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

Design and Basic Experiments of a Transformable Wheel-Track Robot with Self-adaptive Mobile Mechanism

Zhiqing Li, Shugen Ma, *SeniorMember, IEEE*, Bin Li, Minghui Wang, and Yuechao Wang

Abstract—**The mobile robots often perform the dangerous missions such as planetary exploration, reconnaissance, anti-terrorism, rescue, and so on. So it is required that the robots should be able to move in the complex and unpredictable environment where the ground might be soft and hard, even and uneven. To access to such terrains, a novel robot (NEZA-I) with the self-adaptive mobile mechanism is proposed and developed. It consists of a control system unit and two symmetric transformable wheel-track (TWT) units. Each TWT unit is driven only by one servo motor, and can efficiently move over rough terrain by changing the locomotion mode and transforming the track configuration. It means that the mobile mechanism of NEZA-I has self-adaptability to the irregular environment. The paper proposes the design concept of NEZA-I, presents the structure and the drive system of NEZA-I, and describes the self-adaptive principle of the mobile mechanism to the rough terrains. The locomotion mode and posture of the mobile mechanism is analyzed by the means of simulation. Finally, basic experiments verify the mobility of NEZA-I.**

I. Introduction

UPTO day, there have been numerous studies on the mobile robots since they can help human perform the dangerous missions in complex and unpredictable environments, such as planetary exploration, intelligence and reconnaissance, anti-terrorism, and rescue, and so on. For example, when a sudden disaster happens, it is required that the robot should go through the irregular terrain quickly and arrive at its destination in time. If the robot had a poor ability to overcome the obstacles, it would fail to finish its work because it possibly wanders or runs aground in a place. Therefore the robots should have prominent flexibility and traversability. In such situations, various robots have been developed. Generally, the track mechanism and the hybrid mechanism are more adaptive to the rough terrains.

Manuscript received February 25, 2010. This work is supported by The National High Technology Research and Development Program of China (863 Program) (2007AA041502-5) and by The Technology and Innovation Fund of the Chinese Academy of Sciences (CXJJ-09-M22).

Z. Q. Li is with the State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China. He is also with the Graduate School of the Chinese Academy of Sciences, Beijing 100039, China. (e-mail: lzqing@sia.cn).

S. G. Ma is with the Department of Robotics, Ritsumeikan University, Kusatsu-Shi 525-8577, Japan, and also with Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China. (e-mail: shugen@se.ritsumei.ac.jp).

B. Li, M. H. Wang, and Y. C. Wang are with the State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China. (e-mail: libin@sia.cn, mhwang@sia.cn, ycwang@sia.cn).

According as the track configuration is transformable or not, the track mechanisms are categorized into two classes: one class has fixed configuration tracks and the other has the transformable configuration tracks. The former is called as "F-track mechanism" and the latter is called as "T-track mechanism". The robots with F-track mechanisms can show their prominent performances in the off-load mobility when they overcome the obstacles, cross the ditches. However, they usually turn inflexibly and consume much more power. To cope with these problems, the robots with T-track mechanisms have been developed. For example, CALEB-2 [1], VSTR [2][3], ROBHAZ-DT [4][5][6], Single-Tracked [7], and VGTV [8] belong to this kind of robots. They are designed to maximize flexibility and adaptability to the rough terrain by adjusting configuration of tracks. They can reduce the energy consumption by minimizing the contact length with the ground. Conversely, they can also improve the stability by maximizing the contact length with the ground.

The robots with the hybrid mechanisms make full of the advantages of the wheel-type mechanism, the track-type mechanism, and the leg-type mechanism. For example, AZIMUT [9], HYBRID Robot [10], wheel-track-leg Robot [11], and miniature wheel-track-leg mobile robot [12][13] belong to this kind of robots. According to the different terrain features, they can efficiently move by a right locomotion mode among the wheel mode, the track mode and the leg mode. It can also reduce the energy consumption.

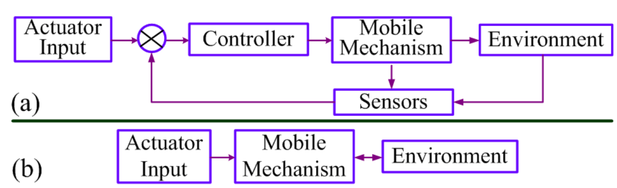


Fig.1. The basic idea of the drive system. (a) The proposal of the active drive systems. (b) The proposal of the self-adaptive drive system.

