Following a Wall by an Autonomous Mobile Robot with a Sonar-Ring

Yoshinobu ANDO and Shin'ichi YUTA
Intelligent Robot Laboratory, Institute of Information Science and Electronics
University of Tsukuba
Tsukuba, Ibaraki 305 JAPAN
Phone: +81-298-53-5155, Fax: +81-298-53-5206
E-mail: ando@roboken.is.tsukuba.ac.jp

Abstract

In this paper, we present a robust method for an autonomous mobile robot with a sonar-ring to follow walls. The sonar-ring is consisted of multiple ultrasonic range sensors. The proposed wall-following algorithm makes a robot be able to follow a wall in various shapes such as a square wall, a circular wall and etc. The autonomous mobile robot "Yamabico" is used for experiments after equipped 12 directional sonar-ring. The on-board controller of the robot decided its motion based on sonar-ring range data every 3centimeters going forward. We made many experiments with this autonomous mobile robot, and investigated the validity and the limits of this method.

1 Introduction

Wall-following is important behavior for mobile robot navigation and avoiding obstacles.

There were a lot of researches about a mobile robot with sonar-ring. Walter investigated sonar-ring ranging system for obstacle detection [1]. McKerrow researched the ultrasonic mapping by a mobile robot using sonar-ring [2]. Gat and Dorais researched an application of conditional sequencing to robot navigation using a sonar-ring [3]. Turennout and Honderd presented the control method that robot with an ultrasonic sensor follows a wall keeping the distance between the robot and the wall [4] [5]. They showed the results of experiments, but they did not treat the cases of that robot should follow a wall in various shapes. Skewis and Lumelsky presented their wall-following method and the results of an experiment using several sensors including a sonar-ring in their paper [6]. But they did not treat the problem of the ultrasonic specular reflection which is most important property of ultrasonics in indoor environment, and the objects were assumed to be static in their experiment.

In this paper, we present a wall-following algorithm for mobile robot with sonar-ring based on the ultrasonic specular reflecting property. And we present the simulation and experimental results to show its robustness not only for the various shape of walls but also for the case when the object is moving slowly. The specular reflection is very serious property of ultrasonic waves and it limits the ability of sensing for mobile robot. So, we also discuss the validity of this method and its limitation.

An autonomous mobile robot "Yamabico" is used for our experiments. The Yamabico vehicle control functions [7] were assumed in designing the wall-following algorithm.

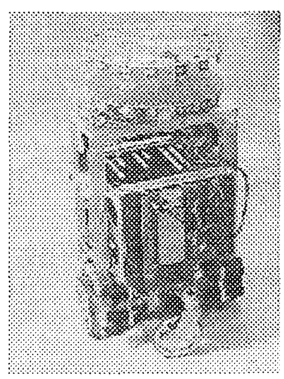

figure 1: The overview of "Yamabico"

For these experiments, "Yamabico" was equipped with 12 directional sonar-ring that ultrasonic sensors

IEEE International Conference
on Robotics and Automation
0-7803-1965-6/95 $4.00 ©1995 IEEE

placed in the front of the robot and at the back of the robot. The photograph of "Yamabico" is shown in figure 1 . The robot on-board controller decides its motion based on sonar-ring range data every 3 centimeters going forward.

The autonomous mobile robot that we use is explained in Section 2 . In Section 3, the wall-following algorithm is proposed, and the simulation and experimental results of the wall-following is presented in Section 4. In Section 5, the validity and limits of this method is discussed.

2 Assumption of the mobile robot functions – overview of "Yamabico"

When the robot behavior based on sensor data is discussed, the algorithm should much depend on the characteristic and the functions of the robot. So we assume the functions of the mobile robot before considering the algorithm for wall-following. The autonomous mobile robot "Yamabico" which is designed and implemented for the experimental autonomous robot research by our group, is assumed as a platform of this consideration.

