Aspects Regarding the Object Following Control Procedure for Wheeled Mobile Robots

ADRIAN KORODI, ALEXANDRU CODREAN, LIVIU BANITA,
CONSTANTIN VOLOSENCU
Departamentul de Automatica si Informatica Aplicata
Universitatea "Politehnica" din Timisoara
Bd. Vasile Parvan 2, Timisoara
ROMANIA
adrian.korodi@aut.upt.ro

Abstract: **-** The wheeled mobile robots are representing an increasing research domain, both the hardware and the software part representing a challenge. Among the many tasks that the robots have to realize, the object following task is one of the most important ones. Almost every group of robots, which are realizing a cooperative action has to be able to accomplish this task, as well as a single robot has to be able to reach a detected object in the environment. The aim of this paper is to provide a control strategy for wheeled mobile robots realizing the object following task. Also, the paper provides a redundant solution for the robot following function in the case of multiple wheeled mobile robots, solution based on wireless communication. Infrared and sonar sensors are used to provide the inputs for the controller. The control strategy takes into consideration that the robot moves in a dynamic environment and it has to follow the target object regardless of other interfering elements.

Key-Words: object following control, PID control, redundancy, wheeled mobile robots, cooperative mobile robots, sensor fault detection, fault tolerance**.**

1 Introduction

It is an increased research interest in systems composed of multiple autonomous mobile robots exhibiting cooperative behavior [15]. Groups of mobile robots are constructed, with an aim to studying such issues as group architecture, resource conflict, origin of cooperation, learning, and geometric problems. As yet, few applications of cooperative robotics have been reported, and supporting theory is still in its formative stages [8]. One of the main tasks for cooperative wheeled mobile robots [7] is the object (target) following task, which usually represents to follow another robot. Also, the following task is important for the wheeled mobile robots in general [10], [11] and the target can be static or a dynamic object.

The availability and fault tolerance of a mobile robot is also an important feature [1], [3], [5]. Regarding this perspective, the robot following control function in case of multiple cooperative robots can be successfully treated using an alternative solution, in a redundant manner.

In this paper, we address the problem of intercepting and following a moving target with a wheeled mobile robot. Intercepting a target and tracking it is an important problem in a wide range of applications [2], [4]. The paper will use infrared sensors to provide the distance to the dynamic object for the control algorithm and sonar sensors to realize a fault detection procedure for the infrared sensors. Also, the paper provides an alternative solution for the robot following control in case of multiple cooperative robots, solution based on wireless communication.

The paper is divided into seven parts. The first part presents the X80 wheeled mobile robot and the sensors that can be used for the object following task. The second part analyzes the requirements and the problems that have to be taken into consideration in the design of the control strategy. The third part shows how the robot perceives the environment using the infrared and the sonar sensors. In the fourth part, the control strategy is presented, pointing out the characteristics of the controllers, describing the supplementary modules that have to be included in order to follow the target object even if one sensor is losing the object, explaining the ability to detect a fault occurring at one of the main sensors, and showing a practical result from the real implementation. The sixth part is presenting an alternative solution based on wireless communication for the robot following control in case of multiple cooperative robots. The alternative solution can be used in a redundant manner, if a fault is occurring using the first control method. The final part is the conclusions.

2 The X80 Robot

Like it was mentioned before, the researches focusing on mobile robots and especially on the two wheeled mobile robots are increasing and they are focusing on many aspects: target following [6], path planning [12], [16] and so on.

The robot used in this research is the X80 wheeled mobile robot presented in fig. 1. The X80 mobile robot is used to implement and verify the object following task, the goal of the current research. The main hardware components of the mobile robot are: the motors which are positioned at each wheel, the sonar sensors, the infrared sensors, the human sensors, the Wireless module, the encoders, the microphone, the speaker and the camera. The algorithms developed during the research are written in Visual C++.

