Self-reconfigurable Quadruped Robot: Design and Analysis

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Abstract. Self-reconfigurable robot is a kind of robot that is able to recover its original function after partial damage of the robotic system. This is achieved by making changes on the partially damaged robot. This paper put forward a kind of self-reconfigurable quadruped robot based on the resilient theory. First, the concept of the self-reconfigurable robot and the recovery strategy were introduced. Secondly, a novel architecture of modular quadruped robot made by LEGO material was proposed. The connector of interfaces was taken into consideration. At last, the overall mode of the motion and control method with the help of NXT - G program were proposed. The analysis of the overall gait ensures the stability of motion in this phase. As for the uncertain environmental damage to the robot, the robot is able to repair itself by changing the movement type automatically to ensure it continues to work. The result shows that the quadruped robot meets the requirements of resilience and self-reconfiguration.

Introduction

Self-reconfigurable robot is a kind of robot which can change the configuration of itself according to the specific task. The kind of robot can execute unpredictable tasks in a changing environment and has become one of the hotspots in the field of robotics research in recent years.

Self-reconfigurable robot usually consists of a set of interchangeable modules with a variety of size and performance characteristics. These modules can be assembled into robots of different structures, so as to adapt to different work environment and fulfill the related work requirements [2].

The realization of the reconfiguration is mainly decided by the design of the mechanical structure and related components, which involves planning reconfigurable path and reducing the energy consumption. Therefore, the design of mechanical structure and related components is the key part in the whole process [3]. Some efforts have been done on the structure of the self-reconfigurable robot, Kasper et.al [4] proposed the chain structure, which is composed of chain connection between the modules. The chain structure benefits from its diversified gait, good flexibility and it fulfills various mobile functions; S. Murata and Y. Suzuki et.al [5, 6] put forward lattice structure. The modules are placed in one lattice structure while the position and direction of the modules are limited by the lattice. The lattice structure simplifies the requirement for mechanical control, move on itself and make it easier to achieve the self-reconfiguration; Haruhisa et.al[7] described the hybrid structure which can realize the conversion among the chain structure, lattice structure and tree structure. This method selects the best structure to full the specific function. Electronic components provide self-reconfigurable robot with information processing and platform for communication, which plays a key role on the performance of the robot [8]. The design of the interface is also the essence of the robot. J. W. Suh [9] used electromagnetic connections in the "Telecube Robot", making it possible to control the connection and disconnection of the interface, but the control accuracy is low; A. Campbell [10] in the robot CONRO, M.Yim [11] in the robot PolyBot used mechanical connection, which shows good stability and mechanical performance but with difficult control; New developed interface designs of the self-reconfigurable robots based on the electronic force, good mechanical properties and process automation are realized. The size of the connection device should be minimized in the future and its wear resistance should be improved [12].

The Strategies of Self-reconfiguration

The self-reconfigurable strategies depend on the structure of the robot. There are four kinds of self-configurable strategy: (1) Change of a function via the behavioral change (i.e., change of the relationship among states). Further, the change of a behavior may be due to the change of the principle, and therefore this strategy may also refer to the change of principle; (2) The structural change via the change of connectivity among components (i.e., rearranging the constituent parts); (3) Change of a component in itself; (4) Mixed strategy: combine the three kinds of strategies mentioned above. As shown in figure 1, we can use the three self-reconfigurable strategies to prove the repair process of the damaged robot. Initially, the robot moves (A). Later a leg is damaged (B), the robot try to restore its functions (i.e., mobile) by crawling (C1, strategy (1)), or rearrange one of the rest components (C2, strategy (2)), or change the shape of a component (C3, strategy (3)).

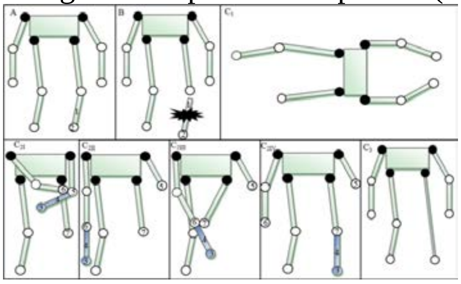


Fig. 1 Recovery strategy of the robot

（A）Original state of a robot；（B）One leg damaged;（C1）The first recovery strategy;（C2）The second recovery strategy.（C3）The third recovery strategy

Design of the Self-reconfigurable Quadruped Robot

The Material of the Robot. The body of the robot is composed of LEGO components. LEGO material is made up by many scattered small parts. It can build various structure with its own pin or hole connections and be able to be removed to the minimum module. There is a cooperative relationship between any two modules and the whole structure is able to achieve a specific function.