For the above robots, most of them adopt the active drive systems (Fig.1.(a)). Each degree of freedom (DOF) of the mobile mechanism is driven directly by a motor. These robots require more motors and more sensors. When they move over the rough terrain, their mobile mechanisms will be restricted by the constraint force from the environment. To enhance the self-adaptability to such rough terrain, they have to collect sufficient information about environments. According to such information, they can change their locomotion modes or postures to overcome such constraint force under the control of their own control systems. However, the constraint force varies with the different terrain. It causes their control algorithms to be more complicated. Meanwhile, their control systems have to spend much more time determining the right locomotion modes or postures of the mobile mechanisms. So, the motions of the robots have the characteristics of time-lag when they meet the obstacles.

In the paper, we propose a novel robot (NEZA-I) with the self-adaptive mobile mechanism. Its mobile mechanism consists of two TWT units. Each TWT unit is driven only by one servo motor, and can efficiently move over the rough terrain by changing the locomotion mode and transforming the track configuration without any sensors. So, it has self-adaptability to the different terrain. Section II proposes the design concept of NEZA-I. Section III presents considerately its mechanism design. Section IV introduces the self-adaptive principle and mechanical structure of the drive system. Section V presents the basic experiments. Finally, our conclusions are offered in section VI.

II. CONCEPT DESIGN

A. Robot Concept

1) Mobile mechanism type: A wheel mechanism has good performance in turning flexibility and energy efficiency. T-track mechanism has more prominent performance in off-road mobility and less energy consumption than the F-track mechanism to a certain degree. Combining their merits, the TWT mechanism is chosen as a hybrid mechanism.

2) The drive system: Based on a novel idea as shown in Fig.1.(b), we propose the self-adaptive drive system. When the robot moves over rough terrain, its mobile mechanism can get the constraint force information by acting with the environment directly instead of the sensors. According to such information, the drive system can drive the robot to move efficiently on the different terrain by changing locomotion mode and transforming the track configuration. For such drive system, the motor is used effectively and efficiently. It makes the efficiency of the motors improved. That is, the robot can be operated more easily and controlled more conveniently.

3) Design method of robot structure: It is thus necessary for the robot to install simply and maintain conveniently. So, the modularization design method is adopted when the structure of NEZA-I is designed.

4) The number of actuators: Less motors and higher efficiency of motors can minimize the robot in volume and in weight, and can simplify the control complexity to the robot. Meanwhile, it can also get less energy consumption and reduce the production cost.

Based on the above considerations, a transformable wheel-track robot (NEZA-I) with self-adaptive mobile mechanism is proposed (Fig.2). It should entail the features as follows:

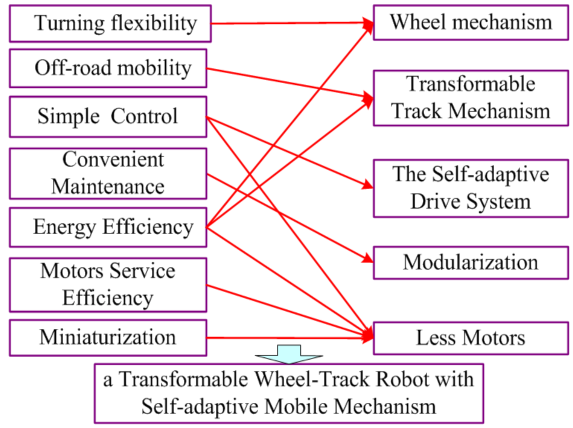


Fig. 2. The design concept

--First, the TWT unit is one of the mobile mechanism of NEZA-I, and is driven by only one servo motor. It can move on the different terrain by wheel mode or by track mode. The configuration of its track is transformable.

--Second, the drive system of the TWT unit makes NEZA-I have the self-adaptability to the rough terrain. According to the constraint force from environment, it can drive the TWT unit to move by wheel mode or by track mode, and can also transform the track configuration and change the locomotion mode.

--Third, it is simple and convenient for NEZA-I to be installed, dissembled, maintained, redefined, and relocated.

B. Structure proposal

As shown in Fig.3, the NEZA-I mechanism consists of a control system unit and two symmetric TWT units. The TWT unit is composed of a transformable track mechanism and a drive wheel mechanism. NEZA-I is developed based on the modularization method. It is simple and convenient for the mobile mechanism of NEZA-I to be installed and redefined.