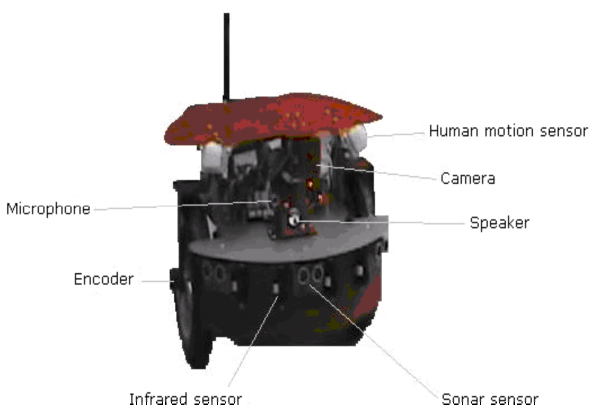

Fig. 1 The X80 mobile robot

The sensors that can be used for the object following control are the infrared sensors and the sonar sensors. Regarding the requirement of the current task (object following task), the sensors have to be used properly. After testing the sensors, their significant characteristics are shown in the following table:

	Infrared Sensor	Sonar Sensor
Range	0.08-0.8 m	0.04-2.5 m
Response to the change of the environment	fast	slow

Table 1. Infrared and Sonar sensor comparison

Although the sonar sensors have a bigger view range, in the control process to realize the object following task the infrared sensors have to be used due to their faster response to the change of the environment.

The infrared sensor provides a value (value in impulses). This value can be converted to voltage by the following formula [14]:

$$Sensor\ output\ voltage = \qquad (1)$$
$$= Value\ in\ pulses * 3.0/4095$$

The distance in centimeters (necessary for a proper control) was obtained by creating a function, which approximates the voltage-centimeter dependence from fig. 2, [9].

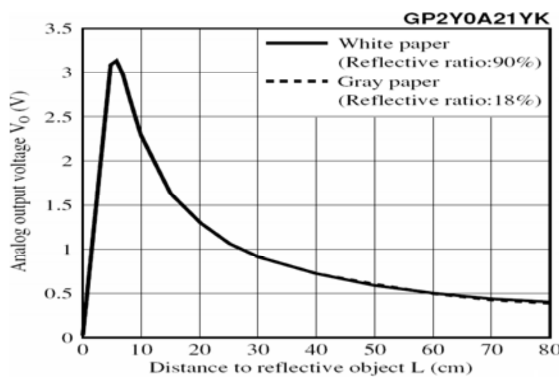

Fig. 2 Voltage-centimeter dependence of the infrared sensor

3 Requirements and Problems for the Object Following Task

It can be a difficult task to choose the proper controller for the robot to realize the object following procedure. The requirements associated with the wheeled mobile robots, especially when they are realizing the object following task, are the followings:

- There is a need of a fast response;
- There is a need of a small settling time;
- The overshoot has to be as small as possible.
- The problems which are occurring when realizing the object following task by the wheeled mobile robots are:
- The robot looses the object;
- The robot hits the followed object or goes very close to it;
- The robot oscillates around the prescribed

distance for a long time but its speed is different than the speed of the followed object;

- In a dynamic environment the robot choose not to follow the desired object and goes after another detected object from the environment;
- The information delivered by the sensors can sometimes be disturbed and the robot changes its speed when it is not necessary.

The first three problems have to be solved by a proper controller, which is able to meet all the three requirements mentioned before. The importance of the three requirements is pointed out by the followings:

- If the response of the robot is not fast enough then the followed object can be lost. If the robot responds too fast then there is a chance of a big overshoot which can lead to hit the object or to move too close to it.
- The overshoot is a very important factor in a proper control. With a big overshoot the robot cannot follow the object properly: every change of the followed object orientation may lead to undesired behaviors, a sudden change of speed or a sudden stop of the followed object may lead to collisions and if the overshoot is very big there is a chance to hit the object.
- A small settling time means that the robot is adjusting fast its speed to the speed of the followed object. If the settling time is big then the robot speed and the distance to the followed object are oscillating too much and if there is many changes of the followed object's speed the robot may never reach the stationary regime. If there are more collaborative robots, which are following each other, and every one of them has settling time problems then the magnitude of the error increases.

