = \begin{bmatrix} t_x & t_y & t_z \end{bmatrix}^T = \overline{n_B n_C} $$

The falling path of node A and node D is expressed

$$ n_i^d = n_i^0 + R_t\left(n_i^0 - n_t\right), \text{ i=A、D}, \; n_t = \frac{n_B + n_C}{2} $$

Rotational matrix

$$ R_t = \begin{bmatrix} t_x t_x \upsilon\phi + c\phi & t_x t_y \upsilon\phi - t_z s\phi & t_x t_z \upsilon\phi + t_y s\phi \\ t_x t_y \upsilon\phi + t_z s\phi & t_y t_y \upsilon\phi + c\phi & t_y t_z \upsilon\phi - t_x s\phi \\ t_x t_y \upsilon\phi - t_y s\phi & t_y t_z \upsilon\phi + t_x s\phi & t_z t_z \upsilon\phi + c\phi \end{bmatrix} \tag{10} $$

Where

$c\phi = \cos\phi$, $s\phi = \sin\phi$, $\upsilon\phi = 1 - \cos\phi$, n_i^0 is the original position of node i, n_i^d is the desired position of node i.

Different walking path can be planned through choosing different roll axis. It is seen that the tetrahedral rolling robot could change its walking direction anytime, so it has great agility.

C. Touchdown phase

In this phase, the tetrahedral rolling robot is simplified as a rigid body, so the mass of the whole mechanism focus on a point, as shown in figure 8. Supposing that the reaction force is R, Newton-uler equation is

$$ R = m_C\left(\ddot{n}_C + g\right) \tag{11} $$

$$ \vec{R} \times \vec{r} = \overrightarrow{I_C}\alpha_C + w_C \times \overrightarrow{I_C} w_C \tag{12} $$

Note: r is the position vector from center of mass (m_C) to n_A .

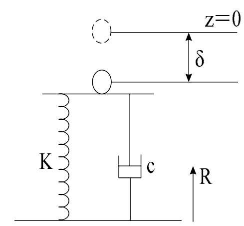


Fig.8. Dynamic model of touchdown phase

The touchdown process of the tetrahedral rolling robot is regarded as a spring-damp system [10][11], as shown in figure 8. So there is

$$ R = k\delta + c\dot{n} = \begin{bmatrix} k_i^x & 0 & 0 \\ 0 & k_i^y & 0 \\ 0 & 0 & k_i^z \end{bmatrix} \begin{bmatrix} \delta_i^x \\ \delta_i^y \\ \delta_i^z \end{bmatrix} + \begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & c_z \end{bmatrix} \begin{bmatrix} \dot{\delta}_i^x \\ \dot{\delta}_i^y \\ \dot{\delta}_i^z \end{bmatrix} \tag{13} $$

Where, K is the spring matrix, C is the damping Matrix, ∂_i is the micro displacement at the touchdown time. Reaction force is proportional to displacement ∂_i and velocity $\dot{\partial}_i$.

IV. SIMULATION AND EXPERIMENT

The simulation model is built for validating the effectiveness of the kinematic analysis method. The parameter of the model is as follows: original length of extension strut l_0 =1000mm; fixed component of the extension strut l_d =900mm; active component of the extension strut l_u =960mm. Initial velocity of the strut is zero, and the four strut (AB, AC, AD, BC) extend at the same speed. The motion rule is as follows: 0~2s, accelerate equably and extend, acceleration a=150mm/s^2; 2s~3s, extend with even velocity; 3s~4s, decelerate equably and extend, acceleration a=-300mm/s^2; 4~t_e, free fall.

Simulation result indicates that the tetrahedral rolling robot can realize rolling according to the above motion pattern, as shown in figure 9. At the moment of t=4.0s, tetrahedral reaches the rolling critical condition, and the strut length is about 1715mm. This is almost consistent with the rolling critical condition $2l_0 \geq l \geq \sqrt{3}l_0$. The small difference is due to the difference between simulation model and kinematic model, but the primary reason is because that the rolling critical condition has not considered the effect of dynamics.

In the paper, the velocity of the extension strut is slow, then the dynamic effect is small. But when the velocity increases, the dynamic effect will become great. The next work will study this problem deeply.

