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Behavior Fusion for Visually-Guided Service Robots

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1. Introduction

Mobile service robots are the class of robots that have tools to understand the environments at home and office. The development of mobile robots is increasing world-wide due to the availability of moderate price sensing and computing devices. Moreover, there is a strong belief that the market for service robots is just about to undergo a radical increase in the next few years.

Despite the huge literature of the mobile robot navigation, the development of intelligent robots able to navigate in unknown and dynamic environment is still a challenging task (Walther et al., 2003). Therefore, developing techniques for robust navigation of mobile robots is both important and needed.

The classical approach for mobile robot control used the "Model, Sense, Plan, Act", MSPA serial strategy, which proved to be inherently slow and totally fails if one module is out of order. We may call this approach as a planner-based control approach. The appearance of behavior-based navigation approach (Arkin, 1998; Brooks, 1986) was a remarkable evolution, in which the reactive behaviors were designed to run simultaneously in parallel giving tight interaction between sensors and actuators. The reactive behaviors allow for incremental improvements and addition of more application-specific behaviors. Building several behaviors, each concerned with a sole objective, will produce different decisions for the robot control parameters, and they have to be combined in some way to reach the final motion decision.

The fusion of independent behaviors is not an easy task and several approaches were proposed in the literature to solve this problem (Arkin, 1998; Borenstein & Koren, 1991; Carreras et al., 2001; Saffiotti, 1997). Coordination of behaviors can be classified into two further approaches, a competitive, as was originally proposed by (Brooks, 1986), and cooperative strategies (Carreras et al., 2001).

Depending on the environment, the competitive approach may fail and become unstable in critical situations demanding higher switching frequencies between behaviors. In the subsumption architecture (Brooks, 1986) behaviors are activated once at a time but this may be inadequate for a variety of situations requiring several behaviors to be active at the same time.

In the cooperative approach, all behaviors contribute to the output, rather than a single behavior dominates after passing an objective criterion. An example of the cooperative

approach is proposed by (Khatib, 1985) using artificial potential fields to fuse control decisions from several behaviors. The potential field method suffers from being amenable to local minima which causes the control system to get stuck and become indecisive. Hybrid techniques from competitive and cooperative approaches were proposed in (Carreras et al., 2001). However, they used learning to build up the rule set which consumes a lot of time and effort.

The use of fuzzy logic for behavior fusion had been reported in (Saffiotti, 1997) where a hierarchy of behaviors was used for mobile robot guidance. Fuzzy logic approach, since its inception (Zadeh, 1965), have long been applied to robotics with many successful applications, (Luo et al., 2001; Saffiotti, 1997 ; Zimmermann, 1996) and regarded as an intelligent computational technique that enables the proper handling of sensor uncertainties. Fuzzy rules can be used to design the individual behaviors as well as the way they are integrated to reach a final decision (Arkin, 1998; Luo et al., 2001).

In this work, we propose a new method to integrate the behavior decisions by using potential field theory (Khatib, 1985) with fuzzy logic variables. The potential field theory proved to be very efficient especially for fast robots (Borenstein & Koren, 1991). The theory relies on the physical concept of force vector summation. Forces are virtual and describe the attractions and disattraction in the robot field. The potential field theory had been criticized for being susceptible to local minima and consequently unstable motion. We show that when the vector field is applied to the output from a single behavior, which is smooth due to the use of fuzzy logic, it can significantly enhance the performance of the robot navigation system. The control system is implemented and used to navigate a small indoor service robot so that it can track and follow an object target in an indoor flat terrain.

The chapter is arranged as follows, the next section presents the model of imaging and measurements of target location from the color image. In Section 3, we describe the design of fuzzy logic controller responsible for target tracking behavior, obstacle avoidance behavior and combining both behaviors. The results of robot control experiments for the behaviors are presented in Section 4. Conclusions are finally given in Section 5.

2. Measurement model

The RGB color space is the most popular color system since it is directly related to the acquisition hardware, but the RGB space is not perceptually uniform. The Hue, Saturation and Intensity, HSI color space is preferred when humans are involved, since it is perceptually uniform. The cylindrical representation of the HSI system is shown in Fig.1.