4 Viewing the Object

The robot's ability to get information from the environment using its sonar and infrared sensors is depicted in the fig. 3.

The 7 sensors (4 infrared sensors and 3 sonar sensors) are providing 7 distances. The 4 infrared sensors are providing 4 distinct points from the environment. The 3 sonar sensors are providing points, which can differ, or can be the same with those obtained from the infrared sensors.

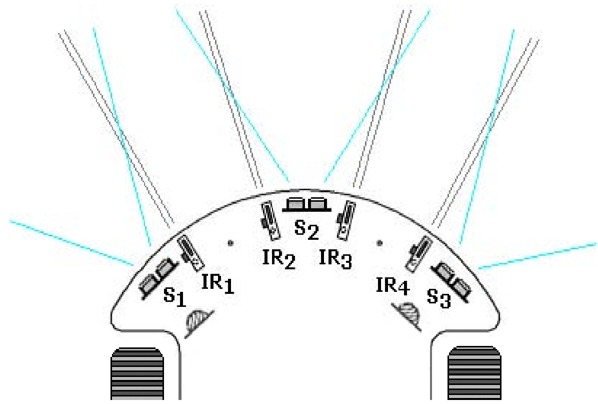

Fig. 3 Reading the environment with the infrared and sonar sensors

5 The Control Strategy

The control strategy to realize the object following task has to take into consideration the requirements and problems mentioned before and the capability of the robot to view the object. The conceived strategy is using two infrared sensors (IR_2 and IR_3) to provide the distance to the target object. The IR_1 and IR_4 infrared sensors are used to estimate the values for the first two infrared sensors in case of losing the target object. The S_2 sonar sensor is used to occasionally to detect a faulty sensor behavior for the IR_2 and IR_3 infrared sensors. The target object is considered flat as long as the X80 back side was made flat for a better accomplishment of the object following task.

5.1 The Controllers

A motor is positioned at each wheel of the mobile robot (fig. 4) and the scope is to control the angular speed of the two wheels ($Speed_1$ and $Speed_2$).

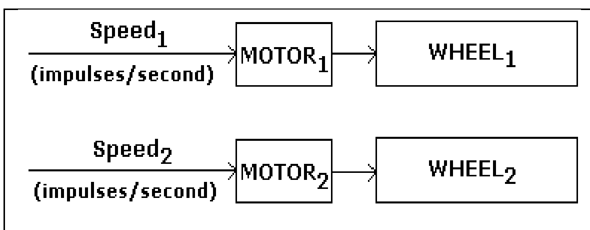

Fig. 4 The two motors driving the wheels of the mobile robot

The linear speed of the mobile robot is depicted by the following formula:

$$v = \frac{(Speed_1 + Speed_2).R}{2} \quad (2)$$

where v is the robot's speed and R is the wheel radius.

The next relation shows the orientation variation speed of the mobile robot:

$$\dot{\theta} = \frac{(Speed_1 - Speed_2).R}{l} \quad (3)$$

where θ is the orientation of the robot and l is the distance between the two wheels.

The control strategy regarding one wheel is shown in fig. 5:

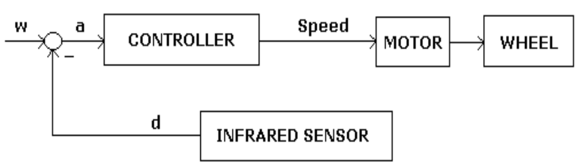

Fig. 5 The control loop for one wheel

where w is the prescribed distance between the robot and the followed object, d is the distance provided by the sensor (in this case sensor IR_2 or IR_3 from fig. 3) and a is the error between the prescribed distance and the distance provided by the sensor.