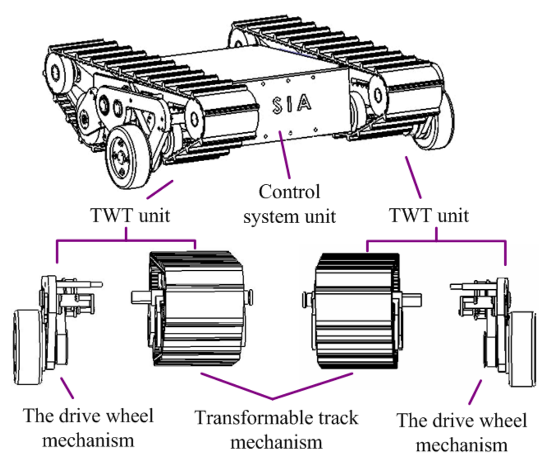


Fig. 3. Modularized structure proposal.

C. Motion proposal

As shown in Fig.4(a), when the robot moves on the flat ground, each TWT unit contacts with the ground by wheel and track. The track is thought to be an imaginary wheel since it is tangent to the ground. This locomotion mode is called as "wheel mode". Fig.4 (b) and Fig.4(c) show that the robot moves by tracks. This locomotion mode is called as "track mode".

As shown in Fig.4, the front adjusting link of each TWT unit can rotate about the basic shaft. That can make NEZA-I change the locomotion mode between the wheel mode and the track mode. That can also transform the track configuration and make the track generate various attack angles to cope with diverse obstacles.

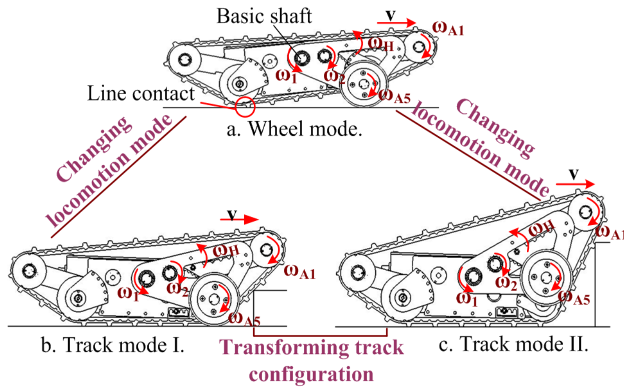
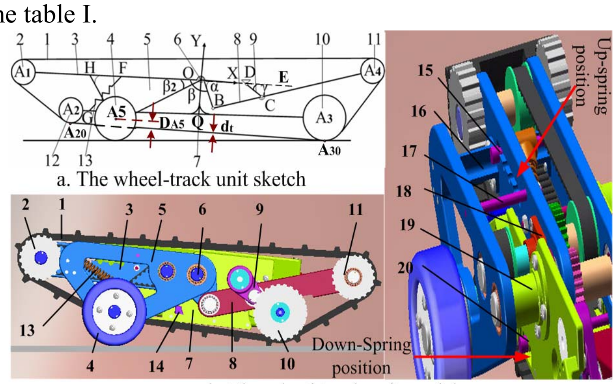


Fig. 4. Motion Proposal.

III. MECHANISM DESIGN OF THE TWT UNIT

For NEZA-I, its TWT unit has great effects on the performances in overcoming obstacle, turning flexibility, moving stability, motion efficiency, and so on. Fig.5 shows the mechanism of the TWT unit. We have studied the method of parameters design for the mobile mechanism by GA-based parametric optimization and simulation [14]. Here is another group of the design parameters for the mobile mechanism in the table I.



1.track 2.sprocket A_1 3.front adjusting link 4.drive wheel A_5 5.wheel supporter 6.basic shaft 7.chassis 8.rear adjusting link 9.short adjusting link 10.pulley A_3 11.pulleyA_4 12.pulley A_2 13.spring 14. positive stop 15. up-spring link 16. front fixed link I 17. front fixed link II 18. flange 19. fixed mount 20.down-spring link

Fig. 5. Mechanism of the transformable wheel-track unit.

A. The transformable track mechanism

As shown in Fig.5, the transformable track mechanism consists of a four-bar linkage, the sprocket A_1, the pulley A_2, the pulley A_3 and the pulley A_4. The four-bar linkage is composed of the front adjusting link A_1OB, the rear adjusting link BCA_4, the short adjusting link CD, and the chassis where the point O and the point D are fixed on. Its functions are: 1) When the robot meets high obstacles, it drives the front adjusting link to rotate about the basic shaft and adjusts the track configuration; 2) It ensures that the length variation of the track is too small to influence on the adjustment of track configuration and the motion of NEZA-I.