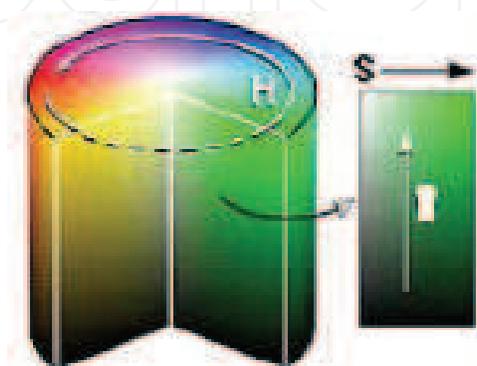


Fig. 1. The Hue-Saturation-Intensity (HSI) color space by cylindrical representation.

Perceptually Uniform, PU, color spaces are more suitable for color recognition than the RGB space, since the quality of recognition will always be judged by a human observer (Cheng & Sun, 2000 ; Kim & Park, 1996 ; Littmann & Ritter, 1997; Tseng & Chang, 1992).

The PU color space of HSI has the advantage that the object color is encoded mainly in the angle of the hue. This angle representation of color is easier in target color definition and less sensitive to changes of illumination intensity, but certainly changes when the illumination color is changed.

Therefore, we can compute the Hue, H and Saturation, S using the following formulae (Kim & Park, 1996) :

$$H = \arctan \left(\frac{\sqrt{3}(G-B)}{(2R-G-B)} \right) \quad (1)$$

$$I = (R + G + B) / 3 \quad (2)$$

$$S = 1 - \left(\frac{\min(R, G, B)}{I} \right) \quad (3)$$

The target object color is defined in terms of limiting hue angles and limiting saturation values describing the boundaries of a color zone in the H-S diagram that can be described by the following constraints:

$$H_{\min} < H < H_{\max}, \text{ and } S_{\min} < S < S_{\max} \quad (4)$$

Where subscript *min* refers to the minimum limit, and *max* refers to the maximum limit. The target is detected in the image by this selection criterion based on whether the pixel color lies within the boundaries of the H-S zone, known *a priori* for the target.

The segmented image is written into a monochromatic image, in which the target area color is written as white pixels and the background is written as dark pixels. The resulting binary image is then used to compute the area in pixels of the target area by counting the white pixels. This inherently uses the assumption that pixels are clustered in one group and that scattered pixels are a small portion in the image. The average horizontal coordinate of the target region is also computed and forwarded as input to the controller, as shown schematically in Fig. 2.

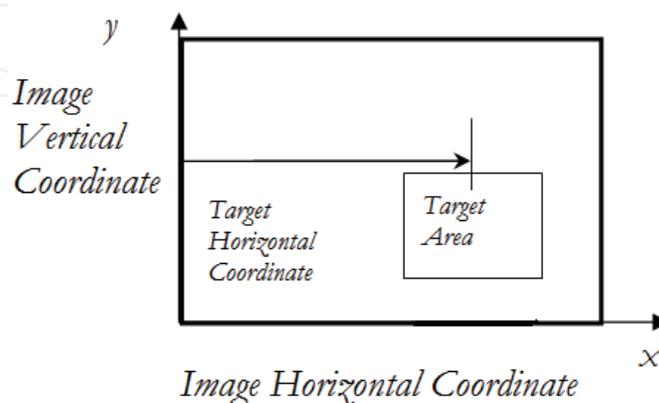


Fig. 2. Schematic representation of target measurement in the gray image showing extracted target region.

3. Design of controller

The goal of the controller is to enable the mobile robot to satisfy two objectives namely: target following and obstacle avoidance simultaneously. The objectives are implemented in separate behaviors which run independently in parallel and their output should be combined into a single command as shown in Fig.3. In this section, we describe the design of each behavior and then show how to combine their decisions.