To realize the object following task, two controllers are used, one for each wheel. Each controller provides the speed for the corresponding wheel motor regarding the error a. The control diagram for the left wheel is illustrated in fig. 6:

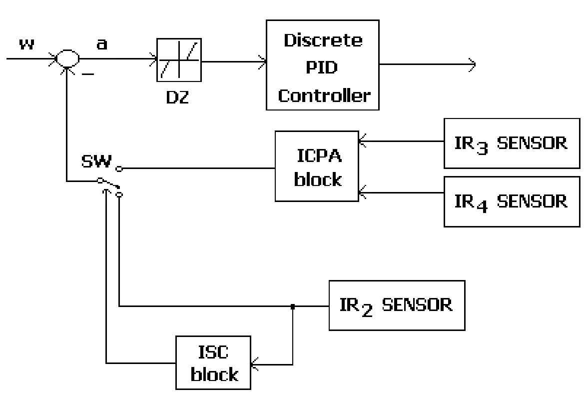

Fig. 6 Detailed control scheme for the object following task

The notation significance from fig. 6 are:
DZ – the dead zone block,
ISC block – infrared sensor check block,
ICPA block – input calculating and providing block.

The DZ block is necessary because of the fast change and instability of the signal provided by the infrared sensor. Therefore the dead-zone is set to a 2*ε width, where ε=3.

The other two blocks will be detailed in the next paragraph.

The authors used two different approaches to realize the controllers. The first approach was to use a discrete PID controller and the second approach was an interpolative type controller. First, to evaluate the differences between the two approaches, a Simulink model of a two-wheeled mobile robot was used and the parameters were set to match the characteristics of the current mobile robot. Then, the two approaches were implemented in the real X80 robot. Mentioning that mobile robot's behavior was slightly different in the Simulink model than in the real situation, and the real robot was facing different limitations, the chosen approach was to use the discrete PID controller, which was responding better in the real situation.

The Simulink model of the wheeled mobile robot is practically usable to evaluate the rectilinear movement for one wheel. The model is illustrated in fig. 7) and it has the characteristics of a classical continuous current motor extended for robots. For the two-wheeled robot, there are two motors (one at each wheel) and the implementation consists in setting the same parameters for each wheel. Therefore the analysis can be made on one wheel of the mobile robot and then extended to both.

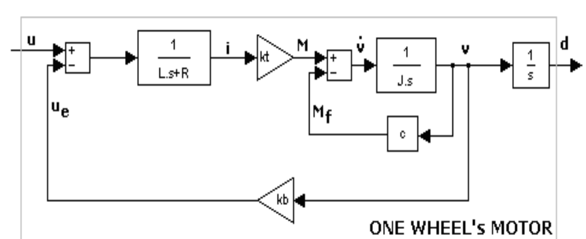

Fig. 7 Simulation scheme for one wheeled mobile r
motor

The formulas that are guiding the concept are illustrated in (4):

$$u = R.i + L\frac{di}{dt} - u_e$$
$$M = k_t.i$$
$$J\dot{v} = M - M_f$$
$$M_f = c.v \quad (4)$$
$$u_e = k_b b$$
$$J\_robot = m\_robot.raza\_r^2.1{,}1$$
$$J = J\_motor + \frac{J\_robot}{g_r^2}$$

The notations are the classical ones used for the continuous current motors, so only some of them will be explained, which are related to the robot extension:

v – the speed;
d – the distance covered by the robot;
u – the input from the controller;
raza_r – the robot's wheel radius;
m_robot – the robot's mass;
J_robot – the moment of inertia of the robot (the part different from the motor).

The controller for one wheel is a discrete PID controller presented in (5):

$$Speed[t] = Speed[t-1] - 10*(a[t] - a[t-1]) - 0{,}3*a[t] - 10*(a[t] - 2*a[t-1] + a[t-2]) \quad (5)$$

The implemented values of the parameters are: k_p=10, k_i=0,3, k_d=10.

These values (implemented for the X80 robot) were obtained cvasi - empirically, starting from three values and leading towards accomplishing the previously presented requirements.

The discrete PID controller for one wheel was first tested through simulation, and the results are presented in fig. 8.

