Motion Planning for a Reconfigurable Robot to Cross an Obstacle *

Minghui Wang1,3, Shugen Ma1,2, Xinyuan He4, Bin Li1, Yuechao Wang1

1Robotics Laboratory, Shenyang Institute of Automation, Chinese Academy of Sciences
Shenyang 110016, China
2Organization for Promotion of the COE Program,
Ritsumeikan University
Shiga-ken 525-8577, Japan
3Graduate School of the Chinese Academy of Sciences
Beijing 100039, China
4Technology Center,
Shenyang Machine CO., LTD
Shenyang 110016, China

mhwang@sia.cn shugen@fc.ritsumei.ac.jp hexinyuan@sia.cn libin@sia.cn ycwang@sia.cn

Abstract - A reconfigurable modular planetary robot system (RMPRS) consists of a parent body and multiple asymmetric wheel-manipulator child-robots. As an agent, the child-robot independently performs locomotion and manipulation. The child-robots have reconfigurable capability so that a group of child-robots are combined to a variety of configurations. Moreover, the child-robot gives output in different forms under various constraint conditions from one driving force. Utilizing this characteristic, it can cross an obstacle automatically. But the guiding wheel and the arm have fatal influence on the height of the obstacle that the child-robot can cross. A motion planning method for highly improving the capability of crossing an obstacle for the child-robot is proposed, which makes use of the environment and the posture of arm. The validity of the planning method is demonstrated by the experiments of the physical prototype.

Index Terms – reconfigurable modular planetary robot, wheel-manipulator child-robot, cross an obstacle, motion planning.

I. INTRODUCTION

Reconfigurable robots [1]–[7] consist of a group of modules that can be assembled into different configurations for better suiting their given task in some specific environment. This modular system shows the possibility of great versatility, robustness, self-repair and low cost. The general principle is to simplify the design and decrease manufacturing cost while enhancing functionality and versatility through a larger number of identical modules. Because the environment in some applications, such as exploration in space and military scouting, inspection in nuclear plants, is unstructured and the requirement of the task cannot be predetermined, the reconfigurable robots with the ability to organize shape change have more advantage in such applications.

Due to a wide range of potential future application, there has been some research work to be done on building and controlling reconfigurable robotic systems, such as space-robotics, disaster-area robotics. The PolyBot and polypod [1]–[3] as reconfigurable robot were developed for planetary exploration by Stanford University. Shen presented the

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batteries, chargers for child-robots and the instruments used to carry out various scientific experiments. The parent body cannot move by itself, however child-robots may support the parent body to locomote by the arms as its active wheels.

As an independent agent, a child-robot in RMPRS, when separating from the parent body, can independently locomote and manipulate [10], [11]. It consists of a wheel for locomotion and a 6 DOF arm with a manipulator for manipulation. Owing to specific characters of this mechanism, a child-robot module has two primary modes: manipulation mode and locomotion mode displayed in Fig. 2., and can transform between the two modes autonomously.

Three fingers of the manipulator in the child-robot may be controlled to close or open by one motor. The manipulator can grip the protuberant connecting part on the bottom and top of the triangle wheel. Position Sensory Detector (PSD) is adopted to implement the docking between the child-robot [12]. The docking mechanism includes the three fingers of the manipulator, PSD Receiver in the manipulator and three PSD Emitters respectively on the palm of the manipulator, on the bottom and the top of the wheel. Utilizing the above special design, the connection and disconnection between the child-robots is implemented as the base of the reconfiguration. Therefore multiple child-robot modules can mutually combine and reconfigure to different configurations as Fig.3.

III. DESIGN OF THE CHILD-ROBOT UNIT

A. Mechanical Design of the Child-Robot

Fig.4 demonstrates the principle of mechanical design of the child-robot [13]. The direct current servo-actuator drives the input wheel that is fixed to the same shaft as the sun wheel. The transmission wheel is responsible for driving the planetary wheel, which is fixed to the same shaft as the output wheel. Three output wheels are linked each other by the track. The output wheel and the planetary wheels are held on triangle-shaped link. The arm part is fixed on the shelf.

According to the characteristic of the wheel mechanism, this system can give output in different forms under various constraint conditions. When the load is low, the output of the system is that the output wheel is rotating. If the obstacle has the motion-opposing effect on the child-robot, the output moment of the servo-actuator will increase. When it is beyond
the range, the vehicle will roll over. In the manipulation mode, the wheel part contacts with the ground. Hence the output wheels don’t rotate in restraint of the ground. And the output of the system is that the arm part is rotating around on the shaft of the input wheel.

