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Multi-sensor systems and information processing of mobile robot in uncertain environments

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Abstract: The PBJ-01 robot is a kind of mobile robot featuring six wheels and two swing arms which can help it to fit many terrains. The robot has a sophisticated sensor system, which includes ultrasonic sensors, tentacle sensors and a vision sensor. The PBJ-01 adopts behavior-based reactive control architecture in which the key part is an object recognition system based on a fuzzy neural network. Simulation validates that this system can conclude the obstacle type from the sensor data, and help the robot decide whether to negotiate or to avoid obstacles.

Key words: mobile robot; behavior-based reactive control architecture; neural network

The PBJ-01 robot was developed by Research Institute of Robotics of Shanghai Jiaotong University. It can do a lot of hazardous tasks such as explosives handling, airport security and nuclear surveillance. The customers for such a system include military police and other law enforcement and security entities.

1 PBJ-01 Robot

The PBJ-01 robot is actually a joint-wheeled mobile robot. It is 1.2 m long, 0.7 m wide and 1.2 m high (see Fig.1). Two swing arms are mounted in front of the robot, and they can turn up and down when the robot negotiates some obstacles. The PBJ-01 robot can turn left or right when the speed of the left wheels differs from that of the right. A mechanical hand is mounted on the robot with 4 degrees of freedom (DOF) and can grasp 20 kg weight.

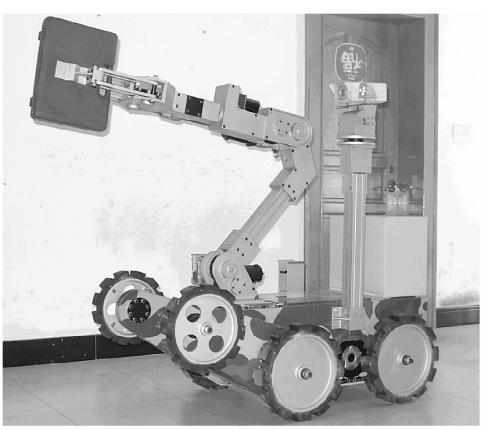

Fig.1 PBJ-01 robot

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2 Sensor Systems

The first problem for local autonomous mobile robot is to sense the state of robot and environment reliably and correctly. In fact the robot usually runs in a dynamic, uncertain or unknown environment. So the sensors that bring much information about the surroundings are more important[1]. The sensor system of the PBJ-01 robot includes posture sensors, ultrasonic sensors and a vision sensor.

2.1 Posture sensors

The posture information of the PBJ-01 robot includes the rotary angle of the swing arms, pitching and sideways angles of the body and the bottom headroom of the robot. The rotary angle of the swing arms is measured by the simple potentiometer; the pitching and sideways angles are respectively measured by the clinometers which are parallel with lengthways and transverse direction; the bottom headroom of the robot means the distance between its bottom and ground. The headroom sensor is actually a kind of tentacle sensor which will engender a signal when it touches something. We install an array of these sensors on the chassis: 5 columns and 4 rows. There are two kinds of tentacles: 6 cm in length and 15 cm in length. If the longer tentacle engenders a signal while the shorter does not, the bottom headroom is in normal range; if the shorter engenders, the bottom headroom is under the lower limit and the robot is in danger of collision against ground; if neither engenders a signal, the bottom headroom is bigger than the upper limit and the robot is in danger of an overturn.

2.2 Ultrasonic sensors

Twenty ultrasonic sensors are mounted on the front board of the PBJ-01 robot: 5 columns and 4 rows; 4 ultrasonic sensors are mounted on two sides of the body: 2 sensors each side. The sideward sensors measure the distance between the body and obstacles on the left or right. The half of the sum of right and left sensor data and the width of the body will be taken as the ideal position of the robot when it avoids obstacles. If there are obstacles on only one side and none on the other side, we will take a fixed value as the ideal position. The ultrasonic sensors on the front will bring many data about obstacles, which will be the brief criterion for the controller to judge whether the obstacle can be negotiated or not.

2.3 Vision sensor

The current vision sensor has poor ability in real-time information processing and requires the use of many computational resources, and it is difficult to satisfy real-time demand for the robot. On the PBJ-01 robot, two cameras are mounted on the camera pan/tilt mechanism, which point the camera relative to the robot. The cameras are not used for decision-making or control at this time; they just provide much scene information for the operator to monitor or for remote control. Many tasks such as explosives handling are much more complicated and require cooperation with the operator using this information.