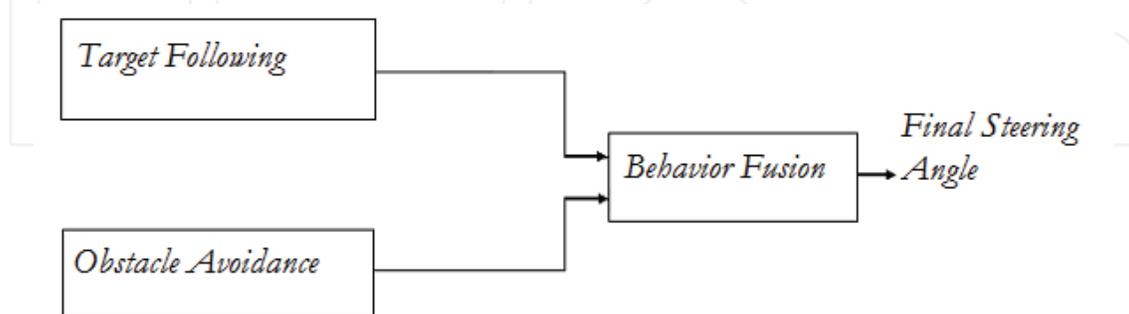


Fig. 3. Schematic of Robot Behaviors.

3.1 Design of target following behavior

The output of this behavior will decide the steering angle of the robot needed to make the target image appears continually in the middle of the image.

The sensory information available for the steering command is the average horizontal target position in the image, shown in Fig.2. The horizontal component of motion is only selected since the robot and target are both assumed to move on an indoor flat terrain and the camera orientation relative to the floor is fixed. The steering changes the target image position and hence, the motion attributes chosen as the input fuzzy linguistic inference layers for the FLC are selected to be:

1. Target image horizontal displacement
2. Target image horizontal velocity.

The membership functions for these two layers are shown in Fig.4. The fuzzy logic controller used to control the mobile robot employs triangular membership functions to fuzzify the data measured by the vision system. The input fuzzy variables are divided into three overlapping fuzzy set functions. In our implementation, the linguistic descriptors for the image horizontal displacement are defined as : 1) Left (L) , 2) Middle (M), and 3) Right (R), as shown in Fig.4. a.

The target image horizontal velocity is described by three fuzzy variables defined as : 1) Getting Left (GL), 2) Getting Middle (GM), and 3) Getting Right (GR), as shown in Fig.4.b. The shape and relative overlap of the fuzzy variables (that is tuning), are determined based on the experience gained from experiments with the robot. The shape of the membership function had been decided after studying the sensitivity of the mean of each membership function on the robot performance. The mean was changed across 10 % of its shown value and had been found to be stable over this range. The two fuzzy variables are then used to derive the output steering state. Three output states are used for steering namely, 1) Steer Right, SR, 2) go STRaight, STR and 3) Steer Left, SL, as shown in Fig.4.c. For each fuzzy linguistic interference process we define 3*3 fuzzy rule matrix as shown in Table 1.