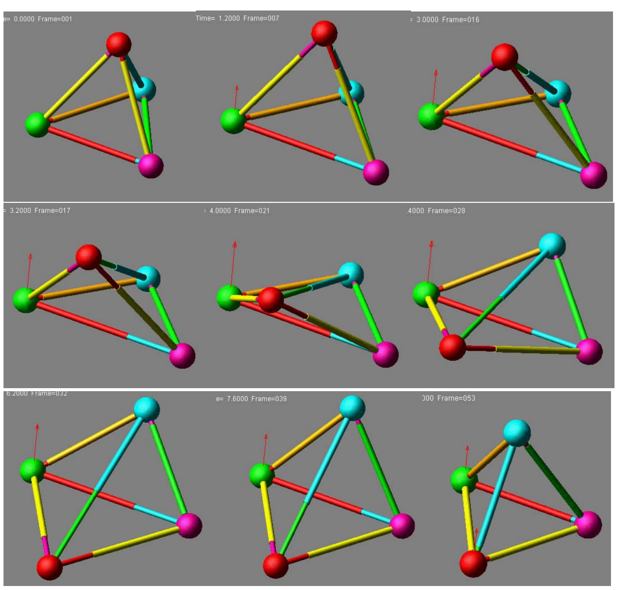


Fig.9. Motion simulation of the tetrahedral rolling robot

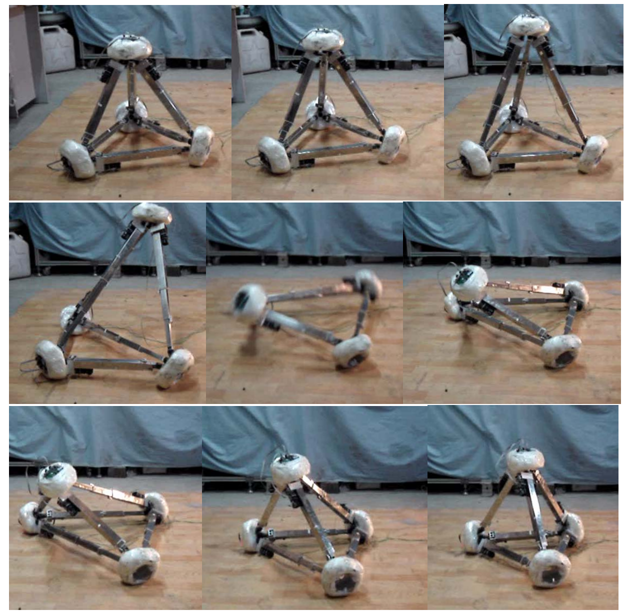
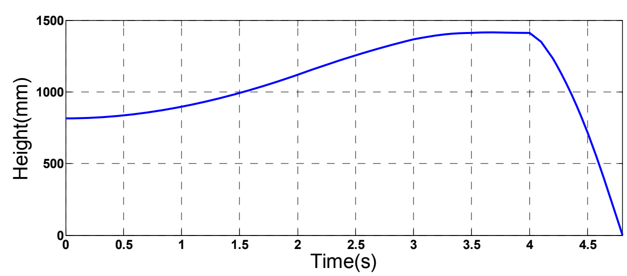


Fig.10. Experiment of the tetrahedral rolling robot

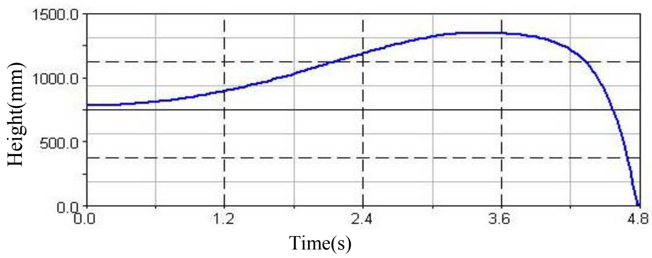
The developed tetrahedral rolling robot is shown in figure.10. Experiment shows that the robot can realize the rolling motion according to the planned path, and then relapse. It indicates that the design method is feasible. The next movement can choose different roll axis, and motion parameter including direction, step length, height can all be set neatly.

V. DATA ANALYSIS

Figure.11 (a) is the node A's position trajectory of tetrahedral rolling robot in Z direction calculated by the kinematic analysis method, and figure.11 (b) is the corresponding position trajectory of the simulation model. Figure.12 (a) is the node A's velocity trajectory of tetrahedral rolling robot in Z direction calculated by the kinematic analysis method, and figure.12 (b) is the corresponding velocity trajectory of the simulation model. It shows that the theory and the simulation trajectory are almost consistent, and reflect the practical robot well. The kinematic analysis method is verified correctly. Miro-difference in some position is due to the difference between kinematic model and simulation model.

