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Design of Disaster Four-rotor Drone Control System Based on Fuzzy Self-turning PID Control

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Abstract. Disasters often manifest as multifaceted crises that pose significant challenges for emergency responders, particularly when accessing hazardous environments such as fire scenes or chemically contaminated areas. The complexity of these situations necessitates the exploration of innovative solutions to augment the efficacy of rescue operations. In this context, the present study introduces a novel approach through the development of a disaster drone control system, predicated on the principles of fuzzy self-tuning control. This paper delineates the conceptual framework and architectural design of a fuzzy self-tuning Proportional-Integral-Derivative (PID) controller. It leverages fuzzy logic to enhance the precision of control actions by employing fuzzy rules, thereby facilitating a comparative analysis between traditional adaptive controllers and their fuzzy counterparts. Furthermore, this study embarks on a comprehensive examination of the current landscape, practical applications, and prospective advancements in the realm of disaster robotics. The findings underscore the superior accuracy and efficiency of the self-tuning PID control mechanism, which significantly expedites the identification of victims. Consequently, the deployment of disaster drones not only streamlines rescue operations by curtailing time and financial expenditures but also contributes to the broader objective of making rescue missions more manageable and effective.

Keywords: complex situation; fuzzy PID control; disaster drone; fuzzy rules.

1. Introduction

Natural disasters have serious consequences for the environment, human life and man-made structures. In addition, cities and countries often face severe social and economic hardship as a result of disasters. A recent development in the handling and access of natural disasters is the use of robots as a platform for disaster management applications. Robotics has been extensively used in natural disaster management throughout the last few years. A shoebox-sized wheeled robot was placed into damaged homes during the 2005 La Conchita mudslide in order to search for victims [1]. A team of people and robots (UGV, UAV) collaborated with the Italian National Fire Brigade at Mirandola, following the 2012 earthquake [2]. Recently, a field experiment was carried out to map the structures destroyed in the 2011 Tohoku earthquake using a team of ground and aerial robots.

Since 1950, robot technology has advanced to become an effective tool for preventing, responding to, and recovering from disasters. Drones, for instance, were able to rapidly survey a variety of disaster sites. Because of their portability and affordability, drones are becoming a useful tool for finding survivors in tight spaces like subterranean passageways or collapsed buildings. Unmanned ground vehicles worked in hazardous sections of damaged nuclear power stations, while remotely piloted underwater vehicles fixed leaks at underwater oil plants. But there's still a long way to go before robots are used in real-world applications.

This paper introduces a new disaster drone control system based on fuzzy self-turning PID control, which is an efficient way to search for the survivals in natural disaster or chemical accident. The paper also compares the difference between fuzzy self-turning PID control and conventional PID control, then find that the result of fuzzy logic controller has high accuracy and long stability time.

2. Systematic literature analysis

Natural or man-made disasters have become more widely recognized over time, as has the necessity of taking action to lessen their effects. The issue is not just the disaster per se, but also the readiness of the impacted areas to deal with it. The four phases of disaster management are readiness, response, mitigation, and recovery [3]. The ability of communities to react and recover is determined during the pre-disaster phase, sometimes referred to as mitigation and preparedness.

Robots designed to prevent and prepare for disasters will be essential in helping us deal with the recent surge in natural and/or man-made calamities. It's conceivable that we won't be able to enter during a crisis due to inefficiency, physical restrictions, or unsafe conditions. Robots are designed to be a compliment to humans and/or sniffer dogs, not to take their place, especially when it comes to lowering the risk to their lives.

Disaster robots are mobile robots, or a variety of robot types that are often tiny and portable enough to work in disaster zones and be used mostly for victim search and rescue operations following a disaster. In contrast to military robots, disaster robots must adhere to three design requirements: (i) severe operating circumstances, unobstructed site; alterations over time may impact the robot's dimensions, sensor efficacy, and range of motion. (ii) extremely constrained cellular communication and the capacity to function in locations without GPS. (iii) the capacity to function both alone and in conjunction with the victim and operator [4].

The field of robotics has advanced significantly in terms of creating autonomous robots. Intelligent control technology advancements and robust, useful, and intricately functional electrical and mechanical components that are applicable in the field are supporting this. The robot can readily work on demand so that it can be used in regular circumstances (and not in a state of emergency). For instance, the robot can move to avoid a tree by simply recognizing its presence as an impediment. However, in the event of a disaster, humans are frequently unable to recognize things and obstacles—let alone robots—due to the havoc the location has generated. Fully autonomous robots for search and rescue activities are still unlikely to be achieved, so there is a need to create and incorporate robots in collaboration with operators and other rescue operation participants, often referred to as semi-autonomous robots [5].