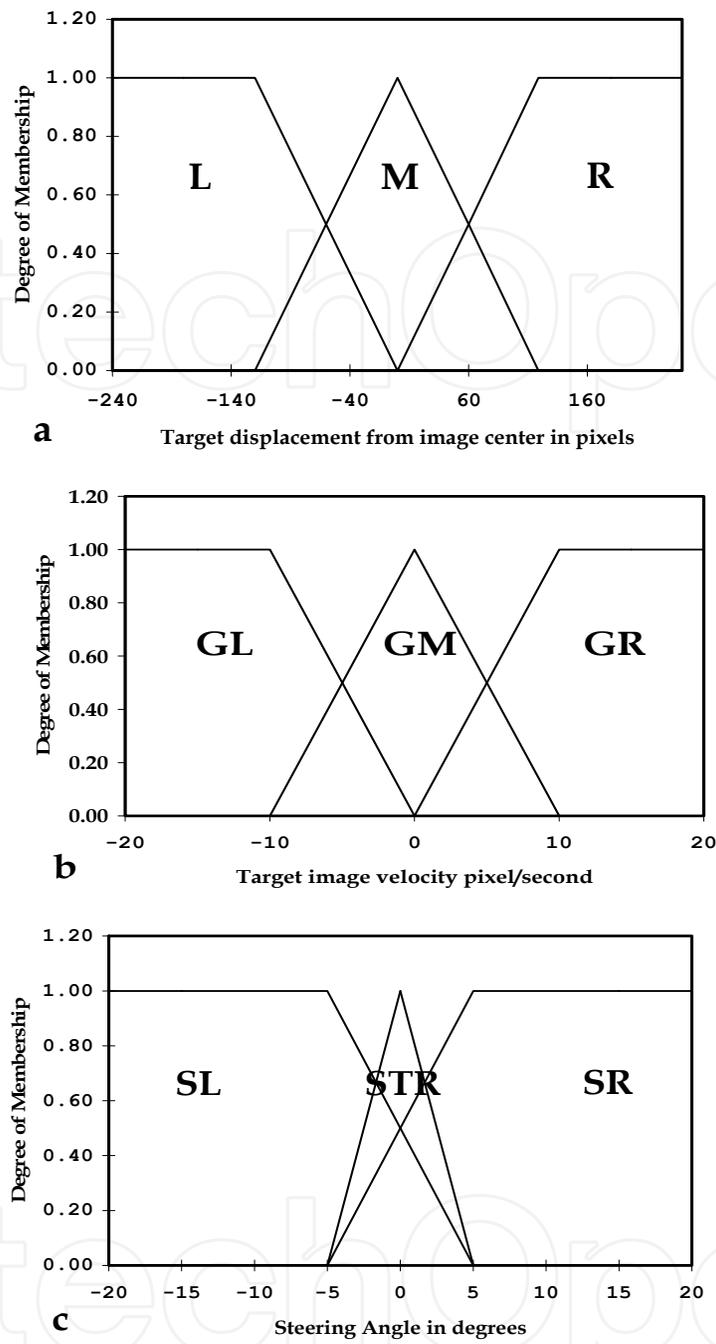


Fig. 4. Membership functions for the input variables of the steering FLC.

	GL	GM	GR
L	SL_1	SL_2	STR_1
M	SL_3	STR_2	SR_1
R	STR_3	SR_2	SR_3

Table 1. The Fuzzy Rule Matrix for the Target following FLC. (The columns show states for the target horizontal velocity, while the rows show states of target horizontal displacement).

The motion decision for the tracking behavior is calculated through the fusion of the image displacement and image velocity in the fuzzy logic inference matrix.

The values of matrix entry is calculated by finding the minimum of the two input variables. The three output variables are then computed using the root of sum squared of contributing variables. Finally, the normalized control command are defuzzified according to the center of gravity method.

3.2 Design of obstacle avoidance behavior

In the obstacle avoidance behavior, the reading of two ultrasonic range sensors are used as input variables for the FLC, while the output variable is the steering angle.

The flow chart of obstacle avoidance algorithm is shown in Fig.5, where the sensor reading are first read. Notations S1 and S2 denote signal of obstacle distance measured by left sensor and right sensor respectively. The sensor readings are then fuzzified (transformed into fuzzy linguistic variables) into three variables, namely, Near, N, Medium, M and Far, F.

The steering angle has three membership functions, Steer Left, SL, Steer Right, SR and STRaight, STR. Table 2, shows a list of the possible sensor states and the corresponding motion decision for avoiding the obstacle.

S1/S2	N	M	F
N	<i>Stop</i>	<i>SR</i>	<i>SR</i>
M	<i>SL</i>	<i>STR</i>	<i>SR</i>
F	<i>SL</i>	<i>SL</i>	<i>STR</i>

Table 2. The Fuzzy Rule Matrix for the Obstacle Avoidance FLC. (The columns show states for the right sensor, while the rows show states for the left sensor)

