Two-dimensional PSD based automatic docking of self-reconfiguration modular exploration robot system

Zhang Liping\textsuperscript{1,2}, Ma Shugen\textsuperscript{2,3}, Li Bin\textsuperscript{2}, Zhang Zheng\textsuperscript{3,4}, Cao Binggang\textsuperscript{4}

\textsuperscript{1 School of Construction Machinery, Chang'an University, Xi'an 710064, China; 2 Robotics Laboratory, Shenyang Institute of Automation, Shenyang 110016, China; 3 COE Research Institute, Ritsumeikan University, Shiga-ken 525-8577, Japan; 4 School of Mechanical Engineering, Xi'an Jiaotong University, Xi'an 710049, China}

Abstract: Based on the design of a docking mechanism, this paper thoroughly investigates the space automatic docking of self-reconfiguration modular exploration robot system (RMERS). The method that leads robot to achieve space docking by using two-dimensional PSD is put forward innovatively for the median size robot system. At the same time, in order to enlarge the detecting extension and the precision of PSD and reduce its dependence on lighting signal, the PSD was remedied by increasing the optical device over its light-sensitive surface. The emission board and LED light scheduling were designed according to docking arithmetic, and the operating principle of docking process was analyzed based on these. The simulation experiments were carried out and their results are presented.

Key words: reconfigurable; modular; position sensing detector; automatic docking

1 Introduction

Today, self-reconfiguration and modularization are two very active research directions. Modularization depicts the components of machine or the whole machine. The modularization not only strengthens the part exchangeability, but also benefits the system maintenance\textsuperscript{11}. Reconfiguration includes self-reconfiguration and manual reconfiguration. The self-reconfigurable robot is connected by many simple but perceptive modular robots. The self-reconfiguration robot system may obtain independent adaptive capacity that can change their structures and shapes autonomously according to their external environment or task demands. These characteristics make them robust and flexible to suit their tasks and environment.

The exploration robot system is used in dangerous circumstances. For example, they are highly desirable in tasks such as fire fighting or survivor rescuing after an earthquake. They can be used in battlefield reconnaissance, where robots encounter unexpected situations and have to perform the tasks that seem difficult for fixed-structure robots. The unknown character of criticality in unexpected situations and limited exploration cost demand that the exploration robot may be used to forecast the circumstance component and danger degree, and demand that the robot ought to be lighter. So the modularization and self-reconfiguration must be the important research aspects in the exploration robot system\textsuperscript{14}.

Robot's docking is the process that two parts of a robot system or two robots connect together under the direction of sensor information. Docking is the basic and key technology for self-reconfiguration. In this paper the modularization and reconfiguration are united to develop robot system, the space docking method is researched in detail.

2 Design of RMERS child-robot and its docking mechanics

In China, the self-reconfigurable modular exploration robot systems are mostly snake robots, search and rescue robots and planetary exploration robot system, which are made by Shenyang Institute of Automation, Chinese Academy of Sciences\textsuperscript{14}. The docking of snake robot and search and rescue robot is limited to manual docking; in this paper, the space automatic docking of RMERS is investigated thoroughly.
2.1 Operating principle of RMERS

RMERS are applied in unknown environments such as reconnaissance, disaster rescue, planetary exploration, etc. Compared with other exploration systems, it has obvious advantage and characteristics. The RMERS consists of one main body and six wheels, as shown in fig. 1. The main body has solar battery cell, communication devices, computer control system, navigation camera, mechanical arm, sample analyzer and battery chargers, etc. Each wheel acts as a child robot, which has a wheel for locomotion and an arm for manipulation. The characteristics of this system are:

(1) The self-reconfiguration includes two meanings: one is between the main body and the child robot, which is inhomogeneous reconfiguration; the other is between the child robots, which are homogeneous reconfiguration.

(2) The main body cannot move by itself, but the child robots hold the main body of RMERS by their manipulators and act as active wheels of the main body. If it is necessary, each child rover can separate from the main body and move around to undergo separate missions. The child robots also connect as different configuration to pass complicated terrain.

(3) Restricted by volume, the child-robots can not carry more electricity equipment, but when necessary, they can connect with the main body and charge up from the main body to recruit their energy.

(4) Each child robot has two operation modes, the work mode and the locomotion mode, when it is in work mode, the child robot may sampling or monitor the environment; in locomotion mode, it can move ahead and back, and can turn.

