Hybrid Type-2 Fuzzy Logic Obstacle Avoidance System based on Horn-Schunck Method

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Abstract

This paper is concerned with a visual navigation method based on type-2 fuzzy logic controllers (T2FLC) and optical flow (OF) approach. A Takagi-Sugeno fuzzy logic controller is used for obstacle avoidance task based on video acquisition and image processing algorithm. To extract information about the environment, the captured image is divided into two parts, the control system uses optical flow values calculated by a Horn-Shunk algorithm to detect and estimate the positions of obstacles. The efficiency of the proposed structure is simulated using Visual Reality Toolbox. The obtained simulation results demonstrate the effectiveness of this autonomous visual navigation system.

Keywords: Visual Obstacle Avoidance; VRML; Type-2 Fuzzy Controller; Horn-Shunck; Optical Flow

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1. Introduction

Navigation and obstacle avoidance are important tasks for mobile robot applications in indoor and outdoor environments. In unknown and complex environments, robots must have powerful control systems and precise perception parts [1], [2]. Many sensors can be used in robotic applications (localization, interception, obstacle avoidance or navigation) [3], [4]. Vision systems are very powerful and attractive sensors used in robotics [5]. The camera mimics natural beings' vision to define visual properties of the environment (colours and shapes). For their use, computer vision is an interesting tool in many applications: image registration and enhancement, matching for stereo vision, pattern recognition, and motion estimation and analysis [5], [6].

Behaviour-based navigation method presents a successful tool to subdivide the global navigation task into small sub-tasks [7], [8] : obstacle avoidance, wall following, goal seeking, target pursuing, etc.

The design of effective robot behaviours is not always easy and becomes difficult with increasing of uncertainties in sensor measurements [8], [9].

Different methods have been proposed for obstacle avoidance task. Visual-based navigation method is an attractive approach used in robotic applications [10], [11], [12]. The vision system can increase the utility of mobile robots in different domains [6], [7], [10].

Optical flow is the important used method for mobile robot vision-based navigation [7], [11], [13], [14], [15]. This approach is a velocity calculation strategy employed mainly in motion estimation, video compression-reconstruction, image segmentation [14], [15], detection and avoiding obstacles [5], [13], [15].

In papers [6] and [7], surveys of visual navigation techniques are presented for robotic applications in indoor and outdoor environments.

For the task of obstacle avoidance, authors in [16] have proposed a real-time robot navigation based on object tracking and obstacle avoidance tasks. The robot uses a stereo vision system to detect the desired target while the laser finder is used to avoid collision. Authors in [13] have studied the obstacle avoidance task using a balancing strategy based optical flow method. The depth is calculated from two consecutive images.

In [4], authors have studied the robot obstacle avoidance task in dynamic and changed environment using monocular vision based on colour segmentation and edge detection.

In the paper [17], Wang et al. 2015 have studied the obstacle avoidance task for a quadrotor with a monocular camera using an improved method based on optical flow.

A survey on the use of optical flow techniques for robotic applications is presented in [15].

On the other hand, fuzzy logic controllers (FLCs) have the capacity to handle and treat robotic uncertainties. [9], [19]. Where, type-1 fuzzy logic system uses crisp and precise fuzzy sets. However, type-2 fuzzy logic system presents a new generation of fuzzy logic controllers based on the extension principle of Zadeh [20]. Type-2 FLCs offer an opportunity to model the increasing uncertainties and give a better representation in robotic fields. For example, papers [21] and [22] present reviews on the most applications of Interval Type-2 Fuzzy Logic for different control problems, especially in robotic field.

In paper [23], the authors have studied obstacle avoidance and wall following behaviours using Mamdani type-2 fuzzy logic controllers. An Interval type-2 fuzzy logic tracker is proposed for mobile robot in paper [24].

Authors in [25], have studied the navigation task in dynamic environments with a hierarchical structure using Type-2 fuzzy logic controller. The three basic robot behaviours have been studied using type-2 fuzzy Logic Controllers in the paper [8].

In the paper [26], the authors have proposed Type-1 and Type-2 Takagi-Sugeno Fuzzy Logic Controllers for controlling a mobile robot. They have studied and compared the performances of the three main behaviours: goal seeking, obstacle avoidance and wall-following. Other contributions have been applied in [9], [27].

