Structure Analysis of Hybrid Self-Reconfigurable Modular Robot

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Abstract. Self-reconfigurable modular robots consist of many identical modules. By changing the connections among modules, the whole configuration of the robot can transform into arbitrary other configurations. In this paper, a hybrid self-reconfigurable modular robot is designed, which is composed of a master module and a slave module. Then, the docking process is analyzed with the geometric method. The docking states between two modules are presented. It is a complicated multi-peg-in-hole process.

Introduction

Self-reconfigurable modular robots (SMR) consist of a set of standardized electromechanical modules which can dynamically change their geometrical shape to complete different requirements of various tasks. Each module has the capability of intelligence, sense, communication and actuators. Therefore, they are more versatile, flexible, and capable than fixed-morphology robots. They can work in unstructured and unpredictable environments, such as the space and deep-sea exploration, rescue operations in earthquake areas.

The SMR can be classified into the lattice-type and the chain-type. The chain-type self-reconfigurable robots, such as the cubic modules (Polybot) [1], CONRO [2], have a higher degree of mobility than the lattice-type systems do. The lattice-type robots, on the other hand, can easily self-reconfigure and are suitable for forming various static configurations, but they have difficulty in generating motion, such as two hemispheres joined modules (ATRON)[3,4], the crystal module (Crystalline) [5], two semi-cylindrical parts (M-TRAN) [6] and M-Cube[7].

In this paper, we describe the configuration of a hybrid SMR. Its mechanical structure is designed, which can finish the docking process between two neighboring modules. The docking process is analyzed with the geometrical method.

Structure of Module

A hybrid self-reconfigurable modular robot is proposed. The basic module in the hybrid self-reconfigurable modular robot is composed of a master module and a slave module. The master module and the slave module are the shape of the triangular prism. Each has three connection sides. The slave module fixes to the master module on the fixed connection port. But it can rotate about the master module. On each module there are two connection ports. For the master module, there are two holes on each connection port. For the slave module, there are two pegs on each connection port (Fig.1). Each peg has a lock system, which can lock the connection when the peg inserts into other module’s hole. Then, two basic modules can connect to each other firmly. The connection ports can rotate along their axes.

Figure 2 shows the inner mechanics of the master module and the slave module. There are three motors in the master module. Motor 1 controls the rotary of the slave module. The other two motors (motor 2 and motor 3) control the holes to work. There are two motors (motor 4 and motor 5) in the slave module to control the pegs to work.
Analysis of Docking

The docking is a crucial action for self-reconfigurable robots. A successful docking action consists of at least three integrated complex stages. First, one action is to move a module on a given trajectory, so that two docking modules are physically positioned close to each other. Second, two docking modules must be aligned to each other to satisfy the constraints of the docking. Third, after two docking modules are aligned, the docking pegs are pushed into the holes and are locked. The undocking is an inverse process of the docking. When a robot decides to disconnect from an existing connection, it releases the latching mechanism by pegs. In fact, for our hybrid self-reconfigurable robot, the docking process is that two-peg of module $i$ inserts two-hole of module $j$. It is a complicated dual peg-in-hole process.

The geometric model of a dual peg-in-hole problem is shown in Fig. 3. Left peg has a radius of $r_{P1}$, whereas right peg has a radius of $r_{P2}$. The radii of left hole and right hole are $r_{H1}$ and $r_{H2}$, respectively. $D_D$ represents the distance between the axes of the pegs, and $D_H$ represents the distance between the axes of the holes. The clearances between the left peg and the left hole, and between the right peg and the right hole are $c_1$ and $c_2$, respectively. The dimensions of a peg and a hole are given as follows (Fig. 3): $2r_{P1} = 9.91$ mm, $2r_{P2} = 9.9$ mm, $2r_{H1} = 10.01$ mm, $2r_{H2} = 10.0$ mm, $D_D = 90.2$ mm, $D_H = 90.25$ mm, $c_1 = c_2 = 0.075$ mm, $\mu = 0.1$. 

$$
\begin{align*}
&2r_{P1} = 9.91 \text{ mm}, \
&2r_{P2} = 9.9 \text{ mm}, \
&2r_{H1} = 10.01 \text{ mm}, \
&2r_{H2} = 10.0 \text{ mm}, \
&D_D = 90.2 \text{ mm}, \
&D_H = 90.25 \text{ mm}, \
&c_1 = c_2 = 0.075 \text{ mm}, \
&\mu = 0.1.
\end{align*}
$$
n the paper, two-dimensional problems are discussed. There is the tilt angle $\theta$ between two docking modules. The boundary state of the docking is shown in Fig. 4. Its geometrical constraint is

$$\begin{align*}
h_0 \sin \theta_0 + 2 r_f \cos \theta_0 &= 2 r_h1 \\
h_0 \cos \theta_0 &= 2 r_f \sin \theta_0
\end{align*}$$

(1)

When $\theta$ is less than $\theta_0$, one-point contact state (Fig. 5) can be reached.

According to Fig. 6 (a), the geometric constraint of two-point contact state $l$ can be expressed as,

$$\begin{align*}
(h_1 - h_3) \sin \theta + (D_p + r_{p_1} - r_{p_2}) \cos \theta &= D_h + r_{h_1} - r_{h_2} \\
\text{(2)}
\end{align*}$$

For state $l$, $h = h_1 - h_3$.

According to Fig. 6 (b), the geometric constraint of two-point contact state $r$ can be expressed as,

$$\begin{align*}
(h_4 - h_1) \sin \theta + (D_p + r_{p_1} + r_{p_2}) \cos \theta &= (D_h - r_{h_1} + r_{h_2}) \\
\text{(3)}
\end{align*}$$

For state $r$, $h = h_4 - h_2$.

If Eqs. (2) and (3) have one solution at least, a three-point contact state can be reached. Fig. 7 suggests that a three-point contact state is relative to the geometry of modules. At the point where two curves of plots intersect, the three-point contact states can exist. From Fig. 7, we can see that three-point contact states are transient. Here $\theta_0$ and $\theta$ are angles between the axes of a peg and a hole, $h_0$ and $h_i$ are insertion depths, $f$ is the contact force.

From above, we can see, the docking is a complicated process. When $\theta$ is more than $\theta_0$, two modules cannot align. Pegs cannot insert into holes. They cannot finish the docking process. So, the tilt angle must be adjusted to make $\theta << \theta_0$ and avoid sticking. When $\theta < \theta_0$, because the uncertainty of geometry and control, contact states exist during two modules docking. Thus, the information of sensors must be used to adjust the pose of each module to finish the docking process.

**Summary**

The hybrid self-reconfigurable robot is designed. Each basic module consists of a master module and a slave module. The inner mechanics of the basic module is presented. Then, the states of the docking between two modules are analyzed with the geometrical method. It shows that the docking process among the hybrid self-reconfigurable robot is a complicated dual peg-in-hole process.
Acknowledgments

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