When the child-robot is in the locomotion mode, the wheel as the foundation is in contact with the ground. Due to the ground constraint on the output wheel and planetary wheel, the two wheels are not output given by the moment of the servo-actuator, and the form that the arm rotates around the input wheel becomes the output.

According to the mechanical design of the child-robot, the characteristic of this system is that the triangle-shaped figure of the wheel part enhances the stability of the child-robot locomotion, and each surface is regarded as the driving surface. Furthermore, the track being as the driving medium of the child-robot makes better use of the weight of the child-robot. With the adhesive power increased, the ability of locomotion on the mushy terrain is improved. On the coordination of the arm part, the system can give the output in different forms under various constraint conditions.

**B. Control System Design of the Child Robot**

For implementing the mechanical and motional characteristics, each part of child-robot should be controlled independently. Based on the distributed controllers and CAN, the modularized control structure of a child-robot [14], [15] is presented as displayed in Fig. 5. The structure and functions are dissembled into the plan and control, communication, computation and actuation of each mechanical part that are all independently encapsulated to modules executed by respective controllers.

This modularized control system contains Monitor_Supervisory System, Wireless Communication Module, Plan_Control Module, Computation Module and Actuation Module. The modularized design of the child-robot system can ensure synchronous motions of the mechanical parts. Moreover, each module uses independent controller so that the failure of the local does not influence other parts.

**IV. PRINCIPLE ANALYSIS OF CROSSING AN OBSTACLE**

When the child-robot is in the locomotion mode, the output wheel and the shelf as the output parts are driven, which give different forms of output according to the environment constraint on the child-robot. If the environment resistance on the child-robot is relatively lower, the moment of the servo-actuator is also lower and the form of output of the child-robot is the rotation of the output wheel. Hence the child-robot goes ahead, as shown in Fig. 6.

When the wheel encounters the obstacle, the exoteric resistance is relatively bigger. By reason of velocity servo in the control system, the moment of the servo-actuator is increasing. To some content, the form of output is that the arm rotates around the wheel, and the aim that the wheel will cross an obstacle is implemented in Fig. 7. It seems that the wheel part of the child-robot possesses the better ability of crossing an obstacle than some general robots.

However, as shown in Fig. 8, the arm and the guiding wheel become the bottle-neck of crossing an obstacle. If $H > R$, the guiding wheel cannot cross the obstacle, where H is the height of the obstacle and R is the radius of the direction wheel.

**V. PLANNING OF CROSSING AN OBSTACLE**

The characteristic of the child-robot in RMPRS is that it possesses two kinds of forms of output under one driving force, which can be utilized to implement the motion that the whole child-robot crosses an obstacle.
The motion condition of the child-robot is firstly analyzed in statics. If the force of friction of the ground is supposed to be big enough, as well as no relative sliding between the child-robot and the ground, only the influence in the motion, which the moment generated by the quality of the arm has, is taken into account.

In the state shown in Fig.9, the form of output is the rotation of the belt wheel. The condition of locomoting rightwards is that the resistance of the belt wheel can be overcome by the input moment of the servo-actuator. The constraint conditions of making the belt wheel motion are

\[ \tau' \cdot n \cdot n' / r > f_B \]

and the moment on the arm is not enough to raise the arm, as well as the condition is

\[ \tau' < G_A l_A \]

where \( \tau \): input moment of servo-actuator wheel;
\( n \): transmission radio from sun wheel to belt wheel;
\( n' \): transmission radio from servo-actuator wheel to sun wheel;
\( f_B \): track resistance to belt wheel;
\( \tau' \): moment on the arm;
\( G_A \): gravity of the arm;
\( l_A \): distance between the gravity of the arm and sun wheel.

Locomotion Direction
Track Wheel
Sun Wheel
Servo-actuator Wheel

Fig. 9 Static analysis of motion condition of the child-robot.

According to the relation between transmission moment and transmission radio of the sun wheel, the servo-actuator wheel and the arm shelf, the follow is deduced:

\[ \frac{\sigma_A - \sigma_b}{\sigma_b - \sigma_8} = n' \]

where \( \sigma_A \): rotational speed of servo-actuator wheel;
\( \sigma_b \): rotational speed of arm shelf;
\( \sigma_8 \): rotational speed of sun wheel.