The reaction of the robot if the followed object changes its speed and therefore the relative distance is increasing is shown in fig. 9b. Fig. 9a shows how much the relative distance between the robot and the object would increase and it can be seen in 9b that the distance between the robot and the object is kept in an acceptable zone by using the object following control. It can be seen (in fig. 9a) that at t=20s the distance between the robot and the followed object begins to change, meaning that the followed object started to move with a different speed.

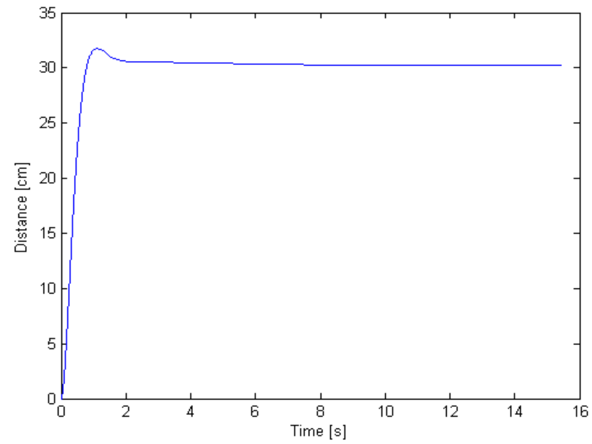

Fig. 8 The system response using the discrete PID controller for one wheel

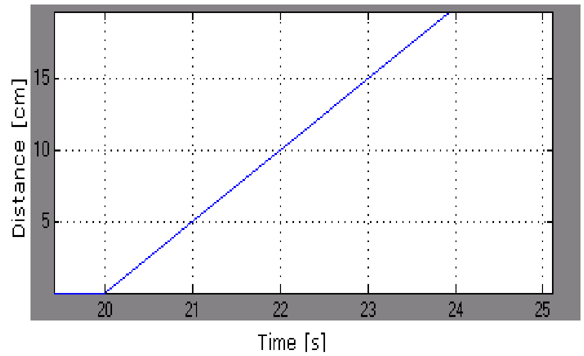

Fig. 9a Increasing the distance between the robot and the followed object

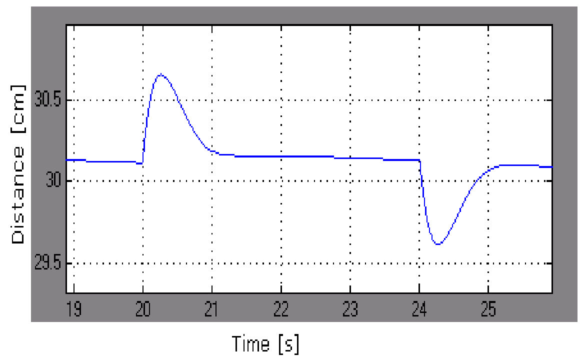

Fig. 9b The distance evolution between the robot and the object using the object following control

The change of speed is occurring again at t=24s. As it is shown in fig. 9b, the controller is adjusting the robot's speed and the distance to the followed object is kept in the acceptable limit.

5.2 Providing the Inputs for the Controllers

For slight turns to the left or right of the object, the controller uses only the inputs provided by infrared sensor 2 and 3 as described in the previous paragraph. For very fast turns of the followed object a different approach is required because the robot may lose sight of the followed object and other objects may appear in the path of some of the IR sensors

The following correction algorithm is used when one of the two frontal IR sensors (IR_2 or IR_3) loses sight of the object. The algorithm replaces the value provided by the sensor, which loses sight of the object, and sends it to the speed controller, so that the robot can follow the object. This algorithm is represented in fig 6 from the previous paragraph as the ISCPA block. The ISCPA block is based on the same algorithm for both wheels, the difference being made by its input and output signals.