![Fig. 1 self-reconfiguration modular exploration robots system](image)

2.2 Design of the child robot and docking mechanism

The child robot, as shown in fig. 2, has six degrees of freedom. Joint 1 may turn around the center axis of the triangle wheel; the axes of Joint 2, 3 and 4 are parallel each other and perpendicular to Joint 1; the sixth degree of freedom controls open and close of the paws. The operation principle of the mechanism inside the triangle wheel is shown as fig. 2 (b). Direct current servo motor 5 drives input wheel 7, the revolution of wheel 7 can drive central wheel 8, central wheel 9, transition wheel 2 and output wheel 1 are made up of a meshing gear mechanism whose momentum is passed from wheel 2 to wheel 1. The active pedrail wheel has the same axis with output wheel, it meshes with the outer pedrail at the same time, and its revolution may drive the pedrail, the pedrail then drives the other passive pedrail wheels, thus the triangle pedrail mechanism move forward or backwards. The central axes of output wheel 1, transition wheel 2 and center wheel 8 are connected top planetary frame 3. Direct current servo motor 5 and arm are fixed on arm frame 6. Such design makes the child-robot of RMERS have two distinct characteristics: one is that the single input may bring two outputs. The input is made by the motor inside the triangle wheel. Two outputs are locomotion of the triangle and revolution of the arm. The other characteristic is the integrative design of the wheel and arm.

![Fig. 2 the child robot's mechanism](image)
had researched automatic docking, by far the basic docking mechanics are: pin-hole-pin, magnetic model, shape matching of the slippage pin, and the snatching three dimension shape matching[1]. In RMERS, considering that docking mechanics are used to connect two mobile robots, which must permit bigger aiming error and proper locomotion tolerance, three dimensional shape matching mechanics are adopted, as shown in fig. 2 (a). A column platform with rounded groove acts as the connecting face, an emitting board equipped with light-emitting diode (LED) array is set just in the middle of the connector. Three fingers are distributed around the end-manipulator; and the position sensing detector (PSD) is installed inside it. When one child-robot snatchs others' emission board inducted by the PSD, the automatic docking is achieved. Based on these, adjusting two child-robots' articulation angles may form different configurations.

3 Sensor selection and emission board design

At present, the self-reconfiguration systems have been developed in two extreme, one is large-sized system docking, Larger system may utilize special sensors according to its characteristics. For instance, satellite communications may be used in outer space, and sonar navigation in ocean. These conditions disagree with most mechanics. For general purposes, the infrared emitter/receiver were usually studied and adopted in small docking systems. Some are equipped with other miscellany sensors such as tilt sensors and miniature cameras[12][13]. The measurement range of the infrared emitter/receiver is limited in very small space, and they are set on the same altitude, the docking should belong to two-dimensional, and can not implement 3-D docking. The vision sensors such as camera are usually used in self-configuration, whose shortcoming is comparatively complex in managing signal. The RMERS has several cameras on the main body. The limit space and managing speed of child robot decide that the cameras can not be adopted. So new sensor must be found.

3.1 Sensor selection

Docking describes the process that two robot modules approach step by step and aim at each other in the end, in which the position offset on every orientation needs to be corrected continually. For space robot docking, the position offsets and rotation offsets on X, Y and Z orientations are the values to be corrected. Usually the rotation offsets may be estimated by measuring positions. So the position sensor is often equipped on the two faces connected. In this paper, PSD and the emitting array constituted by LED are adopted, by designing novel docking arithmetic, two mobile robots are inducted to dock.

PSD is a special light-emitting diode that has big photosensitive face. When the spot light shines on the photosensitive face, the received electricity signals are different. The position of the lighting spot on the photosensitive face can be confirmed according to the electricity signals. PSD's high differentiation ratio and the performance irrespective of the lighting spot intensity, distribution, symmetry and dimension make it very popular in position monitor field. As a four-output apparatus, the two dimension PSD may get the lighting spot's position according to its four output ends, thus high sampling frequency may be achieved and it is benefit for real time sampling. The equipment demands that the volume of PSD is smaller and the active area is larger. In order to make the X and Y orientation equivalence, the PSD whose photosensitive face is foursquare is selected first. So the S1743 made by HAMAMATSU Company was adopted, whose photosensitive face is 4.1 mm x 4.1 mm and view angle is 60 degrees.

In the experiment, the infrared emitters are used to simulate the lighting spot whose diameter ought to be much smaller. At the same time, in order to increase the sensor’s detection range, its visual angle ought to be wider as much as possible. So the standard diffusion LED from Hewlett Packard was adopted whose diameter is 3 mm, view angle is 60 degrees and the length is 4.5 mm.

