Ground Automatic Recycling System for UAVs in the Wild

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Abstract. The safe recycling is a huge challenge for the unmanned aerial vehicle (UAV) in complex terrains, especially in the wild. A ground automatic recycling system (GARS) is designed for UAVs recycling in this paper, and it aims to provide a safe, moving, flexible, level landing platform for drones. The GARS consists of three parts: the UAV positioning subsystem (UAVPS) for detecting and positioning the drone, the ground tracking subsystem (GTS) for dynamically tracking the landing point and the comprehensive undertaking subsystem (CUS) for reliably recycling. In this paper, the working principle and the hardware structure of the GARS are introduced first. Secondly, the algorithms of three subsystems are designed. Finally, the experiments of the UAV recycle are carried out in the wild. The results show that the system can effectively recycle UAVs in the wild environment, which verifies the effectiveness of the algorithms.

Keywords: UAV recycling; Aerial target positioning; Dynamic tracking; Stewart platform

1. INTRODUCTION

Nowadays, recycling has become one of the key technologies for the development of the unmanned aerial vehicle (UAV) [1-7]. Especially for rotary-wing UAVs, when performing missions in the field, they often have difficulties in landing safely due to the lack of flat areas. In addition, the UAV has to reserve a large amount of electric energy in advance for returning due to the limitation of battery capacity, which severely limits the working time and efficiency of the UAV. Therefore, the research on the safe and stable recycling of UAVs in the wild will improve UAV's survivability and working time, which is of great significance to the development and application of the UAV [8-13].

In the methods of ground recycling of rotary-wing UAV, the navigation and positioning technologies by differential GPS and vision are usually used [14]. In this method, the UAV often identify and locate the landable area on the ground. In [15], a visual recognition method is proposed to locate the landing platform by combining global positioning system (GPS) and images, which can realize the autonomous landing of drones. Moreover, a visual recognition method with higher accuracy is proposed to locate the landing platform in [16], which improves the landing effect. In [17], the landing pad composed of multiple circles of different sizes is designed to extend the detection range. In [18], a scheme to set up a camera pan-tilt unit on the ground is planned, which can realize the detection, tracking and positioning of UAVs. In [19], a new type of landing platform with different pads is proposed to ensure a high sampling rate and increase the manoeuvrability of the vehicle.

In this kind of UAV recycling method, the UAV obtains the information from ground platforms. Due to the limited load-bearing capacity of the UAV, only several detection elements can be installed. Therefore, the UAV's positioning results in this method are less accurate and less reliable. In addition, most of these UAV recycling methods require a flat fixed platform on the ground. With the poor anti-interference ability of the UAV motion control, the UAV has fuselage swings and landing shocks because of the wind measurement. Therefore, a high degree of coordination of the drone is required to achieve a safe landing.

In this situation, some scholars have built a moving undertaking platform on the ground to improve the reliability of UAV recovery through the coordinated control of ground and air. But at the same time, it also increases the control complexity of the ground recovery system. An automated UAV launch, recovery, refuel and re-launch system is developed by the Space and Naval Warfare Systems Command (SPAWAR) [20,21]. This system is heavy and specialized so it's not generally applicable. In [22], an intelligent automatic leveling and node docking system (ISLANDS) is designed, which aims to provide a safe and level landing platform for small UAVs. In [23], a self-leveling landing surface is designed to allow helicopters to land on ships traveling in rough seas. In [24], a four-wheel mobile robot with self-horizontal mobile landing platform is designed, which can be leveled on inclined surfaces or uneven terrain.

Fig. 1 The Ground Automatic Recycling System

In summary, most of the undertaking platforms of the ground recycling system are relatively simple. In many researches, both of the ground recovery system and the undertaking table have fewer degrees of moving freedom. Therefore, these systems have difficulties in dynamically tracking the UAV and providing a smooth, shock-absorbing flexible landing platform in order to recycle the UAV safely.