Due to various uncontrollable circumstances, such as building collapses and ground subsidence caused by earthquakes, and the large discharge of hazardous chemicals in small spaces, rescue personnel are unable to enter the disaster relief site in a timely manner for rescue. Therefore, disaster relief robots have become an important method for rescuing disaster victims. Each disaster scenario should have different types of disaster robots corresponding to the execution tasks.

The idea of manipulating robots with behavior-based control techniques is exciting since biological systems consist of many basic behaviors that need to be coordinated to produce those attributes. So how can a robot mimic a biological system whose primary characteristic is its ability to learn? The researchers have provided the following recommendations. For example, Gomez et al. provide layered evolution techniques based on neural evolution, which is the construction of artificial neural networks using genetic algorithms [6]. Each of these levels is combined utilizing proposed behavior-based learning algorithms and reinforcement learning for online and adaptive learning using multi-level approaches. Unfortunately, because the integration between different layers is so complex, the process requires a large amount of computer power.

The traditional classical control adopts Angle deviation as the adjustment of closed-loop control. Although the drone can achieve certain flight effects, the control system has high accuracy requirements on PID parameters, which is prone to overshoot, shock and other phenomena. Meanwhile, it is also harsh on the flight environment. At the same time, the diagonal velocity is controlled by PID closed-loop control, which can suppress the over harmonic oscillation caused by the Angle PID control due to the excessive angular velocity, so the cascade PID closed-loop control system of Angle and angular velocity is used.

Based on fuzzy self-tuning PID control, the post disaster robot manipulates a control method that combines fuzzy logic and PID controller to realize robot motion and task implementation. This method can enhance the control performance of robots in complex and random environments, making them more suitable to perform post disaster rescue tasks.

3. DJI Matrice 100 drone

3.1. Structure

This article employs the DJI Matrice 100 drone as a platform for robot deployment during natural disasters. DJI Matrice 100 drone is a four-rotor UAV. This quadcopter has many ports for connecting third-party components and is quite configurable. Up to 40 minutes of hover time are possible with two battery modules, and a maximum payload of 1 kg can be raised by the stiff, lightweight fuselage frame. The maximum velocity is around 20 m/s. Since these specs allow for a long hover period and high-speed flying with many sensors that will detect victims first, we think they are appropriate for disaster management applications.

This paper fitted an Intel RealSense camera (R200), a Hokuyo Lidar (UTM-30LX scanning laser rangefinder), and a drone computer (manifold) as on-board electronics. LiDAR measurements are reliable up to 30 meters with a scan period of 25 milliseconds, while depth camera measurements are reliable up to 10 meters using real-time RGB and stereoscopic infrared cameras. Manifold has an NVIDIA Tegra K1 SOC and is a GPU-capable computer. These modules can be carried by the Matrice 100, which can handle all sensor and CPU processing internally.

Figure 1 shows the structure and configuration of a disaster robotics drone performed in natural hazard. Constructed with IMU, IR depth camera and lidar to implement the target search and temperature identification tasks.

The lidar provides a complete 2D map of the surrounding environment and landform as the drone reaches the disaster location. The drone then utilizes its map to guide the maneuver by displaying possible flying paths and open entrances. Lastly, the robot visualizes the local 3D scene using a depth camera. Even in the dark, survivors can be found with a stereo infrared camera [7]. Flying robots have succeeded in mapping disaster situations both locally and globally with the use of IMU. Figure 1 shows the structure of DJI matrice 100 drone.

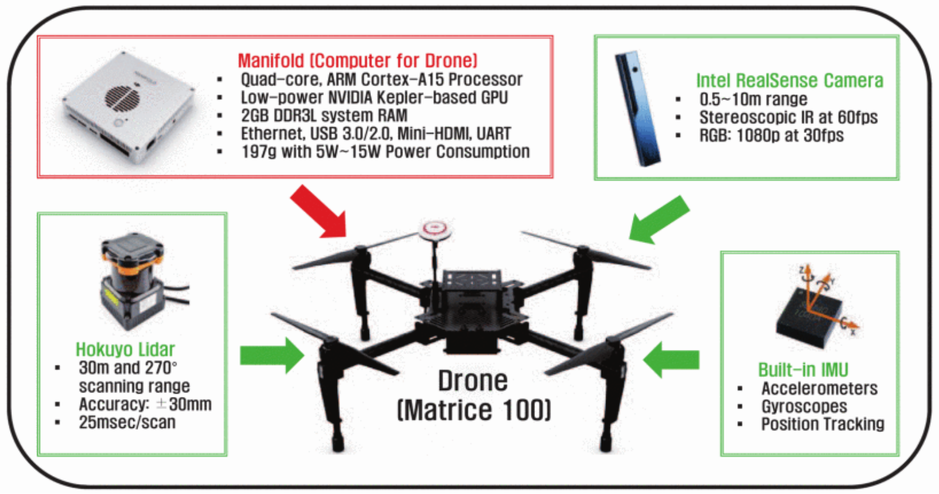

Fig. 1 Structure of DJI matrice 100 drone [8]