The Walking Mechanism of the Robot. The degrees of freedom of the quadruped robot is obtained by the requirement of the design. The design is mainly for the interpretation of the concept of resilience instead of in-depth discussion about the quadruped robot. There is only one joint for each leg of the quadruped robot. This kind of quadruped robot has simple structure and plain motion which is easy to control. To actuate the robot to move forward or backward, only the Angle of the leg movement need to be set. This is realized by controlling the rotation angle of the motor. The structure of the self-reconfigurable quadruped robot is shown in figure 2. The main parameters of the size are shown in table 1.

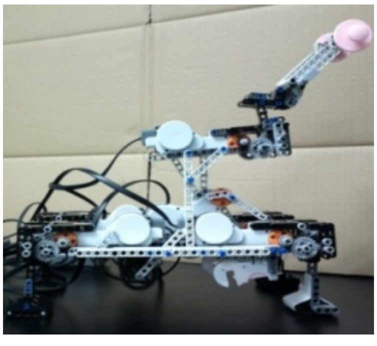


Fig. 2 The structure of the self-reconfigurable quadruped robot

Table 1 The main parameters of the robot

Subassembly	Length / mm	Max Strokemm/mm	Angle/°
shank	135	30	90（inner）180（outer）
thigh	45	10	60

According to the law of barycenter：

$$\sum_{i=1}^{n} m_i \bullet c_i = \sum_{i=1}^{n} m_i \bullet c \qquad (1)$$

The displacement of the barycenter of the robot in the walking process can be obtained from equation 1. In equation 1, mi is the quality of the part i of the robot. Ci is the corresponding barycentric coordinates; C is the barycentric coordinates of the robot. The quality modules are divided into three parts: the robot body, thighs and legs. The body module also includes the quality of the hip and the corresponding auxiliary self-locked gear. The quality of each quality module is known. The simulation of the straight gait of the robot takes literature [13] as a reference and the gait cycle is 8s. The relationship of the displacements of the geometric center and barycenter is shown in figure 3. The dotted line is the geometric center of the robot while the solid line shows the difference between the displacements of the barycenter and geometric center. Positive value means the displacement of the barycenter is ahead while negative value means the hysteresis of the barycenter[13]. It is obvious that the displacements of the barycenter and the geometric center are not coincident with each other completely.

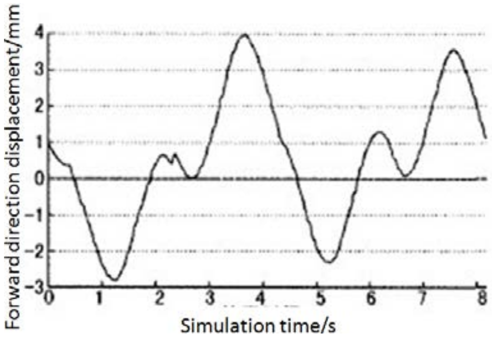


Fig. 3 The relationship of the geometric center and the barycenter of the robot

Analysis of the Stability of the Robot. For the judgment of the stability of the quadruped robot, the model should be built first, as shown in figure 4:

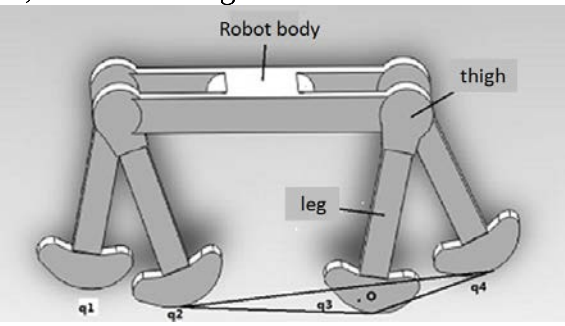


Fig. 4 3D model of the robot

If the triangle Δq2q3q4 satisfies:

$$\Delta q_2 q_3 q_4 = \Delta q_2 q_3 O + \Delta q_2 q_4 O + \Delta q_3 q_4 O \qquad (2)$$

It means that the barycenter of the robot is within the area of the supporting triangle composed of links among point q2， point q3 and point q4 or on the edge of the triangle. The distance from the barycenter to each edge is calculated. According to the supporting foot barycentric coordinates, the coordinates of q2, q3 q4 and the barycenter “o” of the robot, the trilateral linear equations of the supporting triangle are:

Equation of line q_2q_3: $a_1 z + b_1 y + o_1 = 0$ (3)

Equation of line q_2q_4: $a_2 z + b_2 y + o_2 = 0$ (4)

Equation of line q_3q_4: $a_3 z + b_3 y + o_3 = 0$ (5)

The coefficients in Equation(3)、(4)、(5) are：

$$a_1 = y_3 - y_2, b_1 = z_2 - z_3, o_1 = z_3 y_2 - z_2 y_3 \tag{6}$$

$$a_2 = y_4 - y_2, b_2 = z_2 - z_4, o_2 = z_4 y_2 - z_2 y_4 \tag{7}$$

$$a_3 = y_4 - y_3, b_3 = z_3 - z_4, o_3 = z_4 y_3 - z_3 y_4 \tag{8}$$

The distances from the barycenter to each edge of the triangle are :

$$d_i = \frac{| a_i z_o + b_i y_o + o_i |}{\sqrt{a_i^2 + b_i^2}}, (i = 1, 2, 3) \tag{9}$$

a_i, b_i, o_i are the coefficients of the corresponding linear equation. $o(z_0,y_0)$is the barycentric coordinates of the robot.