3 Behavior Control Architecture

It is inevitable that the robot will meet many unexpected events when it operates in an uncertain environment. Thus, the robot should have the ability to respond to these unexpected events and to deal with them rapidly. The PBJ-01 robot adopts behavior-based reactive control architecture[2], which can quickly react to the changing surroundings. Fig. 2

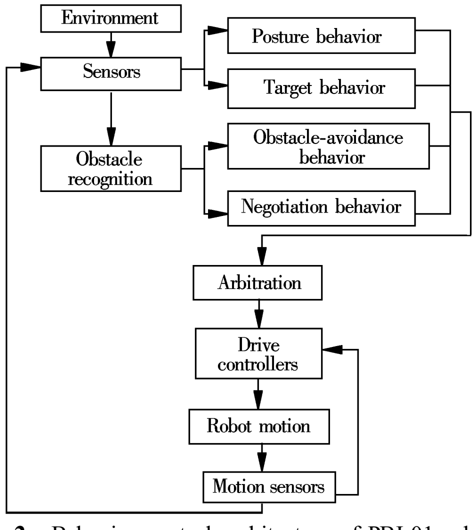

Fig.2 Behavior control architecture of PBJ-01 robot

shows the behavior control architecture that has been developed. The inner motion-control loop of the control architecture uses a simple PID control algorithm, which acts to drive the wheels and swing arms at their desired speed and to force the robot to follow a desired path in space. The innovation developed in this architecture is the outer-most loop, which uses environmental sensor data to compute the paths and yaw angles.

3.1 Target behavior[3]

This behavior mainly ascertains the direction of the target for the robot.

$$\boldsymbol{V}_{\text{goal}} = \frac{v_{\max}}{\sqrt{(x_g - x_r)^2 + (y_g - y_r)^2}} \begin{Bmatrix} x_g - x_r \\ y_g - y_r \end{Bmatrix}$$

where $\{x_g, y_g\}^T$ denotes the coordinate of the target, $\{x_r, y_r\}^T$ denotes the coordinate of the current position, and $v_{\max}$ denotes the maximal speed of the robot.

3.2 Obstacle-avoidance behavior[3]

This behavior mainly avoids the collision between the robot and obstacles.

$$\boldsymbol{V}_{\text{collision}} = v \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{Bmatrix} x_d \\ y_d \end{Bmatrix}$$

where $\{x_d, y_d\}^T$ denotes the vector of the head of the robot, and θ is the rotary angle of the robot.

3.3 Posture behavior

This behavior is used to adjust the posture of the PBJ-01 robot turning the swing arms to ensure the bottom headroom, pitching and sideways angles in the allowable range. This behavior has a high priority, and it will be executed restraining other behaviors when the sensor data is out of the range.

3.4 Negotiation behavior

The characteristic of the behaviors is negotiation behavior, and the PBJ-01 robot can negotiate some familiar obstacles such as stairs and entrenchment by the help of the swing arms.

4 Object Recognition Systems

Object recognition means that the robot makes a judgment whether the object can be negotiated or not. If the conclusion is positive the robot will adopt negotiation behavior, otherwise the robot will adopt obstacle-avoiding behavior. The obstacles the PBJ-01 robot falls across are almost artificial and are classified into 3 types: vertical ones such as stairs, bevel ones such as slope, anomalistic ones which include all that are different from the former two. A good strategy would be to construct a perfect mapping between input sensor data and appropriate control actions. The relationship, however, is very complicated and highly nonlinear. It is well recognized that artificial neural networks have impressive capacity for nonlinear mapping and pattern recognition applications[4]. A neural network system (see Fig.3) is used to achieve the desired pattern recognition results on the PBJ-01 robot. The system is a three-layered, pattern-clustering network. Once it is trained, there is a prototype pattern associated with each cluster. Because we just take three kinds of obstacles into account, we will decide the prototype patterns according to experiment data and man's experience to decrease computation time[5,6] and to simplify the problem.