However, to use optical flow algorithms only for mobile robot movements is not always powerful, fuzzy logic systems are the most common approaches to solve the limitation of action values. Fuzzy logic can achieve a good level of performances with high smoothness and continuous actions. The main advantage of visual based type-2 fuzzy logic control is the introduction of human experience in the form of *If-Then* rules about how to control the robot with increasing uncertainties.

The hybridization of optical flow approach and fuzzy logic method is an interesting research area. In [10], type-1 fuzzy systems have been used to estimate the depth and the rotation angle fast moving object tracking. Two type-1 fuzzy logic controllers with Lucas-Kanade tracker are proposed for unmanned aerial vehicle (UAV) [28].

In [18], the authors proposed a vision system based type-1 fuzzy logic control for unmanned aerial vehicle (UAV) navigation in real-time. They have tested different functionalities: landing, object following and obstacle avoidance.

Authors in [29] proposed visual robot navigation based on bio-inspired approach for optical flow data interpretation and fuzzy inference system.

Fuzzy path following task for a mobile robot is studied in [30] based visual navigation method using a CCD camera.

In the paper [5], the authors proposed a vision based obstacle avoidance system using Scale Invariant Feature Transform (SIFT) and type-1 fuzzy logic system.

The main objective of this paper is the application of type-2 fuzzy logic controller based on image processing step for mobile robot autonomous obstacle avoidance in unknown environment. Horn and Schunck algorithm of optical flow method is used to extract information about the surrounding environment and to estimate the obstacles positions.

The paper is organized as follows in:

- Section 2, we present briefs on type-2 fuzzy logic controllers and optical flow methods;
- The proposed fuzzy visual navigator is introduced and explained in Section 3;
- The obtained simulation results are presented and discussed in Section 4;
- Section 5 concludes the paper.

2. Brief on type-2 FLC and Optical Flow Methods

In this section, we will present briefly the two used approaches in this work: type-2 fuzzy logic controllers (T2FLC) and horn-Schunck optical flow algorithm.

The first method is used as a controller to generate the steering angle for mobile robot motion, and the second is applied to detect the surrounding obstacles and objects in the environment based on a virtual camera.

2.1 Type-2 Fuzzy Logic Controllers

The structure of a Type-2 fuzzy logic controller is same as the structure of a type-1 controller, the difference between them is in the block of output processing [8], [20]. The membership functions of type-2 fuzzy sets are three dimensional functions. Type-2 FLC is composed of the five elements [20], [21]:

- *Fuzzification:* converts the real inputs (X) into fuzzy values $\overline{\mu}_{\tilde{A}}(x)$, $\underline{\mu}_{\tilde{A}}(x)$;
- *Rule-Base:* is composed of linguistic description of the expert operator to define quantify the input-output relationship. The rule-base is defined by *If-Then linguistic expressions*;
- *Inference Mechanism:* interpret and apply the operator knowledge using the rule-base;
- *Defuzzification:* converts the calculated results into real values (*Y*);
- *Type reducer:* This block defined the centroid of type membership function according to the left and right points based on the Extension Principle of Zadeh [21].

We can summarize the calculation of the output value by the following steps:

If we consider a type-2 Takagi-Sugeno fuzzy logic system with M fuzzy rules, using a vector of p inputs ($x_1 \in X_1,\dots,x_p \in X_p$) and generates one output ($y \in Y$).

The r^{th} fuzzy rule is expressed as follows:

$$\text{IF } x_1 \text{ is } \tilde{F}_1^r \text{ and } x_2 \text{ is } \tilde{F}_2^r \text{ and...and } x_p \text{ is } \tilde{F}_i^r, \qquad (1)$$
$$THEN\ y^r = c_0^r + c_1^r x_1 + \ldots + c_p^r x_p$$

After a fuzzification step, The firing strength of the i^{th} fuzzy rule is calculated by the following equations :

$$W^i(x') = [\underline{w}^i(x'), \overline{w}^i(x')] \qquad (2)$$

$$\underline{w}^i = \underline{\mu}_{\tilde{F}_l^i}(x_1) * \ldots * \underline{\mu}_{\tilde{F}_p^i}(x_p)$$
$$\overline{w}^i = \overline{\mu}_{\tilde{F}_l^i}(x_1) * \ldots * \overline{\mu}_{\tilde{F}_p^i}(x_p) \qquad (3)$$