Minimum distance is the margin of stability to be calculated:

$$d = \min\{d_1, d_2, d_3\} \tag{10}$$

The calculation of the stability of the robot based on the instantaneous barycenter from equation (9), (10) is on the basis of the calculation of the stability margin of the instantaneous barycenter and the geometric center. The difference between the two calculations is small and the biggest difference is occurred when the difference value is the biggest in figure 4. In order to show the difference more clearly, the difference value of the two curves is calculated in this paper. Positive value means that the stability margin based on the instantaneous barycenter is greater than the stability margin based on the geometric center and a negative value is opposite. The conclusion is that the stability margin based on the instantaneous barycenter is not necessarily smaller than the stability margin based on the geometric center and the result is associated with the gait planning and the robot structure. Real-time control of gait can simplify the barycenter as the geometric center. The stability margin calculation based on the geometric center can reduce the amount of the calculation and improve the response characteristics.

Self-reconfiguration of the Quadruped Robot

Realization of the Resilience in the Quadruped Robot. Based on the concept of the resilience theory, a self-reconfigurable quadruped robot is designed and manufactured. The self-reconfigurable quadruped robot based on the resilience theory is shown in figure 5.

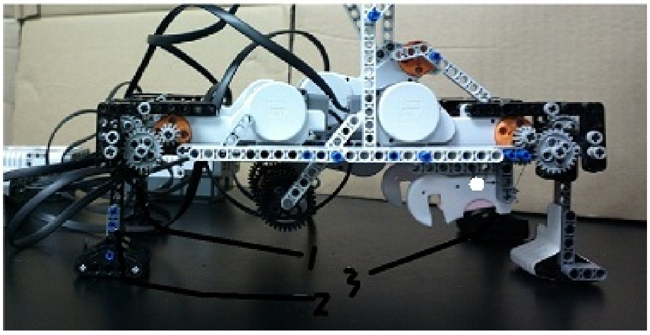
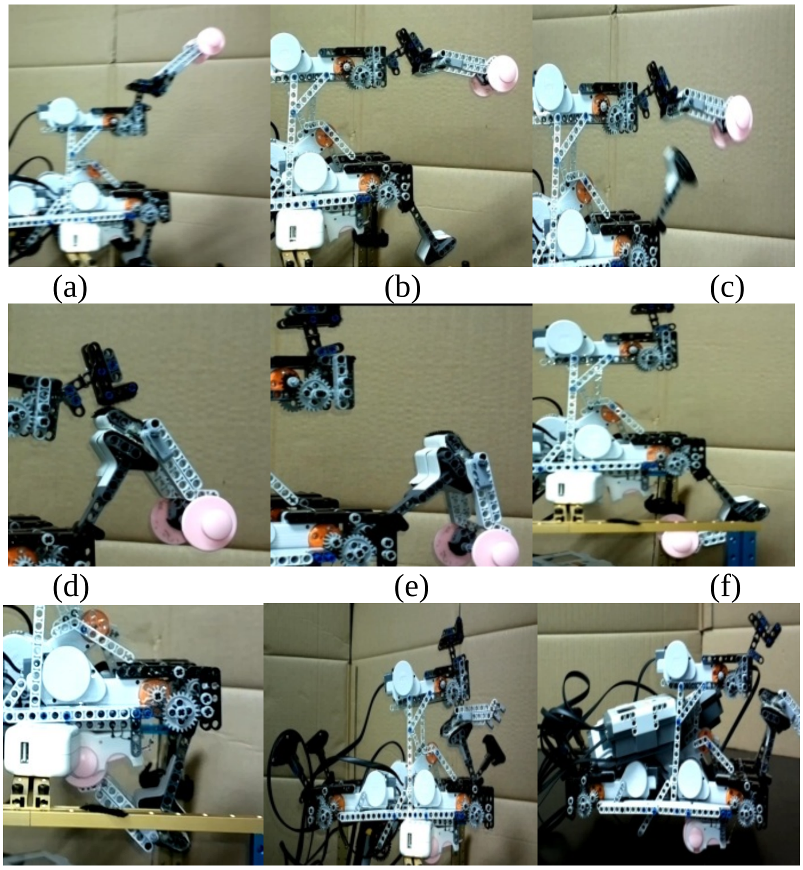