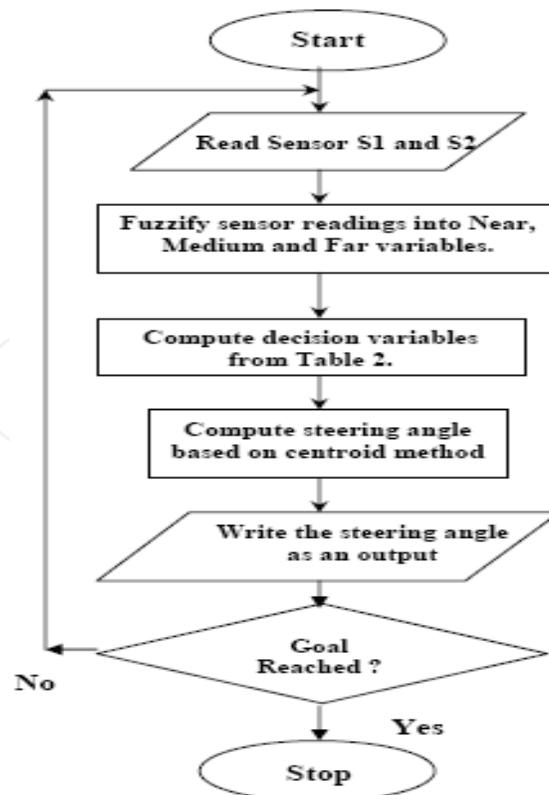


Fig. 5. Flow Chart of the Obstacle Avoidance Behavior.

It should be noted that based on the limit of the obstacle distance corresponding to the "N" linguistic variable, the robot may escape the obstacle by steering or may have to stop, in case the distance is very small to enable maneuvering without crash. The minimum distance in our case is 40 cm, and the robot speed is moderate, therefore we rarely get in the situation that the robot should stop unless it is besieged completely.

Then using the center of gravity methods, the steering angle is computed based on the decisions computed from Table 2 and made as a stand alone output signal that will be handled by the fusion algorithm.

3.3 Fusion of behaviors

We have two decisions for the steering angle computed from the two behavior implementations as shown before in Fig. 3. The decision is fused through using the potential field method by vector summation of the two vectors resulting from each behavior. The velocity vector from goal seeking behavior has a velocity amplitude maximum when steering is straight and decreases according to a linear model when the steering is off-axis. Then, using vector mechanics, the combined Euclidean magnitude and direction are computed and used to steer the vehicle. This method differs from the main potential field theory in the way the input vectors are generated, in our case it is generated through the fuzzy logic in each separate behavior in contrary to the direct construction of such vector in the main theory by linear scaling functions (Khatib, 1985; Saffiotti, 1997).

4. Experiments

4.1 System configuration

The robot had been constructed to have four wheels to move easily on flat terrain as shown in Fig.6. The two side wheels are driven by two independent servo motors, while the front and rear wheels are castor wheels and provided only to improve the mechanical stability of the robot. The robot consists of three layers of strong acrylic sheets supported by four long pillars. The lower level contains microcontroller circuit for controlling low level motor motion and reading of ultrasonic sensors and encoder readings. The second level carries the foursight vision processor and screen for displaying camera image, while the third carries the two cameras and the main microprocessor.

The robot is equipped with 16-ultrasonic sensors to enable perception of its environment. The resolution of the sensor measurement is around 1 cm. The robot has two color video cameras installed onboard. The cameras provide the image that is used by the target following behavior.

The main microprocessor receives data from the motion control system and the vision module. Inputs from both the cameras are fed into the Matrox Foursight module to process the image as a dedicated vision processor. The images received from the cameras are digitized via a Meteor II frame grabber and stored in the memory of the Foursight computer for online processing by specially designed software. We implemented algorithms that grab, calibrate the color image to eliminate the camera offset. The target color is identified to the system through measurement of its Hue-Saturation zone. The color attributes of the target are stored in the program for later comparison. Then the motion attributes of the target extracted area are computed and passed to main microprocessor where the data is needed for the FLC module. The movement of the vehicle is determined by the main microprocessor

with inputs from different components. All programs are implemented in C++ code and several video and data processing libraries are used, including Matrox Imaging Library, MIL and OpenCV.

