Configuration Analysis of a Variable-Topology Mobile Robot

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Abstract—Based on metamorphic principle, a variable-topology robot is presented to adapt to the conflictive requirements of complex fields. The robot has a body and 4 articulated unit. Each articulated unit consists of transformable link, coxa joint, thigh, knee joint, joint wheel, crus and foot wheel. In different stages, the robot uses some DOFs and meantime locks other DOFs, so it has many changeable configurations. The concepts of all-phase kinematic chain and working-phase mechanism have been presented. Then the topology change of the robot was studied by topological graph theory. The robot's configuration transformations during the courses of the degenerating process, the aggregating process and the conversing process was analyzed by metamorphic mechanism theory.

Keywords—variable-topology; mobile robot; configurations; transformation analysis.

I. INTRODUCTION

Mobile robot would face to variety of outdoor environment when working^[1]. These environment requirements are incompatible^{[2][3]}, for instance, sometimes a wide ground clearance of the robot is needed for the robot roving through ground heaves, and other times the robot's breadth should be small to traverse caves, which need a robot can change its configurations in time. It is difficult to a ordinary robot. Metamorphic mechanism is a new kind of mechanism originated from the configuration and mobility researches of decorative cartoon folds, which was put forward by Dai J S and Rees Jones^[4]. In contrast with traditional mechanisms, its total number of all effective links and degree of freedom changes as it moves from one configuration to another or a singular condition occurs that makes it behave differently^{[5][6]}. Based on metamorphic principle, a new variable-topology robot was presented in the paper and several concepts of this kind of mechanisms would be introduced in subsequent text. Then, the configuration transformations of the robot were analyzed.

II. STRUCTURE OF A VARIABLE-TOPOLOGY MOBILE ROBOT

A new mobile robot was designed, shown in Fig.1, which can be thought as a 5-link mechanism. The body is a fixed component, and the 4 articulated unit are 4 links that coexist in a plane. Each articulated unit consists of transformable link, coxa joint, thigh, knee joint, joint wheel, crus and foot wheel.

The robot may move in a way of wheels (Figure.1a) or wheel-legs (Figure.1b). When it moves by wheels, the joints on the legs would be fixed. When moving by wheel-legs, all

wheels' drivers would be locked. Besides, it can change its configurations, which shifting itself wider or narrower, higher or lower. This function can turn the viewing angle of CCD camera which helps the robot attain real-time and reliable information of the terrain. Faced to different obstacles, the robot may use different DOF(degree of freedom) to transverse them. When climbing a high obstacle, the robot may rotate its calves; when veering, the robot may rotate its thigh; when adapted to caves or heaves, the robot may rotate the transformable links to change the width of the robot. In different stages, the robot uses some DOFs and meantime locks other DOFs. From the view of the theory of mechanisms, the robot has the character of variable-topology mechanisms^[7].

Figure 1. The structure of a variable-topology mobile robot

III. ALL-PHASE KINEMATIC CHAIN AND WORKING-PHASE CHAIN OF VARIABLE TOPOLOGY MECHANISMS

Refer to the concept of source-metamorphic mechanism and working-phase mechanism in [7] and [8], the definitions of all-phase kinematic chain and working-phase chain of variable topology mechanisms were listed as follows.

Definition 1

In the time domain of $T=[t_0, t_e]$, if $\exists t_0 < t_s < t_r < t_e$, the topology of variable topology mechanism m is $TS_M(t_s \rightarrow t_r) = (L_s, J_s, F_s)$ and is unchangeable in this period, the mechanism at the moment is a working-phase mechanism of variable topology mechanism and the corresponding chain is a working-phase chain.

Definition 2

All-phase kinematic chain is a various-DOF chain which contains the complete topological elements (L, J, F) of all working phases and is able to degenerate to any working-phase mechanism $TS_M(t_s \rightarrow t_r)$ in a simplest way.

The relation between all-phase kinematic chain and working-phase chain is illustrated in Figure. 2.

Figure 2. The relation between all-phase kinematic chain and working-phase chain

IV. CONFIGURATIONS OF THE ROBOT

Firstly assume its forward direction as the orientation of the robot. Left-front, right-front, left-rear and right-rear position is defined as the 1st, 2nd, 3rd and 4th position. Sign transformable links 1~4 as parts 1~4 separately; 1~4 thighs as parts 5~8; 1~4 joint wheels as parts 9~12; 1~4 crura as parts 13~16; 1~4 foot wheels as parts 17~20; the body as parts 21; the ground as parts 22. Taking the ground as the frame, all components of the robot is a closed chain. Then all-phase kinematic chain of the robot would be shown in Figure.3.