The robot is as large as 50 x 36 x 62 centimeters and about 10 kilograms as weight. The robot has two independently driven wheels on the center line. Two caster wheels are placed in front and back. For this research, "Yamabico" is equipped with 12 directional ultra-sonic range sensors.

2.1 Locomotion command system of "Yamabico"

Power Wheeled Steering Method is used in this robot. The vehicle control command system named SPUR [7] is installed on vehicle control subsystem. The master control module of this robot gives the reference trajectory as a straight line or a circular arc by SPUR commands. When the SPUR command is issued, vehicle subsystem controls its wheels to follow the given trajectory. The maximum velocity of the robot is 30 cm/sec.

The important SPUR commands used in this research are shown below. Several coordinates may be used to gives the robot the trajectory as a straight line or a circular arc. The FS coordinate is the one of which the origin is attached at the center of the robot.

Spur_line_FS(x,y,θ) : gives a straight line through a point (x,y) with direction θ. The direction is taken counter-clock-wise against the x axis on the FS coordinate.

Spur_arc_t_FS(x,y,θ,r) : gives a circular arc which touches to the tangent line through the point(x,y) with the direction(θ) on FS coordinate, which has the radius ($|r|$).

Spur_stop_Q() : requests the robot to stop with a given maximum deceleration.

Spur_spin_FS(θ) : requests to make spin motion to keep stopping state with the robot direction θ.

2.2 Sensor Subsystem (Sonar-Ring)

A disc with a diameter of 28 centimeters is put on the top of the robot which is equipped with 12 directional sonar-ring in figure 2 . Each ultrasonic sensor takes 30 milli-seconds to measure range data of its direction. Half of sensors works at same time and another half works next. So each sensor of 12 directions works every 60 milli-seconds. The ultrasonic beam angle of each sensor is about 50 degrees. So the directivity beam pattern overlaps about 25 degrees with the neighbor sensors.

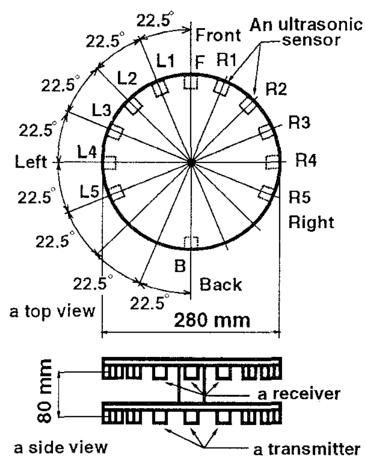

figure 2: The overview of Sonar-Ring

Generally, ultrasonic waves have the characteristic of a specular reflection at the flat surface. And, the in-door environment is usually consisted with several flat surfaces of the objects. So only when the measurement direction is almost perpendicular to the target plane, the ultrasonic range sensor can get the range data between the sensor and the target plane.

The practical range of measuring distance by this sensor is between 20 centimeters and 2 meters, and the precision of this sonar-ring measuring is about 1 centimeters.

3 Proposal of wall-following algorithm

3.1 Sensor-data

Generally, ultrasonic waves have the characteristic of a specular reflection in the in-door environment. So, when the ultrasonic transmitting and receiving beam, i.e. the measuring direction, is directed almost perpendicular to the target plane, the ultrasonic range sensor can detect the reflection and know the distance from the sensor to target plane as shown in figure 3. This property is considered as base of the algorithm.

To realize a robot behavior of following various shapes of the walls using the sonar-ring data, the robot decided its motion every 3 centimeters while going forward. Here, we denote each directional range data from sonar-ring as "L1, ..., L5, F, B, R1, ..., R5".

The robot keeps the distance about 50 centimeters between the center of robot and the wall.

The motion of the robot is decided in every 3 centimeters, in terms of issued vehicle command, as following. And the simplified program is shown in Appendix.