3.2. Function

The function of disaster robotics are generalized in four parts. First of all, since disaster robots can accurately search for victims, it can strongly improve the survival rate of victims. Secondly, due to the expansion of search scope and robot scale, the cost of time and manpower evidently decreased into a low level. Thirdly, because of the excellent temperature recognition system, the disaster robotics could Help humans collect body temperature information and perform tasks that humans cannot accomplish [9]. Besides, when robots can detect potential threats and hazards before humans, it could help us reduce potential risks from radiation or explosion of chemicals.

Recent DJI matrice drone integrates infrared depth cameras with lidar to provide local victims and overall maps of the disaster area, which is an efficient way to discover the accurate location and increase the survival rate of victims.

4. Fuzzy Controller

Three steps make up the fuzzy process: deblurring, rule evaluation, and fuzzification. The destroyed values are converted into fuzzy rules during the fuzzification stage. The fuzzy inference system then plans input values within a given range using the rule library and database, and it establishes the output controller values. (i) Rule assessment: Each fuzzy rule is now assigned a strength value. The membership function's ability to extract values from a fuzzy set's clear values input. (ii) Deblurring: The fuzzy output is transformed into equivalent clear values during this stage [10].

The fuzzy adaptive controller and traditional adaptive controller have the following similarities and differences. Similarities consist of two main aspects. Firstly, the basic framework and principles are more or less similar; Secondly, the mathematical tools used in the design and analysis of control systems are very similar. There are also three differences that need to be announced. The expert experience related to the dynamic characteristics of the controlled object and the control strategy is embedded in the fuzzy adaptive controller, which is not considered in traditional adaptive control [11]. Fuzzy adaptive controller is a nonlinear controller that can be universal for different controlled objects, while the structure of traditional adaptive controllers varies depending on the controlled object. Human knowledge related to the control strategy and dynamic properties of the thing under control can be easily embedded into fuzzy adaptive control systems. The model of fuzzy controller system is shown in figure 2 [12].

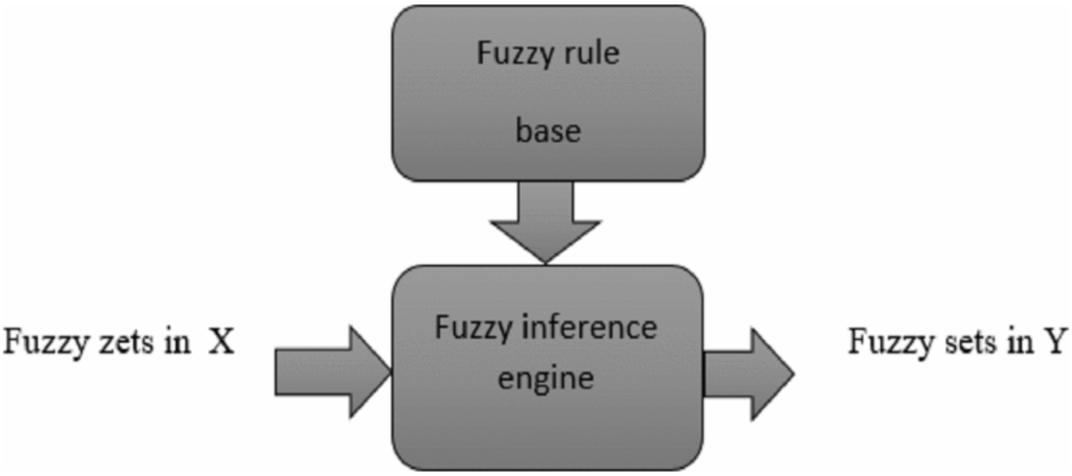

Fig. 2 The model of fuzzy controller system [12]

5. Methodology

5.1. Mathematical Modelling

To maintain the mathematical model's generalizability, the model is predicated on the following assumptions [13]. One may consider the four-rotor UAV to be a uniformly massed, symmetric rigid body; The four-rotor UAV's resistance and gravity stay constant throughout flight, regardless of altitude changes; The four-rotor UAV's pulling power is precisely proportional to the square of the propeller speed in all directions.