The following assumption is made: the visible surface of the object the robot follows is flat. The IR sensors see it like a straight line. To solve the problem for the sensor that loses sight of the object, the ISCPA block provides a distance that would be shown by the sensor if it had been seeing the object. It does so by finding the straight line obtained from the other two IR sensors, and extending it to intersect the straight line coming from the IR sensor that loses sight of the object. The obtained value is transmitted to the controller, which then adjusts the robots speed. The correction is necessary to calculate the speed modifications for each wheel of the robot, so that it follows the object, after a certain relationship between past and present errors.

The imaginary lines coming from the four infrared sensors meet in a point, in the center of the robot. The robots shape is approximated to a circle. The distance from the center to the infrared sensors is approximately the radius of the circle. The angle between two infrared sensors is approximately 20 degrees. The center of the robot will be the origin point for the Cartesian system that will help in the distance calculations.

When the followed object makes a fast turn to the right, the 3rd and 4th IR sensors will be used in the algorithm to compensate for the 2nd IR sensor that is losing sight of the object. This situation is shown in fig. 10.

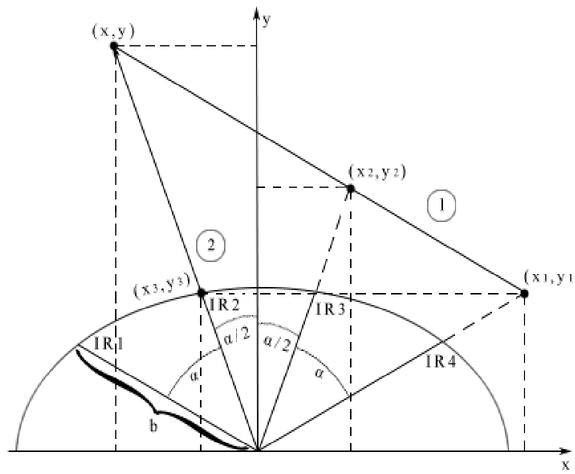

Fig. 10 The IR_2 sensor loses sight of the object

By using the 2 points obtained from the 3rd and 4th IR sensors we will obtain the line, which will be used to give the 2nd IR sensor the distance, it would indicate, if it had seen the object. In order to achieve this, the straight line obtained form the 3rd and 4th IR sensors will be crossed with the straight line that goes through the origin of the system and the 2nd IR sensor. Once the intersection point is calculated, the distance from the 2nd IR sensor to the extension of the object is automatically obtained.

The same idea will be used if the object makes a fast left turn, using the 1st and 2nd IR sensors to compensate for the 3rd IR sensor losing sight of the object, shown in fig. 11.

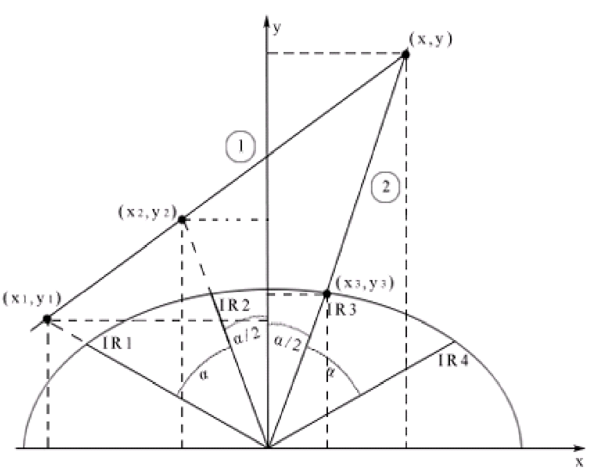

Fig. 11 The IR_3 sensor loses sight of the object

For a better understanding, the following notations are made: d_2 and d_3 represent the distance to the followed object provided by IR_2 and IR_3 sensors.

Fig. 12 describes a situation in which one of the frontal sensors (IR_2 or IR_3) loses sight of the object.