Therefore, on the basis of the research on the mobile recovery technology, a ground autonomous recycling system (GARS) is designed for the recycling of rotary-wing UAVs in the wild environment. The system can autonomously recycle the drone without ground-air communication, which can greatly reduce the movement requirements of UAVs and avoid communication delay problems during ground-air cooperative work. When the drone landing near the expected area in the wild, the GARS can autonomously realize the accurate positioning, dynamic tracking and reliable undertaking of it.

2. SYSTEM OVERVIEW

The GARS is specially designed for the recovery of UAV in the wild. It focuses on high reliability of positioning, tracking and undertaking of the UAV. Therefore, based on three functions, we design the structure of the robot system as shown in **Fig. 2**. It consists of three subsystems: the UAV positioning subsystem (UAVPS), the ground tracking subsystem (GTS) and the comprehensive undertaking subsystem (CUS).

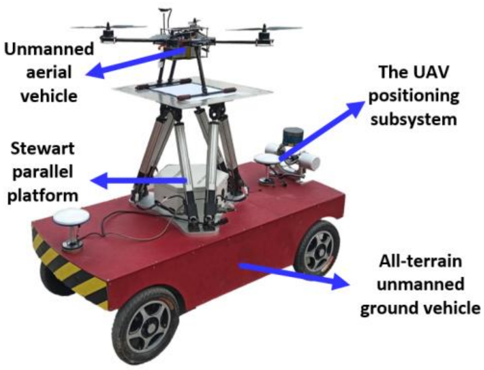

Fig. 2 System Structure

UAVPS is a one-dimensional turntable equipped with a lidar and a visible light camera, located in front of the unmanned ground vehicle (UGV). It can fuse the data of the two sensors to locate the UAV in order to control the turntable to track without ground-air communications.

GTS is an all-terrain four-wheel UGV. The system can rapidly and dynamically track the landing point of the UAV in a large range. With the advantages of strong motion performance and fuselage stability, it can cross more complex terrain, which significantly improves the terrain adaptability of the platform.

CUS is a Stewart parallel motion platform. It has six degrees of motion freedom so that it can move to any position and attitude its motion space, and it has been widely used in a variety of fields [25-27]. It is installed in the center of the UGV, making the system more stable. With the advantages of high control accuracy and sufficient freedom of movement, it can accurately track the landing point of the UAV in a small range and provide a stably and flexibly recycling table for UAV through a comprehensive undertaking algorithm.

The system framework of GARS is shown in **Fig. 3**. Its architecture is divided into three layers. The first layer is the environment perception layer, responsible for the preprocessing of the perception information. The second layer is the main control computer layer, which is the core of the system. It summarizes all external input information, responsible for system decision planning and issuance of control instructions. The third layer is the motion driver layer. The UGV and the Stewart platform convert the received instruction signal into the control signal of motors to realize the final movement of the system. The specific parameters of the system are in **Table. 1**.

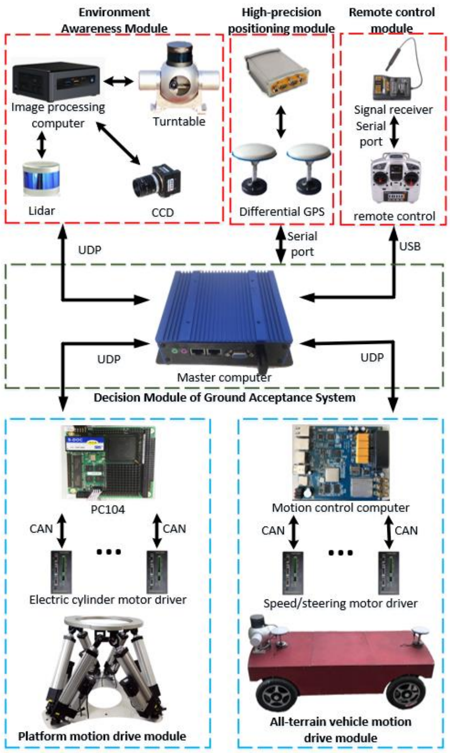

Fig. 3 Hardware Structure

Table. 1 Main Parameter of the GARS

Item	**Value**
Length × width × height (m)	1.43×0.67×1.5
Weight (kg)	100
Load capacity (kg)	100
Vertical detection Angle (°)	±95
Detection range (m)	150
Maximum speed of tracking (km/h)	30
Maximum angle of tracking (°)	25
Battery time (h)	3