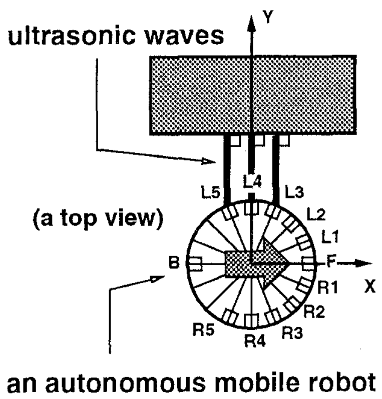

figure 3: A specular reflection model

3.2 Case1 – The robot detects a wall in front or in front-right

The case that the robot detects a wall in front or in front-right of the robot is illustrated in figure 4 .

When the sensing data meet the condition

$$(F < 60cm) \cup (R1 < 60cm) \cup (R2 < 60cm) \cup (R3 < 60cm),$$

the situation is assumed as the existence of the wall in front of the robot. In this case, the robot guess that the flat perpendicular wall is exist in the direction of the sensor which detect the shortest distance. So, robot stops quickly and makes spin turn around its center. And the straight trajectory which is parallel to the imaginary wall, is issued to vehicle sub-controller to follow it.

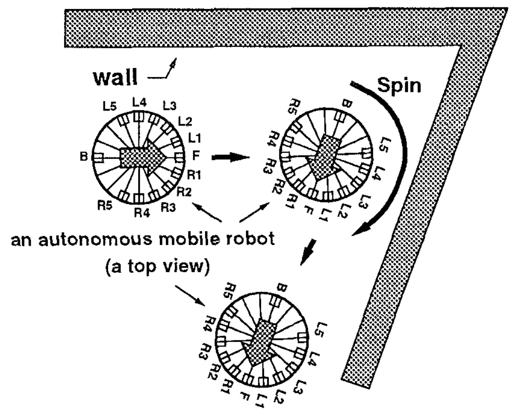

figure 4: A robot detects a wall in front or front-right

3.3 Case2 – The robot detects a wall in front-left

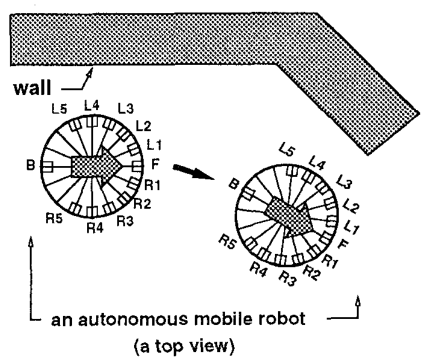

figure 5: A robot detects a wall in front-left

When the sensor data meet the condition

$$(L1 < 60cm) \cup (L2 < 60cm),$$

the situation is assumed as the existence of the wall in front-left of the robot. The robot guess the existence of the perpendicular wall to be followed in direction of the sensor. In this case robot does not need to stop, and calculates the straight line parallel to the imaginary wall to issue the command to vehicle subsystem and to follow it. An example of this situation is illustrated in figure 5 .

3.4 Case3 – The robot detects a wall in left

The example that the robot detects a left wall is illustrated in figure 3 . When two conditions above are not met and at least one of the range sensors of left side (L3, L4 or L5) gives the distance of 1meter or less, the robot is recognized to be following the left wall. In this case, robot regards as the existing the flat perpendicular wall in the direction of the sensor with shortest distance data. And robot issues the straight line command to follow it which is parallel to the imaginary wall with distance 50 centimeters.

3.5 Case4(otherwise) – sensor doesn't detect any object around the robot

When no conditions above are satisfied, i.e. no objects are detected around the robot, the robot makes a circular arc trajectory of the radius 50 centimeters to left until the sensor find any objects. When the robot turn around 360 degrees, the robot regards as that there are no wall to follow around the robot and finishes this task.

4 Experiments

For discuss the validity of the proposed algorithm, we implemented this algorithm on our autonomous robot "Yamabico" with the sonar-ring. We made many experiments of the wall-following in various environments. Before the experiment in practice, we simulated the robot behavior in autonomous mobile robot simulator "AMROS" which is developed by our group [8] [9]. As the result of experiments, the robot can follow the wall in various environment as long as the robot can detect a wall using a sonar-ring.