3.2 Characteristic experiment of PSD

A facility test-bed was put up to validate the PSD's performance and the feasibility in further experiment. The simulating emission board is arranged in fig. 3 (a). Four LEDs at the corner are spaced 20 mm, a 4-way switch is used to control four LEDs respectively, fig. 3 (b) is the area PSD S1743, five leads behind which are the terra lead and four output electrodes. The signal processing circuit is designed in fig. 4. In one sampling period, the analog/digital (A/D) collects signal once and calculates out the LED's image coordinates.
The image coordinates can be solved by:

\[
\begin{align*}
Y &= \frac{\Delta Y_2}{\sum Y_2} \\
X &= \frac{\Delta X_2}{\sum X_2}
\end{align*}
\] (1)

In order to validate the signal processing circuit, make the resistances \( r_1 \) and \( r_2 \) connect in series, \( r_1 \) and \( r_2 \) represent the resistances on \( Y \) orientation between the image of lighting spot and the two ends of PSD. (X orientation follows the same principle), \( U_i \) represents the photoelectric voltage. Put different voltage on \( U_i \), detecting the values of \( U_1, U_2, U_0 \) and \( U_0 \) on \( X \) and \( Y \) directions. According to fig. 4, when \( r_1 = r_2 = R_1 \), we can get:

\[
\begin{align*}
U_1 &= U_2 = U_i \\
U_{00} &= U_i - U_2 \\
U_{0i} &= U_i + U_2
\end{align*}
\] (2)

When \( r_1 = r_2 \), given different \( U_i \), five group values on \( X \) and \( Y \) orientations are detected respectively, table 1 gives the experiment results. From the table, we can get; at \( X \) and \( Y \) orientations, the error of \( U_{00} \) increases along with \( U_i \), when \( U_i = 5 \) V, in ten group values detected, the error variation range of \( U_{00} \) is \( 0 - 0.87 \% \), this indicates that the errors in two circuits are little enough. For very little inductive current and voltage, the role of amplificatory circuit is only to zoom minuteness voltage to normal range. Compared with hardware circuit, the division error calculated by software can be ignored almost. The software division operation is shown in equation (1). Experiments indicate that the circuit in fig. 3 can completely satisfy the practical application.

Four signal changing curves \( \Delta Y_1, \Sigma Y_2, \Delta X_2 \) and \( \Sigma X_2 \) are observed through oscillograph. Open one switch on analog emission board, the LED controlled by it will shine, then move the analog emission board while observing the wave variation on oscillograph. As a result, we can get; (1) When the emission board points to the PSD rightly, the wave shape gets to a stabilized value; (2) Move the emission board to one side, the wave shape changes monotonously until it reaches an extremum; (3) When the emission board is moved in reverse direction, the wave shape has the same
change trend on the other side of \( X \) axis. Two maximums of
\( \Delta Y_j \) and \( \Sigma Y_j \) are shown in fig. 5, the maximum values of \( \Delta Y_j \)
distributed on different sides of the zero scale line, but one value of \( \Sigma Y_j \) is at the zero scale line rightly. The results show that when the spot light is shining at the middle point of
PSD, the value of \( \Sigma Y_j \) is near the zero scale line, \( \Sigma Y_j \) is a
negative value in other position, but \( \Delta Y_j \) value is rightly at the midpoint of its minimum value and maximum value. So
\( \Delta Y_j/\Sigma Y_j \) are varying between positive and negative values, at the same time, the numerical value varies monotonously.
The numerical value of \( \Delta X_j/\Sigma X_j \) has the same varying trend. So \( \Delta X_j/\Sigma X_j, \Delta Y_j/\Sigma Y_j \) can distinguish out the four
sections on the PSD surface. We can also observe from the experiment that the distance between LED and PSD can affect the voltage value, when the distance is farther than 10
mm, PSD can not sense the light signal. One reason is the oversized error occurred by imitating spot light with LED; the other one is great reduction of the light on PSD photosensitive face with the distance increasing. In order to use the two dimensions PSD in this experiment, we must remake
PSD to increase its detecting range, distance and precision, which is explicated in reference\(^{[1]}\).

<table>
<thead>
<tr>
<th>( r_1 )</th>
<th>( r_2 )</th>
<th>( U_1 )</th>
<th>( U_1 )</th>
<th>( U_1 )</th>
<th>( U_1 )</th>
<th>( U_1 )</th>
<th>( U_1 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>0.158</td>
<td>0.108</td>
<td>0.001</td>
<td>0.3</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>2.033</td>
<td>2.016</td>
<td>2.019</td>
<td>1.1</td>
<td>4.00</td>
<td>4.035</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>3.032</td>
<td>3.007</td>
<td>3.012</td>
<td>2.9</td>
<td>5.98</td>
<td>6.019</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>4.03</td>
<td>4.00</td>
<td>4.00</td>
<td>4.5</td>
<td>8.00</td>
<td>8.00</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>5.04</td>
<td>4.99</td>
<td>5.00</td>
<td>6.5</td>
<td>9.99</td>
<td>9.99</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1.008</td>
<td>1.004</td>
<td>1.001</td>
<td>0.1</td>
<td>2.011</td>
<td>2.005</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>2.033</td>
<td>2.027</td>
<td>2.022</td>
<td>1.7</td>
<td>4.03</td>
<td>4.049</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>3.032</td>
<td>3.024</td>
<td>3.017</td>
<td>2.2</td>
<td>6.00</td>
<td>6.041</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>4.030</td>
<td>4.02</td>
<td>4.01</td>
<td>3.0</td>
<td>8.04</td>
<td>8.03</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>5.04</td>
<td>5.02</td>
<td>5.01</td>
<td>4.9</td>
<td>10.04</td>
<td>10.03</td>
</tr>
</tbody>
</table>