3. CONTROLLING SUBSYSTEM

3.1. The UAV Positioning Subsystem

Fusing point cloud data from lidar and image data from visible light camera can give full play to their respective advantages. Therefore, this subsystem integrates the two data to reliably detect and accurately locate the UAV. The frame of this subsystem is shown in **Fig. 4**.

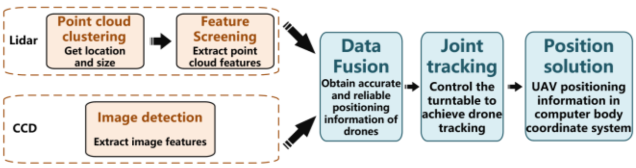

Fig. 4 UAVs Positioning Flow Chart

In positioning by lidar, the point cloud can be preprocessed first. The unnecessary search areas can be removed to speed up the calculation. On this basis, European clustering and size feature selection can be applied in order to initially screen the candidate areas with size and positioning information of the drone.

In positioning by visible light camera, the image data obtain the candidate area through Yolo V5 algorithm. Yolo series of algorithms are classic algorithms in the field of image target detection. It is also currently one of the best target detection algorithms in real-time and accuracy. Therefore, it's widely used on edge devices.

On the basis of obtaining the two data, we assign the depth information of the lidar to the two-dimensional (2D) image by registering the two coordinate systems. Therefore, a point in three-dimensional (3D) space must be projected onto a cylindrical surface that can be expanded to form a plane. In [28], the following projection function is used to project and discretize point clouds:

$$\begin{aligned} \theta &= \operatorname{atan} 2(y, x) \\ \phi &= \arcsin\left(z / \sqrt{x^2 + y^2 + z^2}\right) \\ r &= \lfloor \theta / \Delta\theta \rfloor \\ c &= \lfloor \phi / \Delta\phi \rfloor \end{aligned} \tag{1}$$

where $p = (x, y, z)$ denotes the 3D positioning information of the UAV candidate area. (r, c) denotes the 2D position of its projection. θ and ϕ denote the azimuth and elevation angles when observing the point. $\Delta\theta$ and $\Delta\phi$ are the average horizontal and vertical angular resolutions of the visible light camera respectively.

As a result, we can map the 3D point cloud of the lidar onto the camera image. We select the UAV candidate area obtained through image detection and read the corresponding depth information. The final positioning information of the drone in turntable coordinate system can be obtained. According to positioning information, the turntable can be controlled to track the drone by keeping it at the horizontal line under the turntable coordinate system. The positioning information can also be converted to the coordinate system of the GARS through the coordinate conversion matrix.

3.2. The Ground Tracking Subsystem

On the basis of obtaining the positioning information, the UGV can track the landing point of UAV by dynamic path planning and path tracking.

The artificial potential field method is used for path planning of the moving target point because of its smooth path and simple calculation. In this paper, the GARS is only aimed to track the unique UAV candidate area with the highest confidence level. Therefore, we only need to set the gravitational field function, which avoids local optimization and motion shock. In addition, the ground recovery system is hoped to keep the same trend as possible as the movement of drones. Thus, when setting up the gravitational field, we additionally add a function for attaching to the UAV path. And the final gravitational field function is as follows:

$$\begin{aligned} U_{att}(p, v) &= \frac{1}{2} k_{p\_tar} \left[p_{tar}(t) - p(t) \right]^2 \\ &\quad + \frac{1}{2} k_{p\_path} \left[\min(p_{path}(t)) - p(t) \right]^2 \end{aligned} \tag{2}$$

where k_{p_tar} is the gravitational constant for tracking moving target points. k_{p_path} is the gravitational constant for path adsorption. $p(t)$ is the current position of UGV. $p_{tar}(t)$ is the predicted landing point of the UAV. $\min(p_{path}(t))$ is the minimum distance from the UGV to the UAV path.