Several successful wall following experiments are shown in this section. An example of the result of the simulation in which the robot follows a standstill square wall (75cm x 75cm) is illustrated in figure 6. The trajectory of experiment in real environment recorded by dead-reckoning is illustrated in figure 7. The conditions with which the sonar-ring sensor data meet are also illustrated in figure 7 .

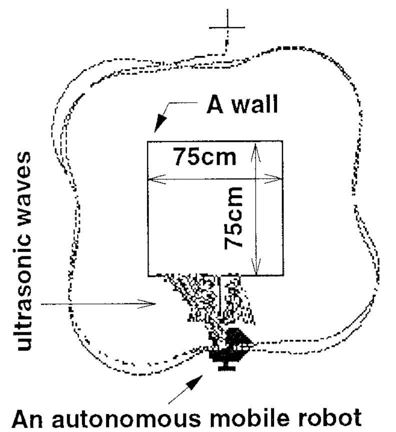

figure 6: A simulation result of the robot following a square wall

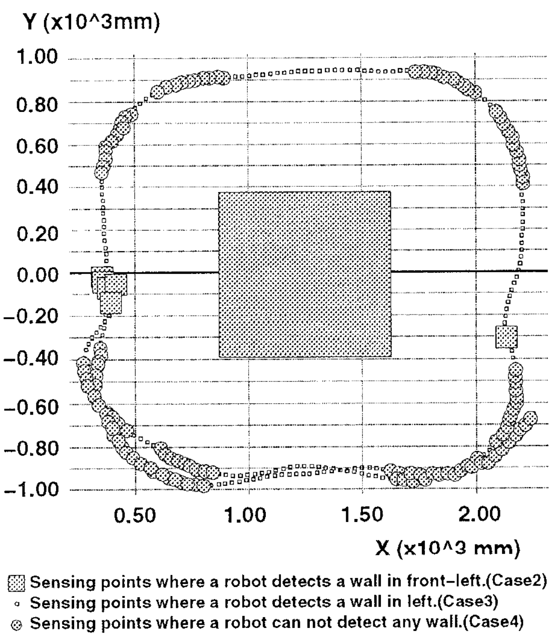

figure 7: An experimental result of the robot following a square wall

The simulation and experimental results of the wall-following around the circular wall are illustrated in fig-