The obtained output is defined by a type-1 set as follows:

$$Y(Y^1,\ldots,Y^M,W^1,\ldots,W^M) = [y_l, y_r]$$
$$= \int_{y^1} \cdots \int_{y^M} \int_{w^M} \ldots 1 / \frac{\sum_{i=1}^{M} w^i y^i}{\sum_{i=1}^{M} w^i} \qquad (4)$$

where $y_i \in Y^i$, and $Y^i = [y_l^i, y_r^i]$, (i=1...M), y_l and y_r are the left and right outputs calculated using the equations 5 and 6.

$$y_l = \sum_{i=1}^{M} w_l^i y_l^i \Big/ \sum_{i=1}^{M} w_l^i \qquad (5)$$

$$y_r = \sum_{i=1}^{M} w_r^i y_r^i \Big/ \sum_{i=1}^{M} w_r^i \qquad (6)$$

The overall output of the system is the mean of the two outputs.

2.2 Optical Flow Method

In this paper, we have used the optical flow approach to detect objects and obstacles in the navigation environment of the mobile robot. This method is used to calculate the pixel motion [31], [32]. It is based on the velocity vectors in the image as follows:

$$I_x u + I_y v + I_t = 0 \qquad (7)$$

where: I_x, I_y and I_t represents the derivatives of the image intensity values in three dimensions spatiotemporal *x*, *y* and the time respectively; *u* and *v* represent horizontal and vertical optical flow vectors.

In optical flow algorithms, there are two basic information. Firstly, the projection of the translation vector in the image plane defines the point called focus of expansion (FOE). The coordinates of this point give information about the direction of the 3D translation of the camera [17].

Secondly, the depth of the pixels defined by the FOE is represented using the projection point in the image. This information is called Time To Contact (TTC) [33]. It was firstly introduced by Lee [34]. The objective is to estimate the necessary time to collision with the captured object in the image. The TTC is expressed by the speed and the distance of the detected obstacles as follows:

$$TTC = \frac{-Z}{dZ/dt} \qquad (8)$$

where:

Z is the distance between the camera and the obstacle,

dZ/dt is the velocity of the camera.

There are several algorithms in optical flow theory: differential techniques, Energy based methods, region based Marching and Phase based techniques. In the first class, there are two algorithms: Horn-Schunck (HS) [31] and Lucas-Kanade [32].

3. Proposed Navigator

This section discusses the proposed control system for mobile robot navigation. We have studied the basic robot task, which is the obstacle avoidance. The block diagram of the control scheme is presented in Figure 1.

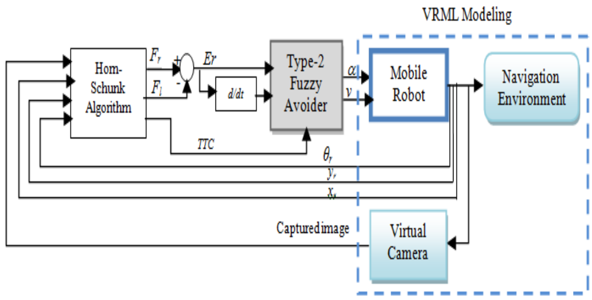

Figure 1. Visual Obstacle Avoidance system

The controlled robot perceives its environment using a single camera with high resolution (a virtual camera). Horn-Schunk algorithm (HS) of optical flow is used to estimate the velocity vectors of the image (optical flow calculation). The image is divided in two parts: right and left. It is treated, resized and subdivided in two parts in order to generate the appropriate control actions.

The designed control system allows the robot to avoid collisions with the nearest obstacles. For each part of the image, the algorithm calculates the mean value of optical flow (F_r and F_l) using the equations: (9), (10).

$$F_r(t) = \frac{1}{N}\sum_{F \in S_r} F(t) \qquad (9)$$

$$F_l(t) = \frac{1}{N}\sum_{F \in S_l} F(t) \qquad (10)$$

where:

- S_l is the half left of the image;
- S_r is the half right of the image;

- N is the number of flow elements in the half right or the left of the image.