Model predictive control (MPC) is used for path tracking of UGV. This method is a well-established technique for controlling multivariable systems in an optimized way. And it can take physical constraints of the system under control into account based on kinematics modeling. In addition, quadratic programming is used to solve a linear MPC by successive linearization of an error model of the path tracking. The

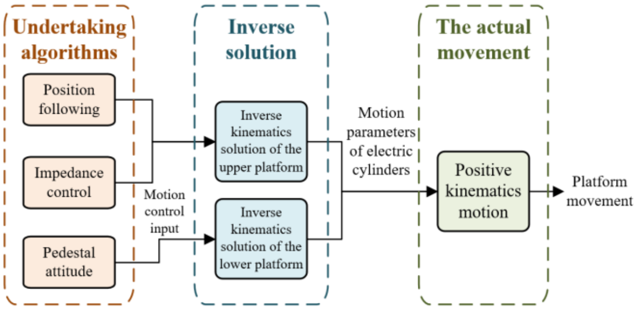

Fig. 5 Stewart Platform Control Block Diagram

system solves the optimization problem (that is, the path tracking effect of the UGV) through repeated prediction and optimization in each control cycle. When the optimal solution is obtained, the result can be output to the UGV to track the path. This approach is applied in [29], although for the unicycle case. In this paper we also use such a linearization approach.

3.3. The Undertaking Platform Subsystem

This subsystem focuses on the precise tracking and stable acceptance of the UAV by Stewart platform with six degrees of freedom. There are two parts of research in this subsystem: the calculation of undertaking algorithms and the motion control of the Stewart platform. The block diagram is shown in **Fig. 5**.

Undertaking algorithms of the subsystem includes the tracking algorithm, the attitude angle correction algorithm and the recycling algorithm.

Tracking algorithm uses linear interpolation strategy to smooth the motion of the platform.

Attitude angle correction algorithm uses a velocity feedforward controller to provide a stable and reliable recycling countertop for the UAV. We differentiate the attitude angle measured by the UGV after filtering, and input the angle changes as the feedforward control into the speed control loop of each cylinder of the platform. Through this method, the platform can respond to environmental disturbances in advance.

Recycling algorithm uses adaptive variable impedance control to counteract the landing impact of the UAV landing. When the force of the receiving platform is near the equilibrium point, the damping characteristic of the impedance controller should be adaptively increased to prevent the fuselage from shaking. While in the process of receiving the UAV, the force deviation increases. Therefore, the damping characteristic should be reduced to speed up the response of actuators. And the adaptive variable impedance algorithm is as follows:

$$M\left(\ddot{X}-\ddot{X}_r\right)+B\left(\dot{X}-\dot{X}_r\right)+K\left(X-X_r\right)=F_r-F_c \quad (3)$$

$$B=B_0\exp\left(-\frac{\left|F_r-F_c\right|}{F_r}\right)$$

where M, B, K are mass matrix, damping matrix and stiffness matrix respectively. X, $\dot{X}$, $\ddot{X}$ represent the position, speed and acceleration of the recycling platform respectively. X_r, $\dot{X}_r$, $\ddot{X}_r$ represent the expected position, speed and acceleration of the platform respectively. F_c represents the force in the Z direction. F_r is the set reference force. B_0 is the set initial coefficient.

In the motion control part of the Stewart platform, the inverse kinematics algorithm is applied. We can obtain the control quantities of the six electric cylinders of the parallel platform by taking the respective degree control quantities of the platform obtained by the undertaking algorithm as the input of the inverse solution algorithm, and realize the movement of the platform.

By solving this function, the optimal control increment sequence in the control time domain can be calculated. On this basis, the optimal control amount at different times can be obtained.

4. EXPERIMENT

4.1. UAV Recycling Experiment on Slope Terrain

The UAV recycling experiment of GARS is carried out on the slope terrain, as shown in **Fig. 6**. Two speed bumps are placed to further increase the complexity of the slope terrain. When landing on this type of terrain directly, the UAV may damage because the rotors will contact the ground.