TABLE I
MECHANISM PARAMETERS OF THE TWT UNIT

Physical Meanings	Sym -bol	Value	Physical Meanings	Sym -bol	Value
A_1O	l_1	145mm	A_2A_3	$2m$	160mm
OB	a	29mm	OQ	h	25mm
$\angle A_1OB$	β	120°	A_1	r_0	20mm
BC	b	42mm	A_2	r_0	20mm
BA_4	l_2	135mm	A_3	r	25mm
CD	c	20mm	A_4	r_0	20mm
OD	d	40mm	A_5	r_5	30mm
OA_5	l_3	83mm	∠BOD	α	variation
OH	l_4	110mm	$\angle A_1OB$	γ	variation
$\angle HOA_5$	β_2	29°	Spring	GF	variation

The variable γ varies with changes the variable α. According to the geometrical relationship of the four-bar linkage, deduce the functional relationship between γ and α:

$$2ac\cos(\alpha-\gamma)+2d(a\cos\alpha-c\cos\gamma)=a^2-b^2+c^2+d^2 \quad (1)$$

The total length L varies with the changes the variable α. It can be described as:

$$L(\alpha)=L_{10}(\alpha)+L_{20}(\alpha)+L_{30}(\alpha)+L_{40}(\alpha)+L_c(\alpha) \quad (2)$$

Here:

$$L_{10}^2(\alpha)=h^2+m^2+l_1^2+\left(h-\sqrt{3}m\right)l_1\sin\alpha-\left(m+\sqrt{3}h\right)l_1\cos\alpha$$

$$L_{20}^2(\alpha)=4m^2-(r-r_0)^2$$

$$\begin{aligned}L_{30}^2(\alpha)=&a^2+m^2+h^2-\frac{2l_2}{b}\left(a^2-dm\right)+\frac{l_2^2}{b^2}\left(a^2+c^2+d^2\right)-(r-r_0)^2\\&+\frac{2ah}{b}(l_2-b)\sin\alpha+\frac{2a}{b^2}\left(bdl_2-dl_2^2-b^2m+bml_2\right)\cos\alpha\\&+\frac{2cl_2}{b^2}(dl_2-bm)\cos\gamma-\frac{2chl_2}{b}\sin\gamma+\frac{2acl_2}{b^2}(b-l_2)\cos(\alpha-\gamma)\end{aligned}$$

$$\begin{aligned}L_{40}^2(\alpha)=&\frac{l_2^2}{b^2}\left(a^2+c^2+d^2\right)+l_1^2+a^2-\frac{2a}{b}\left(al_2-l_1l_2\cos\beta+bl_1\cos\beta\right)\\&-\frac{2dl_2}{b^2}(al_2+ab-bl_1\cos\beta)\cos\alpha+\frac{2acl_2}{b^2}(b-l_2-l_1\cos\beta)\cos(\alpha-\gamma)\\&+\frac{2dl_1l_2}{b}\sin\beta\sin\alpha+\frac{2cl_1l_2}{b}\sin\beta\sin(\alpha-\gamma)+\frac{2cdl_2^2}{b^2}\cos\gamma\end{aligned}$$

$$\begin{aligned}L_c(\alpha)=&\pi(2r_0+r)-r\arccos\frac{r-r_0}{\sqrt{L_{30}^2+(r-r_0)^2}}-r\arccos\frac{r-r_0}{2m}\\&+r\arccos\frac{a(b-l_2)\cos\alpha+(d+c\cos\gamma)l_2-bm}{b\sqrt{L_{30}^2+(r-r_0)^2}}\end{aligned}$$

Fig.6 shows the analysis results in the environment of multi-rigid-body dynamics simulation. The maximum and the minimum of the track length are 722.05 mm and 720.95mm. The maximal variation of track length is 1.1mm, and the variation ratio is 0.1%. It ensures that the track will be neither tight nor loose when NEZA-I changes the locomotion mode and adjusts the track configuration. Considering the assembly precision and the elastic feature of the rubber track, the design value of track length is 723mm.