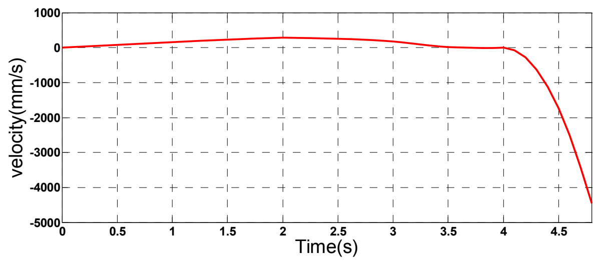


(a) Node A's position trajectory calculated by the kinematic method

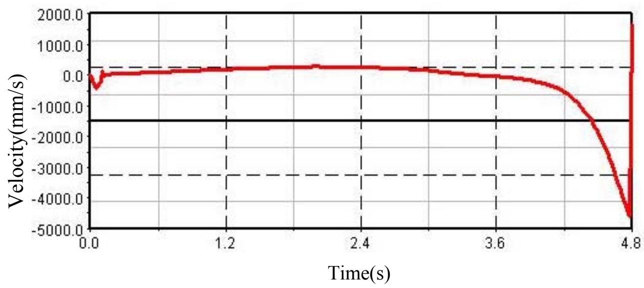


(b) Node A's position trajectory of the simulation model

Fig.11. Node A's position trajectory



(a) Node A's velocity trajectory calculated by the kinematic method



(b) The node A's velocity trajectory of the simulation model

Fig.12. Node A's velocity trajectory

Trajectory of reaction force is shown in figure13. Real line is in the case of $v_{A,z}$ =-600mm/s (velocity in z directon at the time of beginning roll), and broken line is in the case of $v_{A,z}$ =-300mm/s (velocity in z directon at the time of beginning roll). It is seen that higher speed will result in larger reaction force, and the model in Touchdown phase is validated. So, if the speed of node is controlled perfectly and flexible material is chosen, the reaction force could be reduced greatly.

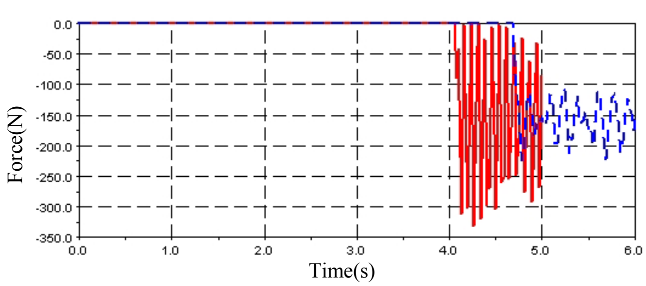


Fig.13 Comparing of reaction force with different rolling velocity

VI. Conclusion

(1) A novel robot mechanism-tetrahedral rolling robot is introduced in the paper. The designing method is proved correct and flexible through experiment.

(2) Kinematic model in different motion phase is analyzed in the paper. The effectiveness of the method is validated through simulation.

(3) The study of the paper will provide important reference for the dynamic analysis, optimization design and control method of the tetrahedral rolling robot.

References

[1] G.J.Hamlinand A.C.Sanderson, A novel concentric multilink spherical joint with parallel robotics applications[C]//Proceedings of the IEEE International Conference on Robotics & Automation. San Francisco, NJ:IEEE, 1994.5: 1267–1272

[2] G.J.Hamlinand A.C.Sanderson. Tetrobot A Modular Approach to Reconfigurable Parallel Robotics[M]. MA: Kluwer Academic,1997

[3] 1.Kenjiro Tadakuma1, Riichiro Tadakuma, Keiji Nagatani, Kazuya Yoshida, Ming Aigo, Makoto Shimojo, Karl Iagnemma, Throwable Tetrahedral Robot with Transformation Capability[C]//Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, USA, 2009:.2801-2808

[4] Y. Li and Y. Liu, Kinematics and tip-over stability analysis for the mobile modular manipulator[C]//Proceedings of the Institution of Mechanical Engineers, Journal of Mechanical Engineering Science, Part C, Vol. 219, No C3, 2005: 331-343

[5] P.E.Clark, S.A.Curtis, M.L.Rilee. Extreme Mobility: Next Generation Tetrahedral Rovers[C]//Space Technology and Applications International Forum-STAIF, America. 2007: 711-718

[6] P.E.Clark, M.L.Rilee, S.A.Curtis. BEES for ANTS: Space Mission Applications for the Autonomous NanoTechnology Swarm[C]//AIAA 1st Intelligent Systems Technical Conference, Chicago. 2004.9: 1-12

[7] Steven Curtis, Matthew Brandt, Greg Bowers, ect. Tetrahedral Robotics for Space Exploration[J]. IEEE Aerospace and Electronics Systems Magazine. 2007, 22(6): 22-30

[8] Miguel Abrahantes, Aaron Silver, Luke Wendt, Dan Littio. Construction and Control of a 4-Tetrahedron Walker Robot[C]//40th Southeastern Symposium on System Theory. University of New Orleans, USA, 2008.3:343-346

[9] Zhu Lei, The Research of a Spatial Rolling-Walk Mobile Mechanism Based on Four-bar Mechanism[D],2008

[10] Woo Ho Lee, Arthur C.Sanderson. Dynamic Rolling Locomotion and Control of Modular Robots[J]. IEEE Transactions on Robotics and Automation, 2002.2, 18(1): 32-41

[11] Woo Ho Lee, Arthur C. Sanderson. Dynamic Rolling of Modular Robots[C]//Proceedings of the 2000 IEEE International Conference on Robotics & Automation. San Francisco, NJ:IEEE, 2000,4:2840-2846