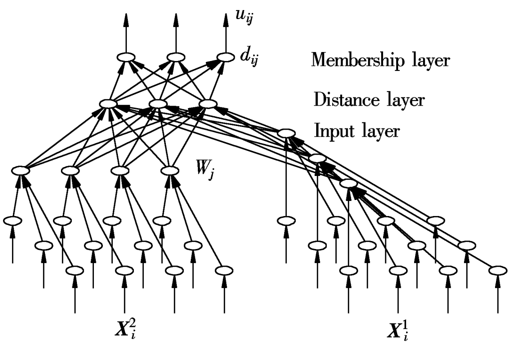

Fig.3 Structure of the neural network system

4.1 Prototype pattern assignment

As shown in Fig.3, the distance layer is responsible for comparing an input pattern with the prototype patterns. Output d_{ij} of node j in the distance layer equals 0 when the input pattern O_i perfectly matches the prototype pattern W_j. The output of the distance layer is computed as follows:

$$d_{ij} = \| O_i - W_j \|^2 = (O_i - W_j)^{\mathrm{T}}(O_i - W_j) \tag{1}$$

where W_j is the j-th prototype pattern. Eq.(1) is a two-norm equation. The larger the difference between O_i and W_j is, the faster d_{ij} will increase by powers of 2. The membership layer is provided to map the distance d_{ij} to membership values u_{ij}. If an input pattern does not match any prototype pattern, then the similarity between the input pattern and each individual prototype pattern is represented by a membership value from 0 to 1. The determination of the membership value can be summarized by

$$u_{ij} = \begin{cases} 1 & d_{ij} = 0 \\ 0 & d_{ik} = 0\,(k \neq j,\ k \geqslant 0,\ j \leqslant n) \\ \left(\sum\limits_{l=1}^{n+m} \dfrac{d_{ij}}{d_{il}} \right)^{-1} & \text{others} \end{cases} \tag{2}$$

where n denotes the number of prototype patterns. The larger the u_{ij} is, the input pattern O_i is more similar to some prototype pattern W_j. The sum of the outputs of the membership layer equals 1. The input matrix $\boldsymbol{X}_i$ of the input layer includes two matrices: $\boldsymbol{X}_i^1$ and $\boldsymbol{X}_i^2$ which are both the transform matrices of the sensor data matrix $\boldsymbol{Q}_i\,(n \times m)$. The transform relationship is as follows:

$$\left.\begin{aligned} x_{ij}^{(1)} &= q_{ij} - q_{i,j-1} \\ x_{ij}^{(2)} &= q_{ij} - q_{i-1,j} \end{aligned}\right\} \tag{3}$$

$\boldsymbol{X}_i^1$ and $\boldsymbol{X}_i^2$ are first-order differences of the sensor data matrix by coordinate x and y, respectively. They are $n \times (m-1)$ and $m \times (n-1)$ matrices, respectively, and they will be quantized by Eq.(4) before inputting:

$$x_{ij}^{\mathrm{Q}} = \begin{cases} 1 & 0 \leqslant x_{ij} \leqslant 10 \\ 2 & 10 \leqslant x_{ij} \leqslant 15 \\ 3 & 15 \leqslant x_{ij} \leqslant 20 \\ 4 & 20 \leqslant x_{ij} \leqslant 30 \\ 5 & x_{ij} \geqslant 30 \end{cases} \tag{4}$$

The output equation of input layer is

$$\left.\begin{aligned} O_i^1 &= \sum_{k=1}^{m-1}\left(x_{ik}^{(1)} - \frac{1}{m-1}\sum_{l=1}^{m-1} x_{il}^{(1)} \right) \quad i = 1, 2, \cdots, m \\ O_i^2 &= \sum_{k=1}^{n-1}\left(x_{ik}^{(2)} - \frac{1}{n-1}\sum_{l=1}^{n-1} x_{il}^{(2)} \right) \quad i = 1, 2, \cdots, n \end{aligned}\right\} \tag{5}$$

Next, we describe the procedure of this prototype pattern:

① A quantized ultrasonic sensor vector (input pattern) constructed from current ultrasonic sensor readings is presented to the neural network input.

② The distances between the input pattern and each prototype pattern are computed by Eq.(1).

③ The similarities between the input pattern and each prototype pattern are calculated by Eq.(2). The similarities are represented by membership values from 0 to 1, according to their distance values.

④ Matching pattern of obstacles will be adopted by

$$u_i = \max_{j=1}^{n}(u_{ij} \mid u_{ij} \in U_i) \tag{6}$$

where U_i is the set of u_{ij}.

4.2 Obstacle character judgment

The lower anomalistic obstacles and vertical obstacles are judged whether to be negotiated by their height; for the bevel obstacles, their gradient will be judgment parameter. If the gradient of a slope is greater than the bounds of the robot's limit (for the

PBJ-01 robot it is 38°), the obstacle will be taken as an anomalistic or vertical one.

According to array sensor data, we fuzzify the height of the obstacle to 5 grades: high plus, high, middle, low and minus low which are denoted by number 5, 4, 3, 2, 1, respectively.