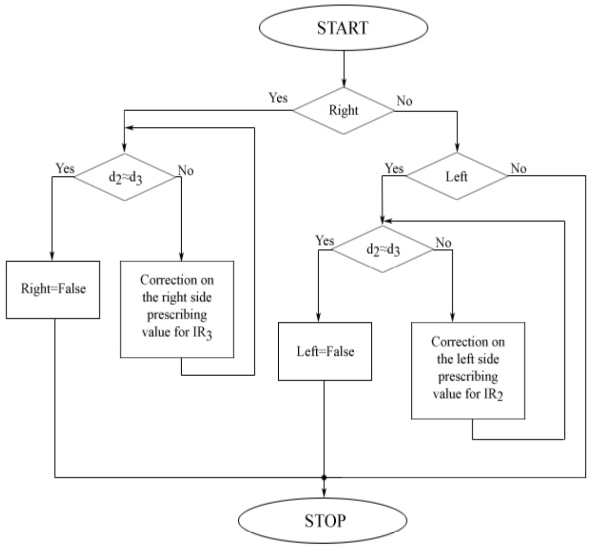

Fig. 12 The situation where one of the frontal IR sensors loses sight of the object

The ISC block from fig. 6 of the previous paragraph can identify this. The ISC block identifies a sudden variation in the IR sensors indicated values. A sudden variation is identified using the following formulas:

$$\left|d_2[t]-d_2[t-1]\right| \geq \lim it\_value \tag{6}$$

In fig. 12 this event being stored in a Boolean variable named "Right".

$$\left|d_3[t]-d_3[t-1]\right| \geq \lim it\_value \tag{7}$$

In fig. 12 this event being stored in a Boolean variable named "Left".

As mentioned earlier in this paragraph a sensor loses sight of the object when the object makes a fast turn. Also the distance between the robot and the followed object is 20 to 40 cm, and the area of visibility of the IR_2 and IR_3 sensors is narrow, making impossible an intercalation of another object from the environment during the rectilinear movement.

5.3 Faulty Sensor Behavior Detection

Like it was said before the availability and the fault tolerance of the mobile robots is important and these days there have to be modules that can handle safety critical situations.

Sometimes, situations involving faulty sensors may arise. Because the control algorithm is heavily dependent on the infrared sensor 2 and 3, a failure of one of these two would lead to the impossibility for the robot to follow the object. To identify these special types of situations, a fault detection algorithm is conceived which may be used in a rectilinear movement (or a movement where both infrared sensors are seeing the target object).

The algorithm consists of comparing the values from infrared sensors 2 and 3 with the data received from the second sonar sensor (S_2 sensor from fig. 3). An infrared sensor is considered faulty if it indicates a value very different from the data of the sonar and the other infrared sensor.

This check should run periodically at a given time considering the response to the change of the environment times for the sonar and infrared sensors, while the robot is moving rectilinear.

5.4 Implementation Results

The control strategy was implemented on the X80 wheeled mobile robot and one of the results is shown in fig. 13.

Fig. 13a The robot follows the object (initial situation)

The experimental scenario is the following: the mobile robot follows an object (fig. 13a), the target turns to the right and the robot is turning also after the object (fig. 13b and 13c) and finally the robot follows the object after the turn (fig. 13d).

Fig. 13b The object turns to the right

Fig. 13c The robot follows the object turning

Fig. 13d The target object finishes the turn and the robot is following it

6 Alternative robot following control solution

For the wheeled mobile robots, as well as for any automatic system, the availability and the fault tolerance is an important factor. A higher degree of availability and fault tolerance can be obtained through redundancy. For implementing redundant structures there is a need of alternative solution to take over the faulty structure's function.

In the current situation, the initial object following control can cover certain fault types like the odometry errors due to the algorithm structure. But, if an infrared sensor if failing, then the localization module is incomplete and the robot cannot locate the followed object. A fault detection method was discussed in the paragraph 5.3, which was based on the sonar sensor measurements. The sonar sensor can act temporarily as a redundant solution to provide an input for the controller, but it is very slow and it cannot respond well to fast movements.