Figure 3. All-phase kinematic chain of the robot

Then the topology change of the robot was studied using topological graph theory. In order to facilitate the analysis, the DOFs of the robot was discussed separately. When one kind of DOFs is being discussed, other DOFs will be locked and the relevant components can be considered as one component.

(1) The topology of the status that the wheels contact with the ground. When transformable links and thighs are all fixed, the robot's joint wheels or foot wheels support the body and contact the ground. There may be 5 cases of all joint wheels contacting the ground, 1/2/3/4 foot wheel contacting the ground. And in every case, there are two subcases of joint wheels contacting the ground or not. Hence, there are 81 types of wheels contacting the ground,

$$C_4^0 + C_4^1 \times 2 + C_4^2 \times (C_2^0 + C_2^1 + C_2^2) + C_4^3 \times (C_3^0 + C_3^1 + C_3^2 + C_3^3) + C_4^4 \times (C_4^0 + C_4^1 + C_4^2 + C_4^3 + C_4^4) = 81.$$

(2) The topology of the status that the robot is steering. After getting rid of unstable cases, there are only three steering cases of front wheels steering, rear wheels steering, four wheels steering. Supposed that all joint wheels contact the ground and all foot wheels don't contact the ground, the topology of the cases are illustrated in Figure. 4.

Figure 4. The topology of the status that the robot is steering

(3) The topology of the status that the robot transforms. Here all the thighs and crura are fixed and transformable links swing to change the configurations of the robot. There are 15 cases, $C_4^1 + C_4^2 + C_4^3 + C_4^4 = 15$. After getting rid of unstable cases, there are 5 cases left. The topology of the cases are illustrated in Figure. 5.

Figure 5. The topology of the status that the robot transforms

In order to avoid the instability of the robot, the robot's steering and transformation could not be executed simultaneously. Hence, there are 1458 configurations for the robot, that is, $81 \times 15 + 3 \times 81 = 1458$. But if the robot's steering and transformation could only be executed when all joint wheels contact the ground and all foot wheels don't contact the ground, there are 99 types of the robot's configurations, $15 + 3 + 81 = 99$.

V. CONFIGURATION TRANSFORMATION ANALYSIS

The robot's configuration transformations can be executed by locking joints or imposing constraints. The reasonability of the robot's configurations should be verified through configuration transformation analyses. The configurations of variable topology mechanisms can be described by topological graph and adjacency matrix which can reflect the configuration change and the relationship between the components.

Firstly suppose all-phase kinematic chain as the original configuration (OC) and its adjacency matrix was given as (1) In the configuration transform process, the component number will change, which may change the matrix, such as increase and decrease the lines and rows. So in the below matrix the diagonal elements denote the serial number of the components, which won't change with the lines and rows changing. In this matrix, other element defines the connectivity between any two components, with joint symbol representing the connection between the components and 0 representing no connectivity between the components. R represent rotate pairs, S represent spherical pairs (Supposed that the connections between wheels and

working phases as $A_1, A_2, A_3, \dots, A_n$, so the adjacency matrix of all-phase kinematic chain is as below

$$A_0 = \bigcup_{i=1}^{n-1} A_i \cup A_{i+1} \quad (3)$$

The aggregating process includes several steps:

- ① According to the known adjacency matrices of working phases, renumber all the components.
- ② Expand the adjacency matrices based on the component numbers.
- ③ Perform aggregating operations on the matrices.
- ④ Based on the configuration transformation process, add and remove corresponding connectivities.

C. The conversing process from one working-phase chain to another working-phase chain

Similarly, there are three steps in the conversing process from one working-phase chain to another working-phase chain

- ① According to the known adjacency matrices, renumber all the components. Expand the adjacency matrices based on the component numbers.
- ② Based on the configuration transformation process, add and remove corresponding connectivities.
- ③ Delete all the lines and rows which elements are all zero except diagonal elements. The new matrix of the other working-phase chain will be gained.

VI. CONCLUSION

Based on a 5-link mechanism, a variable-topology mobile robot is presented. As a variable topology mechanism, the robot has many changeable configurations. The concepts of all-phase kinematic chain and working-phase mechanism have been presented and the

robot's configuration change analysis was given by metamorphic mechanism theory and topological graph theory.

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