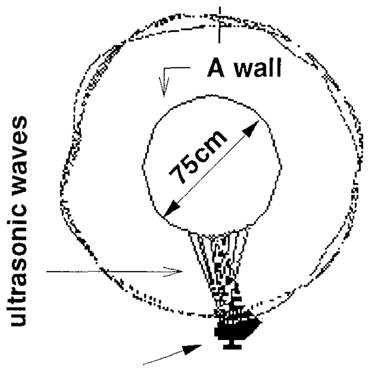

figure 8: A simulation result of the robot following a circular wall

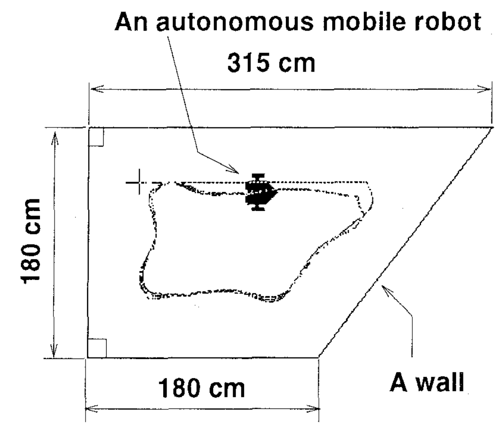

figure 10: A simulation result of the robot following the inside of closed walls

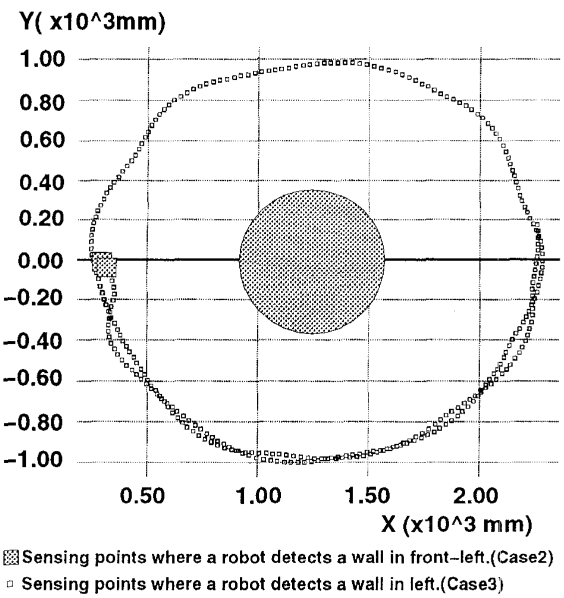

figure 9: An experimental result of the robot following a circular wall

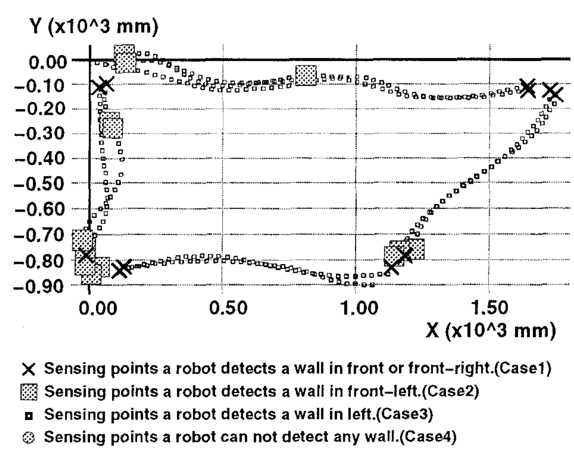

figure 11: An experimental result of the robot following the inside of closed walls

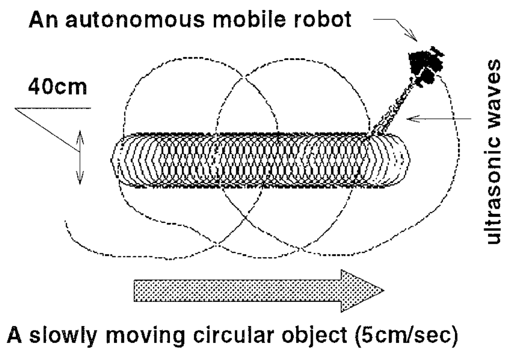

figure 12: A simulation result of the robot following a slowly moving circular object

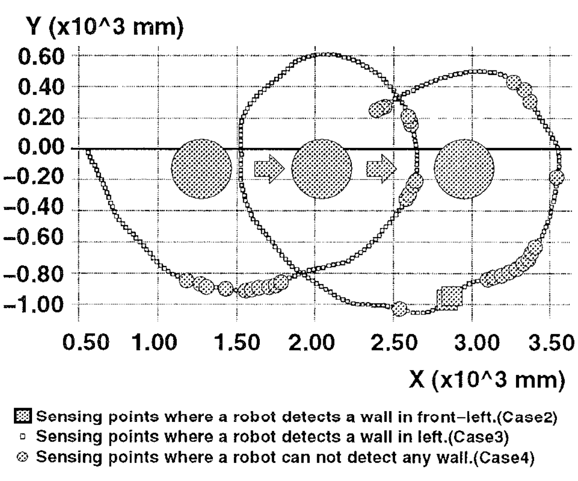

figure 13: An experimental result of the robot following a slowly moving circular object

ure 8 and figure 9 . The velocity of a robot is 30cm/sec and the diameter of the circular wall is 75 centimeters.

The experiments in which the robot follows the inside of closed walls were done. An example of simulation and experimental result is illustrated in figure 10 and figure 11 .