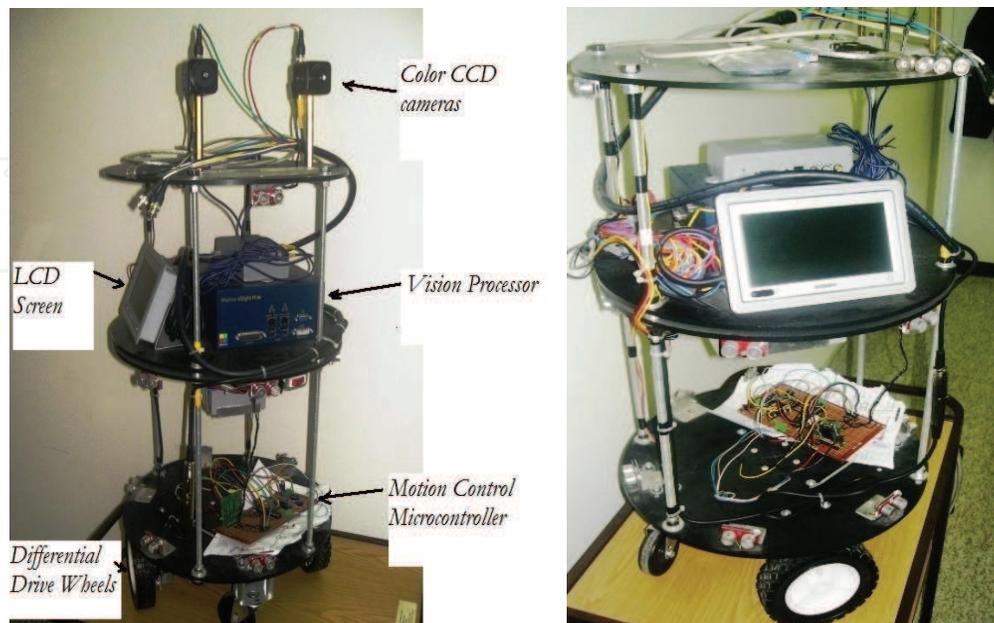


Fig. 6. Photograph of the mobile service robot.

The robot sensors and actuators communicate with the host computer via wired connections. The DC motor is controlled through a motor interface card utilizing the popular H-Bridge circuit with a high torque DC motor, of 8 kg.cm nominal torque at rated voltage of 12 Volts. Test programs were devised to ensure the right operation of the measurement and control system and to identify the resolution of measurements and control signal.

The robot main specifications are summarized in Table 3.

Item	Description
Size	40 cm diameter and 90 cm height.
Weight	20 kg
Power	12 V battery.
No. of Wheels	4
Steer and drive mode	Differential Drive
Camera type	Two Color CCD camera
Frame rate	30 frames per second
Image standard	NTSC
Image size	640×480 pixel × pixel
robot speed	Maximum 50 cm/s

Table 3. Specification of the mobile robot.

4.2 Results

An experimental program was conducted to explore the effectiveness of the control system in guiding the robot through the indoor environment according to desired behaviors.

Experiments were done for separate behaviors and then for the combined behavior. A sample result showing the extraction of target area is shown in Fig. 7. The left image shows original captured image and the extracted target area is shown in the right image.

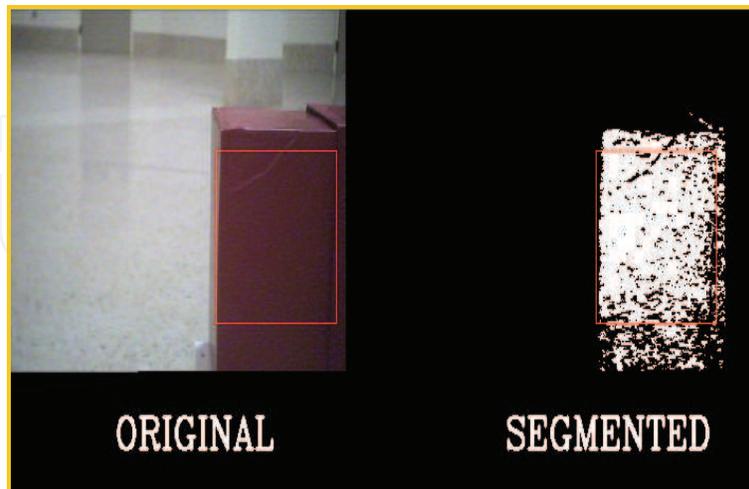


Fig. 7. The segmented image showing the detected target area.