After the drone's motion state was examined, it was determined that its motion state consisted of both translational and rotational motion modes. The vehicle's precise ground-based centroid position is shown by [x, y, z]. The angle [φ, θ, ψ] represents the angle formed by the object's axis and the coordinate system, which includes the rolling, pitch, and yaw angles. A gyroscope can be used to measure the angular velocity around the three axes; the relationship between the three is given as follows [14].

$$\begin{pmatrix} \phi \\ \dot{\theta} \\ \dot{\psi} \end{pmatrix} = \begin{pmatrix} 1 \sin\phi \tan\theta \cos\phi \tan\theta \\ 0 \cos\phi - \sin\phi \\ 0 \sin\phi \,/\, \cos\phi \cos\phi \,/\, \cos\theta \end{pmatrix} \begin{pmatrix} p \\ q \\ r \end{pmatrix} \tag{1}$$

An analysis of the aircraft's force is done using physical knowledge. The air resistance f during the UAV and aircraft's flight, and the aircraft's own gravity G make up the majority of the plane force analysis diagram. The rotor generates lift force F. In line with Figure 3 [14].

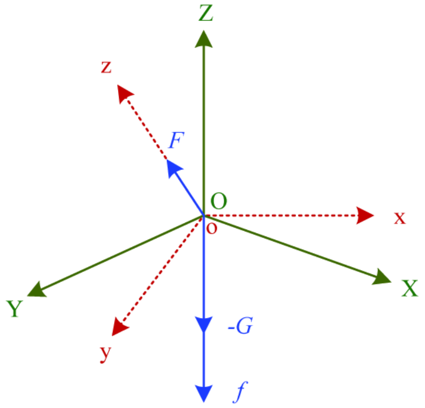

Fig. 3 The plane force analysis diagram [14]

According to the Newton-Euler equation, the mathematical expression of the dynamics model of the disaster drone is (2) [15].

$$\begin{cases} \ddot{x} = \dfrac{-x \cdot K_1 + \cos\psi \sin\theta \cos\phi + \sin\phi \sin\psi U_I}{m} \\ \ddot{y} = \dfrac{-y \cdot K_2 - \cos\psi \sin\psi + \sin\psi \sin\theta \cos\phi U_I}{m} \\ \ddot{z} = \dfrac{-z \cdot K_3 + \cos\phi \cos\theta U_I}{M} - g \\ \ddot{\phi} = U_2 I / I_x \\ \ddot{\theta} = U_3 I / I_y \\ \ddot{\psi} = U_4 I / I_z \end{cases} \tag{2}$$

5.2. Fuzzy self-turning PID controller design

The control signal of the PID controller is determined by three terms, as specified in the equation (3)[16]. Based on the conventional PID controller,

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \tag{3}$$

K and stand for proportional gain, integral gain, and differential gain, respectively. Of these, u(t) is the control signal and e(t) is the error signal, which is obtained from the difference between the predicted signal r(t) and the output signal y(t).

Four principal pieces make up the fuzzy logic controller: a decision unit (which reasons based on rules), a fuzzification interface (which transforms clear inputs into fuzzy variables), a deblurring interface, and a knowledge base (which contains membership function rules and parameters).

5.3. Establishment of Fuzzy rules

The rule set is the main component of fuzzy logic control. Fuzzification, fuzzy reasoning, and defuzzification are examples of fuzzy logic control actions. They provide a definition for control action accuracy. As many sets of number rules as possible are possible. In this paper, we try to use fewer rules to implement controller actions. Error and derivative error are a fuzzy controller's two primary inputs.

The following letters represent the fuzzy rule set and its values: NO denotes a negative error or error rate change; ZO denotes a zero error or error rate change. PO is for positive error or error rate of change; NA stands for negative value; Positive value is denoted by PA and zero value by ZA [17].

Table 1. Fuzzy Rule Set [17]

O/DO	NO	ZO	PO
NO	NA	NA	NA
ZO	PA	ZA	NA
PO	PA	PA	PA

6. Conclusion

In this paper, we discuss the comparison of the performance of traditional PID controllers and fuzzy logic controllers (FLC), resulting in that fuzzy self-turning controller has the advantages of being more efficient, flexible, and easy to adjust. Moreover, the paper discusses the current situation and applications of disaster robots and lists some measures for controlling disaster robots. Besides, the paper uses related literature to discuss a new disaster drone control system based on fuzzy self-turning PID control, which makes the rescue performance easier and improves personnel survival rate and reduce various losses caused by disasters. Building a completely autonomous drone that is capable of autonomous sensing, location, and trajectory planning will be the main goal of future development. Moreover, lower-level sensor fusion using infrared depth cameras and laser scanners will be done to produce more precise map data for robot navigation. Collective systems that include these features will enable real rescue operations and save lives. Autonomous navigation necessitates path planning algorithms and well-designed controllers.

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