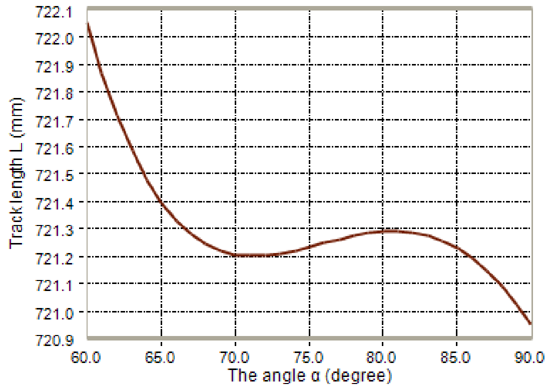


Fig. 6. Track length varies with the angle α.

B. The spring GF functions

As shown in Fig.5 (b), each front adjusting link has five locations as the up-spring positions where the up-spring link is located. The chassis have four locations as the down-spring positions where the down-spring link is located. The spring GF connects the up-spring link with the down-spring link. Its functions are: 1) Keep the drive wheel and the track contact with ground when robot is moving by wheel mode; 2) Make the robot restore to move by wheel mode again when it overcame obstacles and moved on the even road; 3) Act as a cushion when the robot collides suddenly with an obstacle or drops into the ditch; 4) Change the preload capacity of NEZA-I by relocating the up-spring link and the down-spring link.

C. The position-limit mechanism

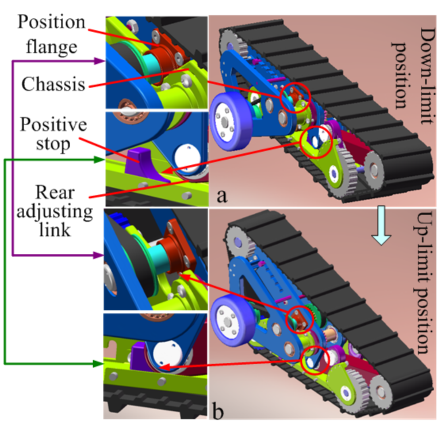


Fig. 7. Position-limit mechanism design

The position-limit mechanism is designed for the TWT unit. It can ensure that the front adjusting link rotates about the basic shaft only to a limited extent. As shown in Fig.7 (a), the front adjusting link is located at down-limit position when the position flange contacts with the dent of chassis. The angle α between the chassis OD and the front adjusting link A_1OB is 60 degree. The robot moves by wheel mode. Meanwhile, the attack angle of the track is the smallest.

As shown in Fig.7 (b), the front adjusting link is located at up-limit position when the rear adjusting link contacts with the positive stop. The angle α is 90 degree, and the robot moves by track mode. Meanwhile, the attack angle of the track is the largest.

D. The wheel supporter mechanism

As shown in Fig.5, the wheel supporter of drive wheel A_5 is fixed on the front adjusting link. It can rotate around the basic shaft with the front adjusting link. That can make the TWT unit change the locomotion mode between wheel mode and track mode. The value D_{A5} is the distance between the center of the active wheel A_5 and the outer sketch line $A_{20}A_{30}$ of the track. R is the radius of the nominal circle A_3, $R=r+d_t$; R_0 is the radius of the nominal circle A_2, $R_0=r_0+d_t$; d_t is the thickness, $d_t=5mm$. It can be described as:

$$D_{A5}(\alpha)=\left|\frac{\sqrt{4m^2-(R-R_0)^2}}{2m}\left[l_3\sin(\beta_2-\alpha-\beta)+h\right]+\frac{R-R_0}{2m}l_3\cos(\beta_2-\alpha-\beta)+\frac{R+R_0}{2}\right| \quad (3)$$

Fig.8 shows the analysis results in the environment of multi-rigid-body dynamics simulation. Displacement A_2 is the displacement between the centre of the pulley A_2 and the ground. Displacement A_5 is the displacement between the centre of the wheel A_5 and the ground. They vary with the angle α, and can describe the locomotion mode and posture of the mobile mechanism.

1) When the value α is 60°, the value D_{A5} is equal to $r_5/3$. NEZA-I is at initial state by the wheel mode.

2) When the value α is 75°, the value D_{A5} is equal to r_5. The locomotion mode of NEZA-I is in its critical state between wheel mode and track mode.

3) When the value α is below 75°, the robot moves by wheel mode. Conversely, the robot moves by track mode when the value α is above 75°.