The height of the obstacles is computed by Eqs. (7) and (8):

$$Y_i = \max_{j=1}^{m} (q_{ij} \mid q_{ij} \in \boldsymbol{Q}_i) \tag{7}$$

where $\boldsymbol{Q}_i$ is the i-th row vector of the sensor data matrix $\boldsymbol{Q}_{ij}$.

$$h = \begin{cases} i+1 & Y_i \neq 0;\ Y_j = 0;\ j = i+1, \cdots, n \\ 1 & Y_i = 0;\ i = 1, \cdots, n \end{cases} \tag{8}$$

We also fuzzify the gradient of the obstacle to 5 grades: big plus, big, middle, small, minus small which are denoted by number 5, 4, 3, 2, 1, respectively.

The gradient of the obstacles is computed by Eqs. (9) and (10):

$$Z = \frac{1}{n+m} \sum_{i=1}^{n} \sum_{j=1}^{m} x_{ij}^{(2)} \tag{9}$$

$$g = \begin{cases} 1 & Z > 37 \\ 2 & 27 < Z \leqslant 37 \\ 3 & 17 < Z \leqslant 27 \\ 4 & 14 < Z \leqslant 17 \\ 5 & Z \leqslant 14 \end{cases} \tag{10}$$

When h or g equals 5, the PBJ-01 robot cannot negotiate the obstacle.

4.3 Fuzzy arbitration

In fact, the basic behaviors of the PBJ-01 robot are all composed of some element behaviors: left-wheel-running, right-wheel-running, left-swing-arm-rolling, and right-swing-arm-rolling. Different element behaviors will combine into different basic behaviors. We will adopt a fuzzy arbitration that can work out the velocities of the wheels and swing arms. These velocities and degrees will become the behavior control commands. The simplified rules tables are described as follows:

If u is U_i and h is A_i , then $(V_{\text{left}}, V_{\text{right}})$ is V_i and θ is Θ_i ;

If u is U_j and g is B_j , then $(V_{\text{left}}, V_{\text{right}})$ is V_j and θ is Θ_j ;

If u is U_k then $(V_{\text{left}}, V_{\text{right}})$ is V_k and θ is Θ_k .

where U_i is a vertical obstacle fuzzy set; U_j is a bevel obstacle fuzzy set; U_k is an anomalistic obstacle fuzzy set; A_i is a height fuzzy set; B_j is a degree fuzzy set; V_i, V_j and V_k are all velocity fuzzy sets; Θ_i, Θ_j and Θ_k are all swing angle fuzzy sets.

5 Simulation

We test the above sections through simulation. In our simulation there are two impassable obstacles, a stair and a slope. There are three up steps and three down steps in this stair and each step is 0.24 m in width, 0. 18 m in height. The slope has a gradient of 36°. The two impassable obstacles are both 1 m in height. This simulation is programmed through Matlab. In this simulation the PBJ-01 robot avoided the impassable obstacles and negotiated the stairs and the slope. The curve in Fig. 4 is running track of the PBJ-01 robot. The obstacles are added to Fig. 4 after simulation to be explicit for readers.

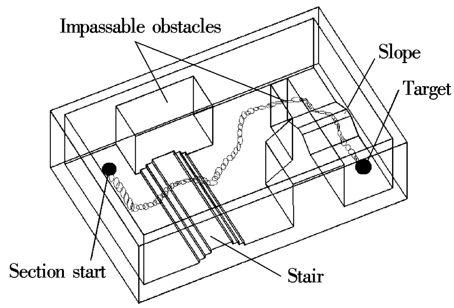

Fig.4 Navigation simulation of PBJ-01 robot in uncertain environments

6 Conclusion

This paper describes the sensor systems of the PBJ-01 robot, with a detailed discussion of its object recognition system. These systems mainly adopt fuzzy neural network technology which can fits models to sensor data, and it is feasible and effective through our simulation.

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非确定环境下移动机器人多传感器系统及信息处理

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摘要: PBJ-01 是一类移动机器人, 它的 6 个轮子和 2 个摆臂能够帮助机器人适应多种地形. 机器人上装有一个复杂的传感器系统, 包括超声波传感器、触觉传感器、视觉传感器等. PBJ-01 采用基于行为的控制体系机构, 其关键部分是基于模糊神经网络的障碍识别系统. 仿真证明该系统能够从传感器的感知数据而识别出障碍类型, 从而帮助机器人在越障行为和避障行为之间进行抉择.

关键词: 移动机器人; 基于行为的控制体系; 神经网络

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