A redundant solution can be provided in case of multiple cooperative wheeled mobile robots. The solution is based on the wireless communication, meaning that the followed robot is providing its current speed of each wheel to the other following robot. So, if $ROBOT_1$ is following $ROBOT_2$ then at each sampling period $ROBOT_2$ will provide its left and right wheels speed to $ROBOT_1$, and $ROBOT_1$ will set its left and right wheels speed according to the received information.

The wireless communication between $ROBOT_1$ and $ROBOT_2$ (used in the second solution for the robot following control) is realized like it is shown in fig. 14.

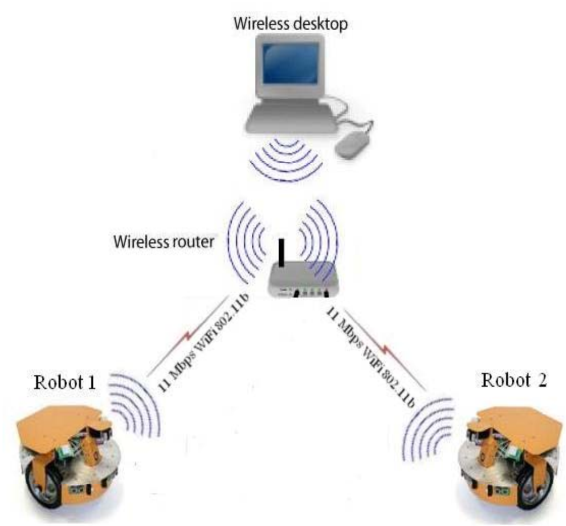

Fig. 14 The wireless communication between the two robots

The main wireless communication between the robot and the computer is made as it is in fig 15.

The alternative robot following control solution based on wireless communication was implemented and the results are illustrated in figures 16. The experimental scenario is the following: the red robot (from the back) is following the green robot (from the front) maintaining the specific distance between them (in this case 35 cm).

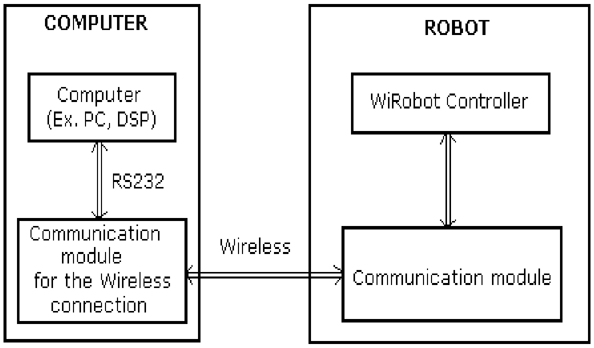

Fig. 15 The wireless communication between the computer and the wheeled mobile robot

The initial situation is the one presented in fig. 16a. In fig. 16b and 16c the green robot makes a turn to the right and the red robot is following, keeping the 35 cm between them. Fig. 16d, 16e and 16f are illustrating the left turn of the first robot and it can be seen that the second robot is following it, keeping the required distance.

Fig. 16a The starting situation, the red mobile robot will follow the green robot

Fig. 16b The followed robot turns to the right and the red robot keeps the required distance

Fig. 16c The red robot follows the green one

Fig. 16d The followed green robot begins to turn left

Fig. 16e The red robot turns also and keeps the required distance to the followed robot

Fig. 16f The left turning ends and the red robot is still following his target

7 Conclusions

The paper presented a control strategy that responds to the requirements of the object following task. The control strategy was conceived based on two discrete PID controllers, one at each wheel's motor, and the data used by the controllers was provided by the infrared sensors. An algorithm was conceived to provide the inputs for the controllers, when one of the infrared sensors loses the object. A fault detection scheme was used, that detects a faulty infrared sensor using the information of another sonar sensor. Then, a result of an implementation on the X80 mobile robot was presented which illustrates the efficiency of the object following control method. Finally, an alternative solution was provided for the robot following control in case of multiple cooperative wheeled mobile robots, based on wireless communication, and the result of its implementation was shown.

A modern solution is to control robot motion based on a sensor networks, based on state identification [13].

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