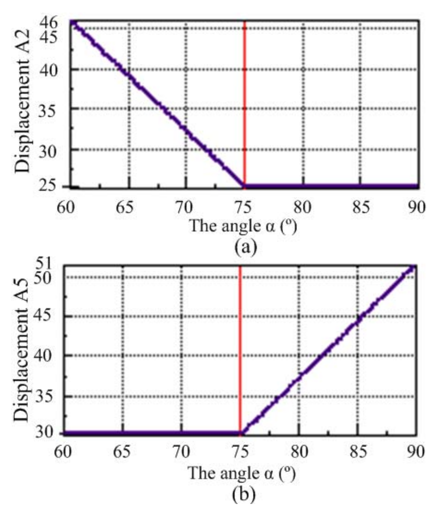
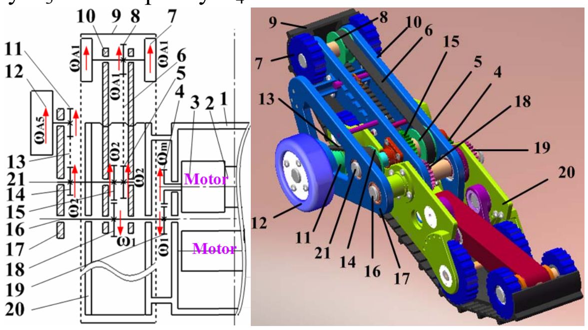


Fig. 8. Displacements relative to the ground. (a).Displacement A_2.(b). Displacement A_5.

IV. Mechanism Design of the Drive System

Fig.9 shows the self-adaptive drive system of NEZA-I. It consists of two symmetrical drive systems of the TWT unit. For the drive system of a TWT unit, it provides two outputs in different form only by one servo motor, or rather it enables the TWT unit to have the abilities to adjust the track configuration of the track and drive robot to move by wheel mode and by track mode. That is, one motor drives the sprocket A_1 and the drive wheel A_5 via the gear G_1, the gear G_2, the gear G_3, the gear G_4, the pulley C_1, the pulley C_2, the pulley C_3 and the pulley C_4.



a. The drive system sketch. b. The drive system model

1.control box 2.motor 3.reducer 4.gear G_1 5.pulley C_1 6.belt CL_1 7.pulley A_1 8.pulley C_2 9.track 10.front adjusting link 11.pulley C_4 12.drive wheel A_5 13.belt CL_2 14.pulley C_3 15.gear G_4 16.basic shaft 17.wheel supporter 18.gear G_3 19.gear G_2 20 chassis 21.passive shaft

Fig. 9. The drive system of a TWT unit.

A. The robot motion

Fig.4 (a) shows that the robot moves by wheel mode when it moves on the flat ground. The contact area is smallest between the mobile mechanism and the ground since the tracks are tangent to the ground. For the robot, it causes the robot to have the prominent performances in turning flexibility and less energy consumption.

Fig.4 (b) shows that the robot moves by track mode when it meets the obstacles. For NEZA-I, it is of great benefit to the obstacle-negotiating performance. Meanwhile, the contact area will become large between the mobile mechanism and the ground. That is, the stability of the robot will be improved.

In above cases, the constraint force from the environment is not enough to make the front adjusting link rotate about the basic shaft. The transmission parts rotate as shown in Table III and Fig.9 (a). Here, ω_m is the rotational speed of the geared motor; ω_1 is the rotational speeds of the axis shaft, gear G_2, gear G_3; ω_2 is the rotational speeds of the passive shaft, gear G_4, pulley C_1, and pulley C_3; ω_H is the rotational speeds of the front adjusting link, and wheel supporter; ω_{A1} is the rotational speeds of the sprocket A_1, and pulley C_2; ω_{A5} is the rotational speeds of the pulley C_4, and wheel A_5.

B. Changes of locomotion mode and track transformation

Fig.4(a→b) and Table II show that the robot goes into the place by wheel mode where the constraint force is so large that it could not move. The front adjusting link starts to rotate about the basic shaft until the robot moves by track mode.

Fig.4(b→c) and Table II show that the robot goes into another place by track mode where the constraint force becomes even larger and makes the robot stop moving. Meanwhile, the front adjusting link starts to rotate about the basic shaft and makes the track configuration transformed. When the robot moves by track mode with the right configuration, the front adjusting link will stop rotating.