The difference between the right and the left flows noted (*Er*) is calculated with its variation (*ΔEr*) using the following equations:

$$E_r(t) = F_l(t) - F_r(t) \qquad (11)$$

$$\Delta E_r(t) = Er(t) - Er(t-1) \qquad (12)$$

These two variables are used by the designed type-2 fuzzy logic controller to infer the motion actions: the steering angle *a* and the robot velocity *v*. The robot motion is defined by the kinematic model shown in eq. (13).

$$\dot{x}_r = v\cos(\theta_r)$$
$$\dot{y}_r = v\sin(\theta_r)$$
$$\dot{\theta}_r = w \qquad (13)$$

where: x_r and y_r are the robot coordinates; θ_r is the heading angle; v is the linear velocity; w is the angular velocity calculated from the steering angle a_r.

The proposed controller is a Takagi-Sugeno type-2 fuzzy logic controller. It uses two inputs: *Er* and *ΔEr* and one output (we consider the robot moves with a fixed speed). Inputs are fuzzified using the same type-2 membership functions (T2MFs) as shown in Figure 2.

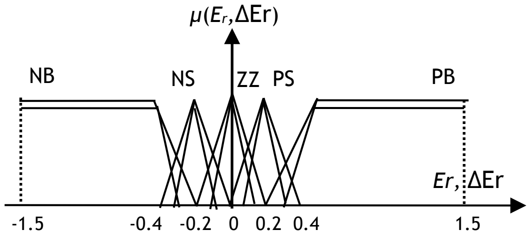

Figure 2. Membership Functions of Er and ΔEr

The output action (steering angle) is represented by singletons as flows:

$$NB = \frac{-\pi}{4},\ NS = \frac{-\pi}{8},\ ZZ{=}0,\ PS = \frac{-\pi}{8},\ PB = \frac{-\pi}{4}$$

The used linguistic labels are: **ZZ:** Zero; **PS:** Positive Small**; PB:** Positive Big; **NB:** Negative Big; **NS:** Negative Small.

Using these variables, the type-2 *If-Then* fuzzy rules are given in Table 1.

Table 1. Type-2 Fuzzy Rule-Base

ΔEr	*Er*				
	NB	NS	ZZ	PS	PB
NB	PB	PB	PS	NS	NB
NS	PS	PS	PS	NS	NB
ZZ	PS	PS	NS	NS	NS
PS	PS	PS	NS	NP	NS
PB	PB	PS	NS	NB	NB

4. Obtained Simulation Results

In this section, we will present examples of mobile robot navigation using the proposed type-2 fuzzy logic controller based optical flow approach.

In our work, the simulation is done using VRML library (Virtual Reality Modelling Language) to define the navigation environment in 2D and 3D forms. The simulated mobile robot is a cylindrical platform with two motorized wheels. To navigate autonomously, the robot is equipped with a virtual camera.

To test the studied visual obstacle avoidance task, we consider the following assumptions:

If the robot environment is free of obstacles, the mobile robot moves forward.

Else, the robot executes the generated control action by the elaborated type-2 fuzzy logic controller to avoid collisions (turn right or turn left).

The simulation results of the obstacle avoidance are presented in Figure 3.

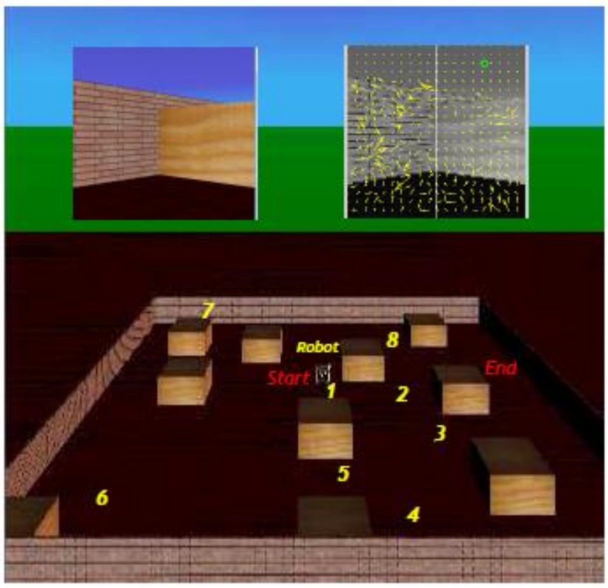

Figure 3. 3D Frames of Robot Navigation

It presents the robot positions during motion with obstacle avoidance starting from initial point (start) to the final destination (end).