The recycling of the UAV includes three parts. Firstly, the drone moves to the place and ready to start landing. The GARS begins detecting and locating it through UAVPS. Secondly, after obtaining the position information, UGV starts to work. The experiment shows that the UGV can still easily cross complex undulating terrain to track the drone. Finally, after the UGV is about to arrive the target point, Stewart platform further accurately tracks the landing point of the drone. And the platform can also realize stable and reliable acceptance of the drone in real time through a series of undertaking algorithms.

Fig. 7 and **Fig. 8** show the attitudes of the UGV and the Stewart platform in this experiment. In 0-7s, the UGV is working on flat terrain. The attitudes of the both are relatively stable. In 7-19s, the UGV starts to go uphill, and the fuselage is tilted with the pitch angle in ±9° and the roll angle in ±7°. At this time, the platform controls the angles both in ±2° through attitude feedforward control, which greatly reduces the tilt of the platform. In 19-35s, the UGV moves to the speed bumps. The fuselage begins to shake violently. Even working in this environment, the platform can still maintain an attitude angle of ±4° at all times. It can be seen from the data that the system has realized the smooth acceptance and delivery of the UAV.

Fig. 9 shows the UAV landing impacts. The blue line is the original impact force curve without impedance control, and the red line is the curve with adaptive variable impedance control. It can be seen that after the drone has landed, the peak impact force of drone landing is significantly reduced from 10.98N to 8.33N. This experiment shows that adaptive variable impedance control can effectively reduce the landing impact force of the UAV, which realizes the platform's compliant recycling of it.

4.2. UAV Recycling Experiment on Grassland

The UAV recycling experiment of GARS is also carried out on grassland, as shown in **Fig. 10**. This experiment is designed to simulate the work in the wild environment. As can be seen in the figure, the GARS can realize the detection, identification, tracking and