C. Automatic reset motion

Fig.4(c→b) and Table II show that the robot goes into the place by track mode where the constraint force is small. The front adjusting link rotates about the axis shaft to restore the track configuration to its former configuration while the robot continues to move by track mode.

Fig.4(b→a) and Table II show that the robot goes into another place by track mode where the constraint force is smaller. The front adjusting link rotates about the basic shaft while robot continues to move. When the robot moves by wheel mode again, the front adjusting link will stop rotating.

TABLE II

TRANSMISSION PARTS TURNING

Locomotion mode and track configuration \ Transmission parts rotation		ω_m	ω_1	ω_2	ω_H	ω_{A1}	ω_{A5}
Wheel mode		►	►	►	▌	►	►
Track mode		►	►	►	▌	►	►
Changing locomotion mode	wheel mode to track mode	►	►	▌	►	▌	▌
	Track mode to wheel mode	►	►	▌	◄	▌	▌
Track transf-ormation	Track mode I to track mode II	►	►	►	►	►	►
	Track mode II to track mode I	►	►	►	◄	►	►

Note: the symbol "►" means transmission part is turning, turning direction corresponds with the direction as shown in Fig.4 and Fig.9; the symbol "◄" means transmission part is turning, turning direction is opposite to the direction as shown in Fig.4 and Fig.9; the symbol "▌" means transmission part stops turning.

V. Basic Experiments

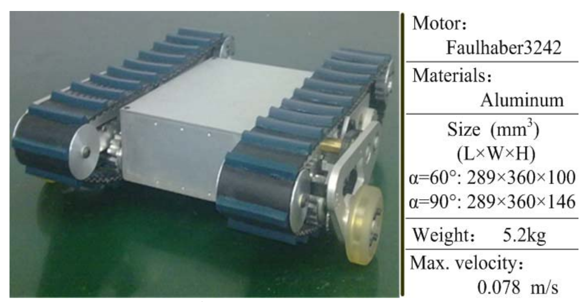


Fig. 10. NEZA-I prototype.

Fig.10 shows the NEZA-I prototype and its specification. In order to verify the self-adaptability of this mobile mechanism, we conduct the following experiments:

1) Moving on the even and uneven road: Fig.11 shows that the robot moves on the flat road by wheel mode, and moves on the uneven road by track mode. It can change instantaneously the locomotion mode and transform continuously the track configuration of the mobile mechanism with the changes of the environment conditions in all time.

2) Overcoming obstacle by track: Fig.12 shows that when the tracks encounter the different obstacles earlier than the drive wheels, the mobile mechanism can overcome them by adjusting autonomously the track configuration.

3) Overcoming obstacle with different heights by wheels: As shown in Fig.13 and Fig.14, when the drive wheels encounter obstacles with different height earlier than the track, the mobile mechanism can overcome them by adjusting autonomously its posture. Fig.14 shows that robot overcomes obstacle by the drive wheel. The highest obstacles which the robot can surmount are 120mm high, and are twice as high as the wheel.

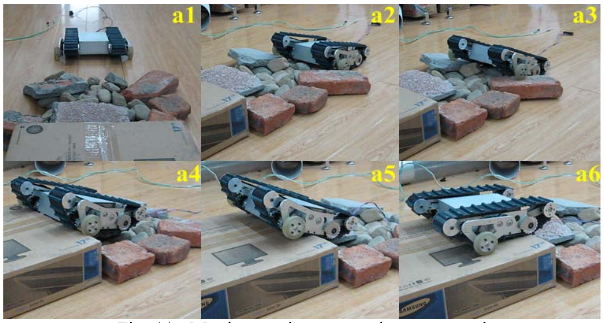


Fig. 11. Moving on the even and uneven road

Fig. 12. Overcoming obstacle by tracks

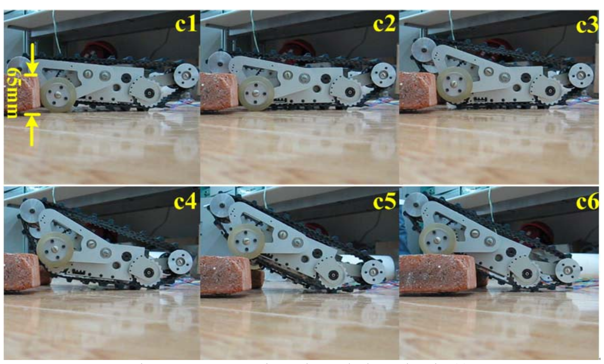


Fig.13. Overcoming obstacle by wheels (I).