The simulation and experimental results that the robot follow a slowly moving circular object are shown in figure 12 and figure 13 . In real experiment, a slowly moving object was realized by the another robot. In the case that the velocity of the robot is 30cm/sec and the velocity of moving object is around 5cm/sec, the proposed wall-following algorithm worked well.

5 Discussion – the case of failure and limit of proposed algorithm

The proposed algorithm is based on an assumption that the robot can observe a wall which faces the robot using an ultrasonic sensor.

In real environment, because of the specular reflection characteristics of the ultrasonics, ultrasonic range sensor may not be able to detect an object even in the indoor environment. For example, as shown in figure 7, the robot can not observe the existence of any wall when the robot turn a corner. Fortunately, the robot succeeded the wall-following in the case of figure 7 . Because the robot decided its motion that the robot circulated counterclockwise with radius 50 centimeters and there were no ill-placed wall. The other hand, if the object moves while the robot could not observe the wall, the robot may very easily collide with the moving object even when robot uses the proposed algorithm.

The simulation and experimental results is illustrated in figure 14 and figure 15, in which, the robot collide with the object. In this experiment, the square object moves slowly with 5cm/sec while the velocity of a robot was about 30cm/sec.

To avoid such a collision, the robot should be able to know the existence of the object in front of the robot. To realize this, the robot is required to have good sensor to observe the front object at any time, or it is required that the robot can estimate the motion of the object and the shape of the object. We think it is difficult to realize when using only ultrasonic waves that have the characteristics of a specular reflection. We are thinking it as a future research theme.

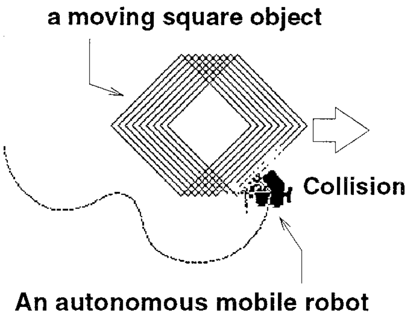

figure 14: A simulation result of the robot following a slowly moving square object

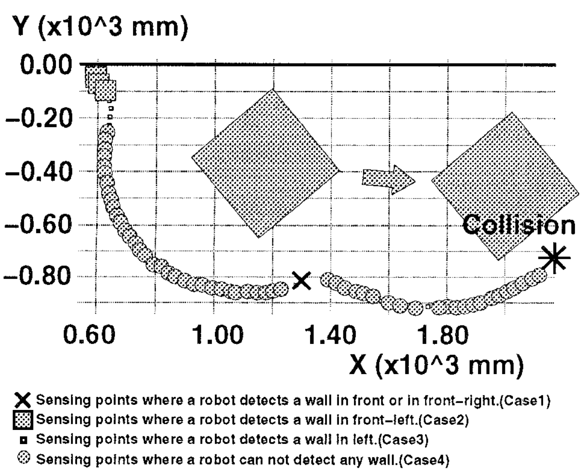

figure 15: An experimental result of the robot following a slowly moving square object

6 Conclusion

When an autonomous robot follows an unknown wall, the ability to detect the wall and the robust wall-following method is necessary. We presented the robust method by which the robot with a sonar-ring can follow a wall. As long as the sonar-ring can detect the specular reflected ultrasonic waves, this wall-following algorithm realizes a robust and reliable behavior of the robot. We presented the simulation and experimental results of the wall-following for the various environments. And we discussed the validity of this method and the limits of this abilities.

References

[1] Scott A. Walter: "The Sonar Ring: Obstacle for a Mobile Robot", Proc. of the 1987 IEEE Int. Conf. on Robotics and Automation(RA'87), pp.1574–1579, 1987.

[2] Phillip John McKerrow: "Control of Ultrasonic Mapping by a Mobile Robot with an Expert System", Proc. Robots for Competitive Industries, Brisbane, ARA, pp.300–309, 1993.