When the arm is in critical state between the rest and motion, the hypothesis is \( \sigma_8 = 0 \). The following is deduced:

\[ \frac{\sigma_A}{\sigma_b} = 1 - n' \quad (1) \]

\[ \frac{\sigma_A}{\sigma_b} = \frac{\tau'}{\tau} \quad (2) \]

From the expression (1) and (2), the result is:

\[ \tau' = \tau(1 - n') \]

When the belt wheel of the child-robot rotates, the condition in which the arm does not motion is

\[ \frac{f_B \cdot r}{n \cdot n'} < \tau < \frac{G_A l_A}{1 - n} \quad (3) \]

In the state shown in Fig.8, the condition in which the form of output is the rotation of the arm is

\[ \tau \cdot n \cdot n' / r < f_B \]

And it is also the condition in which the belt wheel does not rotate.

The constraint condition of raising the arm is

\[ \tau' > G_A l_A \]

When the belt wheel does not rotate, the condition in which the arm rotates is

\[ \frac{r \cdot f_B}{n \cdot n'} > \tau > \frac{G_A \cdot l_A}{1 - n} \quad (4) \]

The expression (3) and (4) are demonstrated in Fig.10, which seems that the demand of child-robot motion can be satisfied according to adjusting \( f_B \) and \( l_A \). The variation range of \( l_A \) is

\[ l_{A_{min}} \leq l_A \leq l_{A_{max}} \]

If \( f_B \) is just between \( f_{B_{min}} \) and \( f_{B_{max}} \), the output is controlled according to adjusting the posture of the arm. If \( f_B < f_{B_{min}} \), only the external environment is utilized to increase \( f_B \) to limit the belt wheel not to rotate for implementing the rotation of the arm. If \( f_B > f_{B_{min}} \), the motion of the child-robot is not implemented in the state in which the belt wheel rotates and the arm does not rotate.

According to the above analysis, if the height of the obstacle is lower than the radius of the direction wheel, the child-robot can cross the obstacle without any planning methods. If being opposite, the planning process of crossing an obstacle is as the following:

1. As shown in (a), (b) and (c) of Fig.11, the driving servo-actuator rotates forward to make the child-robot locomote toward the obstacle until the wheel cross over the obstacle.

Fig. 10 The relation between \( f_B \) and \( l_A \).
(2) After the wheel crossed the obstacle, the posture of the arm is adjusted for decreasing $l_A$, as shown in (d) of Fig.11.

(3) As shown in (e) and (f) of Fig.11, the driving servo-actuator rotates backward. Utilizing the obstacle effect on the child-robot, $f_B$ is increased indirectly, which implements that belt wheel does not rotate and the arm rotates. Hence the arm also crosses the obstacle.

(4) As shown in (g) of Fig.11, the posture of the arm is again adjusted for increasing $l_A$.

(5) As shown in (h) of Fig.11, the driving servo-actuator rotates forward to make the belt wheel rotate and the arm not rotate, and then the child-robot goes ahead again.

Fig. 11 Motion planning of crossing an obstacle.

Although this planning method can increase the height of the obstacle that the child-robot can cross, the height of the obstacle is in the limit. The condition must be satisfied that the obstacle lies between the wheel and the guiding wheel when the child-robot is locomoting as displayed in Fig11 (d). This condition can increase $f_B$ indirectly.

VI. EXPERIMENT

To testify the validity and effectivity of the planning method of crossing an obstacle, it is employed on the physical prototype of the child-robot to perform the experiment as demonstrated in Fig.12. The height of the obstacle is 50mm and the width is 80mm.

Firstly, the servo-actuator drives forward to make the child-robot arrive before the obstacle and then make the wheel cross the obstacle. The obstacle is just between the wheel and the guiding wheel. Secondly, the posture of the arm is adjusted to make the barycentre of the arm approach the wheel. The servo-actuator drives backward, and the obstacle resistance on the wheel raises the arm and makes it arrive before the wheel. In the following, the posture of the arm is adjusted again to be far from the wheel. At last, the servo-actuator drives forward again to implement the locomotion of the child-robot. This is the whole planning process of crossing an obstacle in the experiment.

Fig. 12 Experiment of crossing an obstacle on the physical prototype.

From this experiment, it is found that this planning method utilizes the characteristic that the child-robot possesses two kinds of outputs under various constraint conditions from one driving force, and realizes the aim that the whole child-robot can successfully cross an higher obstacle.

VII. CONCLUSION

This paper discussed motion planning for the child-robot in RMPRS to automatically cross an obstacle. A new motion planning method is presented for the purpose of increasing the height of the obstacle that the child-robot can cross. This method utilizes the environment constraint and two forms of the child-robot’s output from one driving force, simultaneously changing the posture of the arm. As a result, a sequence of the child-robot motions is acquired to allow the child-robot to trace a desired trajectory to cross the higher obstacle. Finally, the experiment on the physical prototype testified the validity and effectivity of the motion planning method.
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