Fig. 14. Overcoming the obstacles by wheels (II)

VI. CONCLUSIONS

To access to the different terrain features, a novel mobile robot (NEZA-I) with the self-adaptive mobile mechanism has been developed. This paper presents the details of the design concept, the structure and the drive system of NEZA-I, and describes the self-adaptive principle of the mobile mechanism to the different terrains. Basic experiments prove that the parameters of the mobile mechanism are valid. Meanwhile, it is verified that the mobile mechanism of NEZA-I has a prominent self-adaptability to the different terrains. That is, the design method and the concept of NEZA-I is reasonable. The obstacle-negotiating performance of the NEZA-I will be studied in future work.

REFERENCES

[1] H. Kwon, H. Shim, D. Kim, S. Park, and J. Lee, "A Development of a transformable caterpillar equipped mobile robot," in *IEEE Int. Conf. on Control, Automation and Systems*, 2007, pp.1062-1065.

[2] K. Choi, H. Jeong, K. Hyun, H. Choi, and Y. Kwak, "Obstacle Negotiation for the Rescue Robot with Variable Single-tracked Mechanism," in *IEEE/ASME Int. Conf. on Advanced Intelligent Mechatronics*, 2007, pp. 1-6.

[3] S. Lim, D. Park, Y. Kwak, B. Kim, and S. Jeon, "Variable Geometry Single-Tracked Mechanism for a Rescue Robot," in *Proc. IEEE Int. Workshop on Safety, Security and Rescue Robotics*, 2005, pp.111-115.

[4] C. Cho, C. Park, S. Kang, M. Kim, C. Lee, and Y. Kwak, "ROBHAZ-DT: Variable Configuration Double-Track Mobile Robot for Hazardous Environment Applications," in *Proc. IEEE Int. Conf. on Control, Automation and Systems*, 2001, pp.150-153.

[5] S. Kang, C. Cho, C. Park, J. Lee, D. Ryu, and M. Kim, "ROBHAZ-DT2: Passive Double-Tracked Mobile Manipulator for Explosive Ordnance Disposal," *J. Field and Service Robotics*, Vol. 24, 2006, pp. 355–364.

[6] C. Lee, S. Kim, S. Kang, M. Kim, and Y. Kwak, "Double-track mobile robot for hazardous environment applications," *J. Advanced Robotics*, Vol. 17, No. 5, 2003, pp. 447–459.

[7] J. Kim and C. Lee, "Variable transformation Shapes of Single-Tracked Mechanism for a Rescue Robo," in *Proc. IEEE Int. Conf. on Control, Automation and Systems*, 2007, pp.1057-1061.

[8] J. Paillat, P. Lucidarme, and L. Hardouin. (2008, November).Variable Geometry Tracked Vehicle (VGTV) prototype: conception, capability and problems. Available: http:// conferences. enst-bretagne. fr/ data.

[9] M. François, L. Dominic, A. Martin, et al. Franc and O. Michaud, "Multi-Modal Locomotion Robotic Platform Using Leg-Track-Wheel Articulations," *J. of Autonomous Robots*, Vol. 18, 2005, pp. 137–156.

[10]M. V. Sin and R. K. Eek, "The Hybrid mobile robot," in *Proc. IEEE Int. Conf. on Industrial Technology*, 2003, pp.262-264.

[11]H. Zhao, X. Li and C. Yao, "A Novel Wheel-Leg-Track Complex Mobile Mechanism and Its Stability Analysis," *J. of the Robot*, Vol. 28, No. 6, pp. 576-581, 2006. (in Chinese)

[12]H. Yin, C. Yao, X. Li, et al, "Research of a Wheel-Leg-Track Complex Mobile Robot," *J. of the Robot*, Vol. 24, No,12-2, 2008, pp. 248-250. (in Chinese)

[13]X. Duan, Q. Huang and K. Li, "Design and Motion Analysis of Miniature Wheel-Track-Legged Mobile Robot," *J. of the Chinese Journal of Mechanical Engineering*, Vol. 41, No. 2, 2005, pp. 109-114. (in Chinese)

[14]Z. Li, S. Ma, B. Li, and Y. Wang, M. W, "Parameter Design and Optimization for Mobile Mechanism of a Transformable Wheel-Track Robot," in *Proc. IEEE Int. Conf. on Automation and Logistics*, 2009, pp. 158-163.