[3] Erann Gat and Greg Dorais: "Robot Navigation by Conditional Sequencing", Proc. of the 1994 IEEE Int. Conf. on Robotics and Automation(RA'94), pp.1293–1299, 1994.

[4] P.van.Turennout and G.Honderd: "Following a Wall with a Mobile Robot using Ultrasonic Sensors", Proc. of the 1992 IEEE/RSJ Int. Conf. on Intelligent Robots and Systems (IROS'92), pp.1451–1456, 1992.

[5] P.van.Turennout and G.Honderd: "Wall-following Control of a Mobile Robot", Proc. of the 1992 IEEE Int. Conf. on Robotics and Automation(RA'92), pp.280–285, 1992.

[6] T.Skewis and V. Lumelsky: "Experiments with a Mobile Robot Operating in a Cluttered Unknown Environment", Proc. of the 1992 IEEE Int. Conf. on Robotics and Automation(RA'92), pp.1482–1487, 1992.

[7] Shigeki IIDA and Shin'ichi YUTA: "Vehicle Command System and Trajectory Control for Autonomous Mobile Robots", Proc. of the 1992 IEEE/RSJ Int. Workshop on Intelligent Robots and Systems(IROS'91), pp.212–217, 1991.

[8] Katsumi Kimoto and Shin'ichi Yuta: "Simulation of an Ultrasonic Range Sensor for an Autonomous Mobile Robot", Journal of the Robotics Society of Japan, (to be appeared).

[9] Yoshinobu Ando, Katsumi Kimoto and Shin'ichi Yuta: "A simulator for programing the behavior of an autonomous sensor based mobile robot –Dealing with a moving obstacle–", Intelligent Mobile Robot Symposium'94, pp.142–147, 1994, (in japan).

A Appendix : An experimental wall-following program for "Yamabico"

```
/******************************
* Getting the sensor data
******************************/
  dist_f = us_ring_dist(US_F);
  dist_r1 = us_ring_dist(US_R1);
  dist_r2 = us_ring_dist(US_R2);
  dist_r3 = us_ring_dist(US_R3);
  dist_l1 = us_ring_dist(US_L1);
  dist_l2 = us_ring_dist(US_L2);
  dist_l3 = us_ring_dist(US_L3);
  dist_l4 = us_ring_dist(US_L4);
  dist_l5 = us_ring_dist(US_L5);
  min_dist = mini3(dist_l3, dist_l4, dist_l5);
/******************************
* Case1
******************************/
if(R3 <= 60&&R3 > 37){
  Spur_stop_Q();
  wait_time(1);
  Spur_spin_FS(-158);
  Spur_line_FS(0, 0, 0); }
else if(R2 <= 60&&R2 > 37){
  Spur_stop_Q();
  wait_time(1);
  Spur_spin_FS(-135);
  Spur_line_FS(0, 0, 0); }
else if(R1 <= 60&&R1 > 37){
  Spur_stop_Q();
  wait_time(1);
  Spur_spin_FS(-113);
  Spur_line_FS(0, 0, 0); }
else if(F <= 60&&F > 37){
  Spur_stop_Q();
  wait_time(1);
  Spur_spin_FS(-90);
  Spur_line_FS(0, 0, 0); }
/******************************
* Case2
******************************/
else if(L1 <= 60&&L1 > 37){
  Spur_line_FS(0, 0, -68); }
else if(L2 <= 60&&L2 > 37){
  Spur_line_FS(0, 0, -45); }
/******************************
* Case3
******************************/
else if(L4 == min&&L4 < 100){
  Spur_line_FS(0, L4 - 50, 0); }
else if(L3 == min&&L3 < 100){
  Spur_line_FS(0, L3 - 50, -23); }
else if(L5 == min&&L5 < 100) {
  Spur_line_FS(0, L5 - 50, 23); }
/******************************
* Case4
******************************/
else{
  Spur_arc_t_FS(0, 0, 0, 500); }
```