A computer program was devised to construct the Hue-Saturation, H-S histogram shown in Fig 8. The advantage of this representation is that it enables better extraction of the target when it had been well identified a priori. We show the histogram for a sample target, which is a red object in this particular case. The hue range is from 0 to 360 degrees and the saturation ranges from 0 to 255. It is worth noting that the hue angle is repeated and hence 0 degree vertical line coincides with the 360 degree vertical line, therefore the region shown can be described in limited bounds. The dark regions in the graph corresponds to a high number of pixels in the target area having the same H-S point. This defines the color zone mentioned earlier in this paper and the bounds are extracted from this figure. It is worth noting that the input image contains the target in several views and distances so that it almost encapsulates all the possible color reflections of the object in all views. For the target following experiments, the robot is adjusted at first to view the target inside the color image.

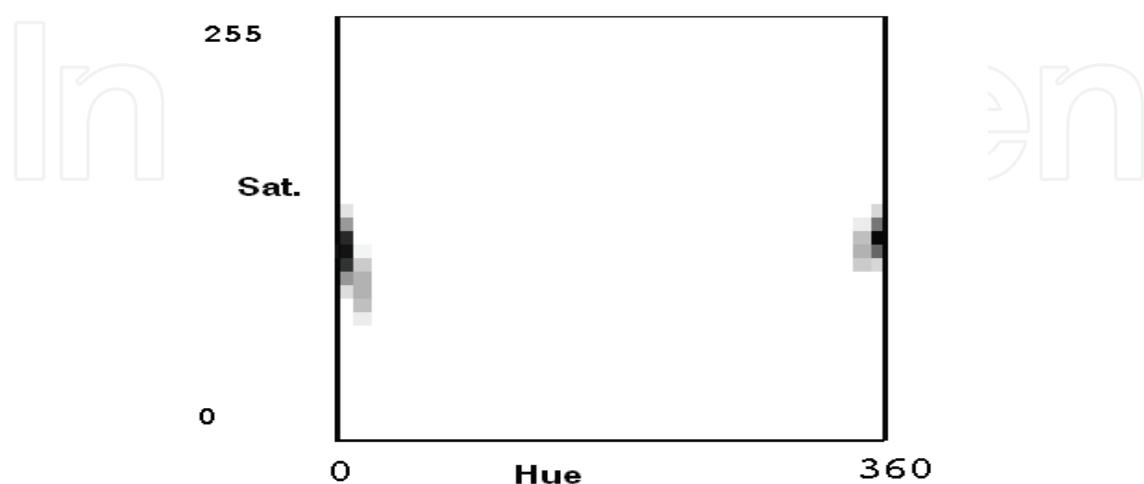


Fig. 8. The Hue-Saturation diagram showing regions of darker intensity as those corresponding to higher voting of the target object pixels.

The robot starts to move as shown in the robot track, Fig. 9 and keeps moving forward.

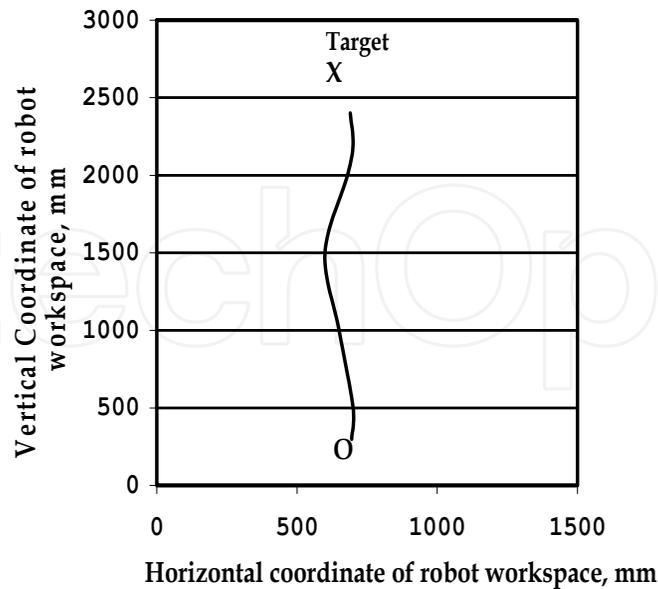


Fig. 9. The real track of the robot while following the colored target.