3.3 Design of LEDs scheduling

Suppose the LEDs in fig. 3 are named as \( A', B', C', D' \), which are used to adjust the corresponding degree between the emission board and the receiving board when docking start. They should work in time-sharing state to ensure that \( A'/D \) can distinguish them out. The light scheduling of them is designed in fig. 6. The pulse cycle of \( A'/D \) is 10 ms, so the lighting duration of each LED is designed as 10 ms, in this way we can ensure that \( A'/D \) can receive the PSD signal in which lighting period. Given the lighting time interval of 10 ms between two LEDs, the PSD will have enough response time. The lighting period of LED group \( A', B', C' \) and \( D' \) is designed as 120 ms, which equals to \( A'/D \)'s twelve pulses. \( A'/D \)'s sampling period is designed as 240 ms. These design can insure that the tester can distinguish the lighting signals of \( A', B', C' \) and \( D' \) and can not consider synchronization between the emission board and receiving board. In one sampling period, the whole lighting time of \( A', B', C' \) and \( D' \) are 80 ms. Begin from arbitrary time, continuously sample 240 ms, if we can collect four signals at intervals of 20 ms, the sampling values are reserved, otherwise ignore them. If the emission board lies in the PSD sight, we can collect a group continuous \( A', B', C' \) and \( D' \) values at least.

![A/D sampling point on PSD](image)

![A' LED](image)

![B' LED](image)

![C' LED](image)

![D' LED](image)

![A lighting period](image)

4 Operating principle of the docking process

After PSD remade and LED array arranged, the space docking can be achieved according to correct docking arith-
The operating principle is a position feedback and closed loop control system in fact, as shown in fig. 7. Two child robots to dock form a closed loop through the photovoltaic electricity induction signal formed between the LED on robot 1 and the PSD on robot 2. After the position deflection is corrected by the processor in robot 2, the end manipulator of robot 2 will move according to the result, thus the position deflection is decreased. Docking process is depicted as: when the docking begins, the main processor of locomotion child robot gives instructions to its control module, the instructions include the A/D pulse frequency, LED’s light frequency, the lighting duration of each LED and the lighting interval of LED, the instructions processed by control module are sent directly to LED’s driving circuit and the LED begins to light. After getting the light signal, the child robot in work mode begins to work. At first, it searches the LED signals in its work space according to the docking arithmetic, when the object is found, its PSD exports four electricity signals to its signal processing circuit that correspond to a pair of X and Y values, from the values we can calculate the position on PSD plane corresponding to the lighting spot. The different positions of LEDs on emission board are differentiated by time scheduling.

Fig. 7 Operating principle of PSD

5 Experimental and simulating results

In order to validate the above-mentioned method, we give an error and criterion to simulate two robots’ docking on the platform that is based on OPENGL and VC ++ (fig. 8 (a)). The development environment was developed by Zheng Zhang in our research group. According to reference [16], when the arm of child robot in work mode moves in work space, the system will be in static balance. The two child robots in docking work space may achieve space dock automatically under the PSD’s induction. Locomotion coordination is constructed the same as reference [14], the initialization pose and gesture of the child robots in locomotion mode and work mode are shown in fig. 8 (b) (1). Simulation result is shown in fig. 8, (1) and (2) are the child robots in work mode whose end manipulator is 60 degrees upwards and is searching objective, (3) shows it found nothing, (4) shows the work mode child robot changes its pose to 60 degrees downwards, (5) and (6) are the course in which work mode child robot finds objective and changes pose to dock, (7) and (8) are the docking process according to the sensors’ information.

6 Conclusion

In this paper, the space docking method using two dimensional PSD is put forward, its operating principle and feasibility are analyzed. Primary experiment was carried out. For PSD demands absolute spot lighting, using LEDs instead of
spot lighting can not meet the demands. In order to improve PSD measurement range and precision, we remade the PSD, added an optical cylinder camera lens on its photosensitive face. At the same time, we simulate emission board with four LEDs on it and their light schedulings are designed, operating principle for dock is analyzed. In the end, the simulation experiments are given on the platform constructed by VC and OpenGL. The result validates the docking process.

References


Biographies

Zhang Liping, female, born in March 1975, lecturer in Chang’an University, specialty in mech-electronics, main research direction: intelligent control of mech-electronic systems, reconfigurable planetary exploration robot systems. Address: School of Construction Machinery, Chang’an University, Xi’an 710064, Shanxi, China E-mail: lipzhi221@163. com