Examples of the camera view in colour and the calculated optical flow vectors are given in the top left and right corners, respectively. At any time-step, the robot perceives the surrounding environment using the virtual camera. The acquired image indicates the state of the environment on the robot front side.

Then, optical flow values are calculated to detect obstacles in the two parts. The detected and the nearest obstacle are defined by the flow vectors (in yellow colour) in the top right. In this last one, we indicate the focus of expansion (FOE) as a green circle.

To illustrate the robot's ability to detect and avoid obstacles.

Figure 4 shows the executed path in the 2D environment. The robot positions are presented by the points (*1, 2,..,8*).

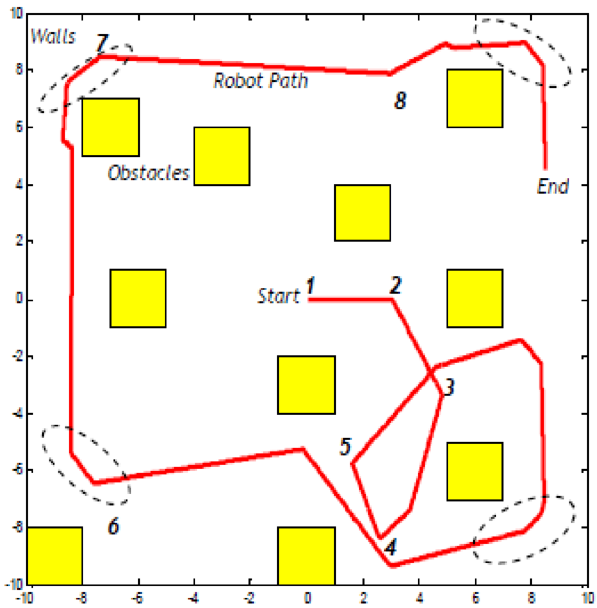

Figure 4. 2D Robot Path

As it can be seen from the previous results (Figure 3 and Figure 4), the proposed type-2 fuzzy controller is able to generate the appropriate control action for obstacle avoidance task. The robot moves freely and autonomously without collisions.

This navigation system is effective to accomplish this task with good performances.

To present the moments of avoidance, the Time-To-Contact (TTC) is computed from the optical flow values as shown in Figure 5.

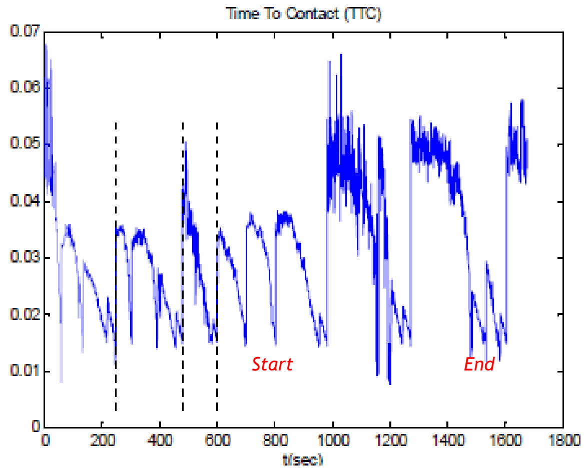

Figure 5. Time To Contact

During movement, according to the value of TTC, the designed type-2 fuzzy logic controller is activated to infer motion actions. Times of avoidance are indicated with dashed lines.

5. Conclusion

In this paper, we have presented a visual obstacle avoidance controller for a mobile robot. The proposed navigator is a Takagi-Sugeno type-2 Fuzzy logic controller.

Horn-Shunk algorithm of the optical flow method is used to detect obstacles in the environment. The proposed T2FLC is used to steer the robot around the nearest obstacles based on the calculation of optical flow values in the two parts of the image (right and left). The proposed navigation system is simulated in 2D and 3D environment using a VRML library.

The obtained results demonstrate the efficiency of the elaborated T2FLC for mobile robot navigation and obstacle avoidance capacity.

As prospective, the interest will be given to the development of type-2 fuzzy logic controllers for other sub-tasks: goal seeking, navigation to goal with obstacle avoidance and pursuing a moving target in cluttered environment.

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