Fig. 6 UAV Recycling Experiment on Slope Terrain

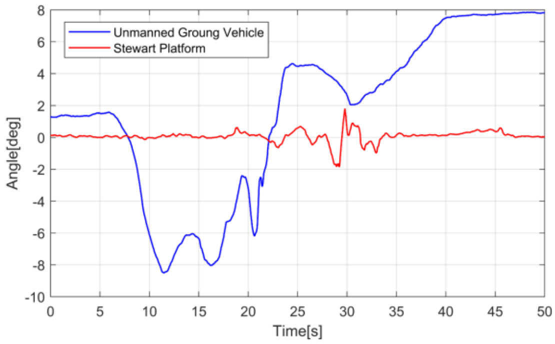

Fig. 7 Real-time Pitch Angle

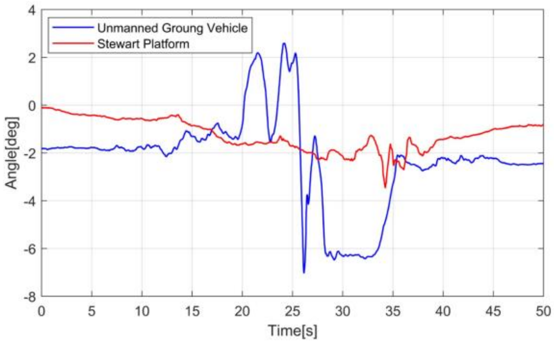

Fig. 8 Real-time Roll angle

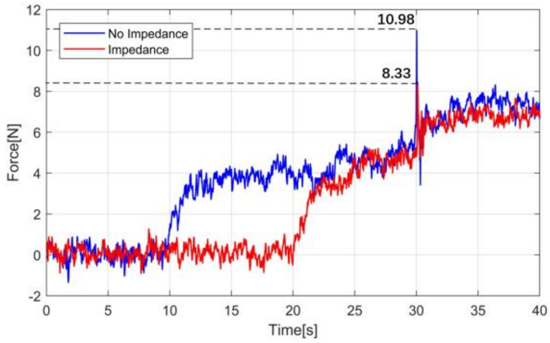

Fig. 9 The Landing Force of UAV

Fig. 10 UAV Recycling Experiment on Grassland

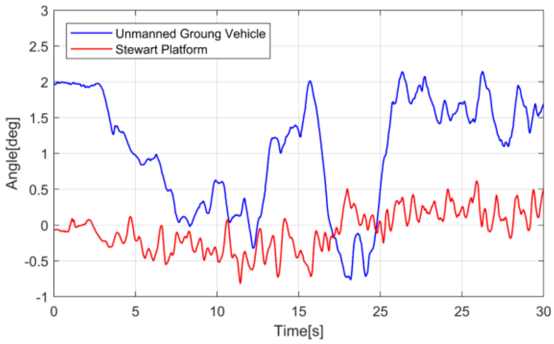

Fig. 11 Real-time Pitch Angle

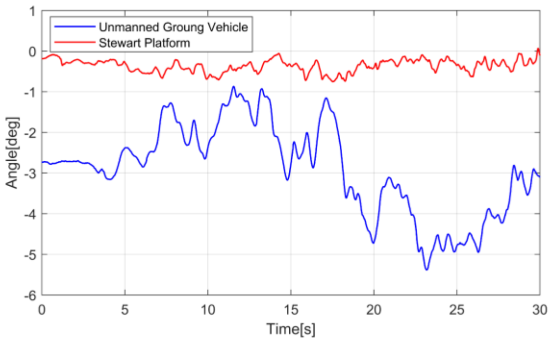

Fig. 12 Real-time Roll angle

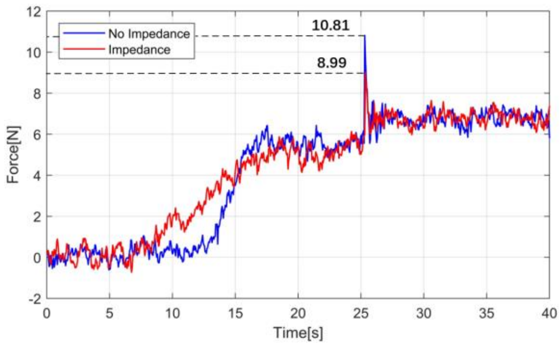

Fig. 13 The Landing Force of UAV

recycling of the UAV with the coordinated work of three subsystems. The experiment also proves the feasibility and practicability of the GARS in the field environment.

Fig. 11 and **Fig. 12** show the attitudes of the UGV and the Stewart platform in this experiment. It can be seen that on grassland, the disturbance amplitude of the system attitudes is smaller, but the frequency is higher. Compared with the previous experiment, the platform attitudes of this experiment are more jittery in a small range. And the GARS can still provide a relatively stable platform for UAV recycling.

Fig. 13 shows the UAV landing impacts in this experiment. It can be seen that the peak impact force of drone landing can be reduced from 10.81N in to 8.99N, which proves that the GARS can flexibly recycle the UAV in a wild environment.

5. CONCLUSION

In this paper, a ground autonomous recycling system for the UAV is proposed. The system integrates UAV detection, identification, positioning, tracking, and undertaking through the research of three subsystems, which realizes the reliable recycling of UAVs by the system in complex wild environments. Specifically, in the UAVPS, the data fusion of lidar and visible light camera is used to reliably position the UAV. In the GTS, the artificial potential field path planning algorithm and the model predictive control path tracking algorithm are used for UGV to quickly track the landing point of the drone. In the CUS, the comprehensive undertaking algorithm of the Stewart platform is used to precisely track and reliably recycle the drone. Finally, the experiment verifies the feasibility and effectiveness of the GARS. And the system can realize the autonomous, safe and accurate recycle of the UAV.

Future work will focus on high-precision, high-real-time coordinated control of ground and air in order to realize the dynamic undertaking of the system to the UAV. These measures will further improve the mobility and environmental adaptability of the system, and can contribute the system to recovery the drone in more complex environment.

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