Fig. 5 The self-reconfigurable quadrued robot based on the resilience theory

Suppose one of the legs (1,2,3) is damaged in the actuational process, the robot loses the ability to continue to work. During the construction of the self-reconfigurable robot, the main principle of the repair plan is to change the rest of the training system structure to perform a new behavior. The initial status of the robot is walking style. When there is something wrong with the style like one of the legs is broken, the sensors on the leg will detect the disorder of the movement, the robot will autonomous install roller and change to the wheeled style. Since self-reconfiguration is a kind of solution of resilience, the quadruped robot in this paper mainly interpret the resilience concept from the self-reconfiguration direction. At the same time the idea has a certain creativity, no matter whether the robot is in damaged condition, it can choose different walking scheme according to the road conditions. For example, the robot can choose walking style when the road is concave and convex and choose wheeled style when the road is flat terrain. The adaptive choose can achieve high speed actuation and improve the efficiency of the quadruped robot.

The Process of Self-reconfiguration of Quadruped Robot. The process of the self-reconfiguration of the quadruped robot is shown in figure 6. The whole time for the self-reconfiguration is 16s.


(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 6 The self-reconfiguration of quadruped robot. (a)The initial state; (b)3s state; (c) 6s state; (d) 8s state; (e) 10s state; (f) 11s state; (g) 12s state; (h) 15s state; (i) 16s state;

The figure 6 (h) is the state after reconstruction and pack up the four legs. (i) is the wheeled style.

Conclusion

In this paper, a self-reconfigurable quadruped robot is designed by selecting the new material: LEGO 8547. The interface of the robot is selected and designed; The whole walking mechanism and the self-reconfigurable mechanism are analyzed; To meet the requirement of the stability of the movement, the instantaneous barycenter and geometric center are calculated; The self-reconfigurable function is under control with the help of MATLAB program and the LEGO executive software; The scheme optimization selection is also performed. The result shows that the self-reconfigurable quadruped robot meets the requirements of self-reconfiguration and verifies the resilient theory.

References

[1] B. Li, Z.W. Wu, D.L. Tan, A research on technology of reconfigurable robot, J. Information and Control. 30 (2001) 685- 691.

[2] B. Li, H.Y. Dong, X. Bai, Research and development of the reconfigurable robot, J. Journal of Shenyang Institute of Technology. 19 (2000) 68- 92.

[3] M. Yim, Y. Zhang, K. Roufas, D. Duff, C. Eldershaw, Connecting and disconnecting for chain in self-reconfiguration with PolyBot, J. Transactions on Mechatronics. 7 (2002) 442–451.

[4] K. Story, D. Brandt, David J, Self-Reconfigurable Robots, J. Transactions on Mechatronics. 8

(2001) 220-245.

[5] S. Murata, H. Kurokawa, S. KoKaji, Robotics and Automation self-assembling, J. Machine and Automation. 1994 441-448.

[6] Y. Suzuki, N. Inou, H. Kimura, M. Koseki, Reconfigurable group robots adaptively transforming a mechanical structure-numerical expression of criteria for structural transformation and automatic motion planning method, J. Intelligent Robots and Systems. 2007 2361-2367.

[7] H. Kurokawa, K. Tomita, A. Kamimura, S. Kokaji, T. Hasuo, S. Murata, self-reconfiguration of M-TRAN III modular robotic system, J. The International Journal of Robotics Research. 2 (2008) 2361-2367.

[8] S.Murata, E.Yoshida, K.Tomita, H.Kurokawa, S.Kokaji. Self- Reconfigurable modular robotic system, J. Transaction on Mechatronics. 7 (2002) 432-441.

[9] J.W. Suh, S.B. Homans, M.Yim, Telecubes: Mechanical design of a module for self-reconfigurable robotics, J. Robotic and Automation. 4 (2002) 4095-4101.

[10] A. Campbell, P. Pillai, S. C. Goldstein. The robot is the tether: Active, adaptive power routing for modular robots with unary inter robot connectors. Inproc[J]. Intelligent Robots and Systems. 2005 246-4115.

[11] M. Yim, Y. Zhang, K. Roufas, D. Duff, C.E. ldershaw, in temers of connecting and disconnect for chain self-reconfiguration with Polybot, J. Transactions on Mechatronics. 7 (2002) 134-185.

[12] M. E. Karagozler, J. D. Campbell, G. K. Fedder, S. C. Goldstein, M. P. Weller, Electrostatic latching for inter-module adhesion, power transfer, and communication in modular robots, J. Intelligent Systems. 2007 2779-2786.

[13] Z.H. Wu. Load type four feet walking mobile platform system Structure analysis and static gait research of quadruped mobile platform system, D. Armored Force Engineering Institute. 2011.