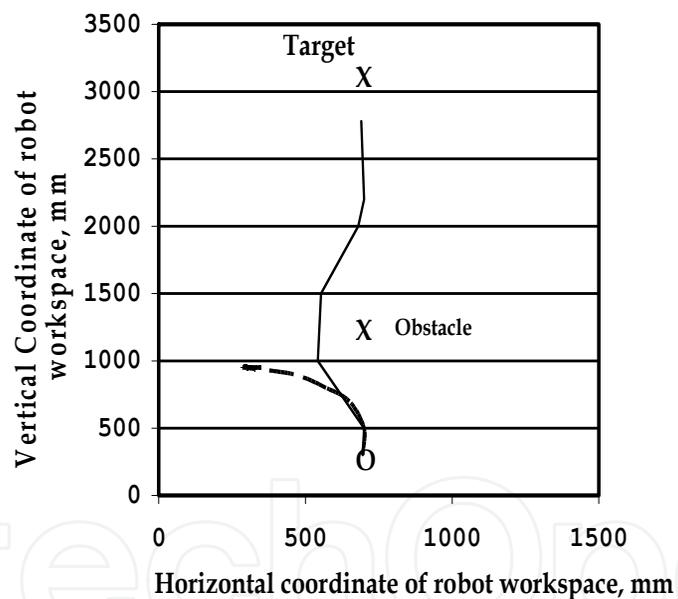


Fig. 10. The real track of the robot while following the colored target.

During the robot motion, the target continuously approach the image center and consequently the target area increases in the extracted target image. The robot followed the target even when it is moving in curved routes, as long as the target is visible in the robot camera and the target speed is comparable to robot speed.

An experiment for the obstacle avoidance behavior is shown in Fig 10. The dotted line shows the robot path when working with obstacle avoidance only. The robot evades the obstacles and move towards free areas based on the sequence of obstacles faced.

The robot stops when the target area in the image exceeds a certain empirical threshold so that the robot stops at about 25 cm in front of the target, or the sensors detect an obstacle less than 30 cm close to it.

The target following behavior is then integrated with the output from obstacle avoidance behavior using vector summation principle. The heading angle is then executed by the differential wheels.

An experiment showing the combined effect of both behaviors is shown also in Fig 10. The solid line shows the robot track when both behaviors are combined, the robot evades the right target but soon recovers and steer right toward the target.

5. Conclusion

We have implemented a control system that enables a mobile service robot to track and follow a moving target while avoiding obstacles. The system was experimentally validated using a real robot equipped with CCD cameras and ultrasonic range sensors. The algorithms for color image processing and extraction of the target image and measurement of target features had been developed. Fuzzy logic controllers had been designed to produce two concurrent behaviors of target following and obstacle avoidance and for combining the results of two behaviors into one set of commands for robot control. The control system succeeded in guiding the robot reliably in both tracking of the target and following it while keeping a reasonable distance between them that ensures the visibility of the target in the camera view. Fuzzy control provided smooth and reliable navigation that circumvents the inherent uncertainties and noise in the sensing process, as well as the smooth blending of behaviors.

Future directions of research include the use of more input information such as that from a human interface or an external planner. The goal is to create an autonomous service robot that will be able to navigate based on information from combined information from visual inputs, sonars and outdoor GPS data that will guide the vehicle in remote target points and have a user-friendly interface.

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Computer Vision

Edited by Xiong Zhihui

ISBN 978-953-7619-21-3

Hard cover, 538 pages

Publisher InTech

Published online 01, November, 2008

Published in print edition November, 2008

This book presents research trends on computer vision, especially on application of robotics, and on advanced approaches for computer vision (such as omnidirectional vision). Among them, research on RFID technology integrating stereo vision to localize an indoor mobile robot is included in this book. Besides, this book includes many research on omnidirectional vision, and the combination of omnidirectional vision with robotics. This book features representative work on the computer vision, and it puts more focus on robotics vision and omnidirectional vision. The intended audience is anyone who wishes to become familiar with the latest research work on computer vision, especially its applications on robots. The contents of this book allow the reader to know more technical aspects and applications of computer vision. Researchers and instructors will benefit from this book.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Mohamed Abdellatif (2008). Behavior Fusion for Visually-Guided Service Robots, Computer Vision, Xiong Zhihui (Ed.), ISBN: 978-953-7619-21-3, InTech, Available from:

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