Toward Cooperative Multi-Robot Control for Detecting and Tracking an Expanding Flood Area

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***Abstract*—This position paper deals with formalization of a practical scenario of using multiple aerial robots for monitoring an expanding area, which is a part of an operational framework and a global information system for real-time management of flood disasters caused by torrential rains. Two typical tasks of the optimal information coverage problem, represented by caging the disaster area and tracking its dynamic expansion are sketched. Three basic component of the minimal configuration of the control system—the image segmentation, Kalman filtering-based tracking, and distributed formation control—are identified and reviewed.**

***Index Terms*—multi-robot control, disaster monitoring**

I. INTRODUCTION

Disaster robotics is a growing research area [1], [2], covering topics from the design to the deployment of robotic devices, often heterogeneous groups of robots in the mitigation, management, recovery and rescue operations in natural (earthquakes, tsunami, hurricanes) or human-made (oil spills, mine waste floods, wildfire, nuclear contamination) catastrophes. Robotic technologies can play a key role in disaster risk assessment and prevention, and the role of these technologies increases yearly together with successes of robotic research and development around the world.

Considering the natural disasters, land slide and flood caused by torrential rains are among the most frequent and costly phenomena in terms of human and economic loss. It is thus highly important to develop and test experimentally scientific frameworks and technological solutions in order to deal with such disasters. While modern technologies for collecting global data for natural hazards assessment and disaster prediction with remote sensing, geographic information systems, and satellites, are largely available, it is of practical importance to develop an information system for real-time disaster management that will use these technologies in combination with various types of robots – unmanned aerial, ground, underwater and surface vehicles.

The use of distributed heterogeneous robotic teams constitutes an operational framework for the disaster site management. In this framework, robotic teams will construct a large collaborative thematic map of a disaster site, which will help human rescue teams to speed up the process of extracting survivors from a disaster site and evaluating dangers of construction collapse and environment pollution, while increasing the safety of human rescuers and survivors.

In this paper, we are concerned with a part of the operational framework that deals with the use of multiple aerial robots for optimal coverage of the disaster area. First, we provide a simple but realistic formalized description of typical scenaria for caging the disaster area and tracking its dynamic expansion by a group of robots. Having set up the scenaria, we identify and review the key components of the distributed control system. In the minimal implementation, they are the image segmentation component, Kalman filtering-based target tracking, and the distributed formation control.

The rest of the paper is organized as follows. In Section II we state describe the research problem. In Section III, we define and review the key components of the control system. Software tools for the initial verification of group control strategies are presented in Section IV. Finally, conclusions are drawn in Section V.

II. FORMALIZATION OF THE RESEARCH PROBLEM

This research aims to track the propagation of an expanding flood zone as illustrated in Fig. 1, by using a group of unmanned aerial vehicles (UAVs) with only some of them having access to GPS. It is assumed that each of the UAV's can generate high-resolution imagery from a bird's-eye view. The research problem is then stated as constructing tracking algorithm for the UAVs such that the motion of the complete shape of the flood area (its approximation) can be monitored from the emergency center.

The construction of the tracking algorithm is combined in two stages as illustrated in Fig. 2 where a flood zone, originally represented by a grey area, has expanded to the a blue area. The yellow blocks represent for the drones. In the first stage, referring to the caging stage, a flock of drones move along the edge of the expanding flood zone. Motions of the drones are represented by the purple arrow.

After moving along the edge of the flood zone for every certain distance, one drone will drop from the flock and track along the propagating direction of the flood zone. This stage refers to the expanding stage. Motions of the drones in the expanding stage are represented by the red arrows in Fig. 2. Note that the caging and expanding stages are conducted simultaneously.

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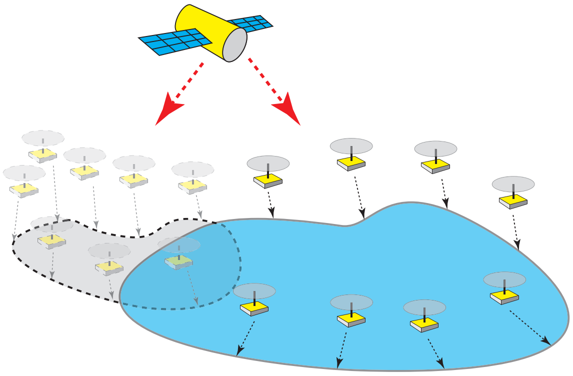

Fig. 1. Statement of the multi-robot tracking problem for expanding flood zone.

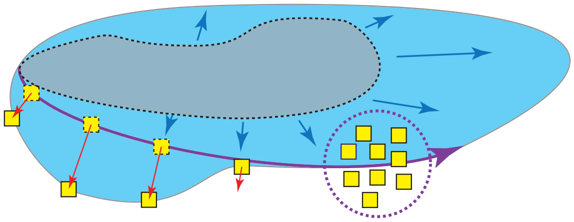

Fig. 2. Illustration of the caging stage and the expanding stage.

A. *Boundary tracking and formation control for multiple drones in the caging stage*

The caging stage requires a flock of drones to track the expanding edge of the flood zone. This tracking problem can be separated into two parts: a group of leaders of the drones track the boundary of the flood zone, and a flock of followers track the group of leaders as a target. It is assumed that only the leaders have access to the GPS while the followers can communicate with and know the relative positions of their neighbors.

1) Boundary tracking for the leading drones: In this research, the boundary tracking problem is tackled by a vision-based approach to achieve real-time autonomous steering of a group of drones along the boundary of a flood zone. Multiple drones are utilized for the reduction in tracking uncertainty, expansion of coverage, and the robustness to failure.

The key problem of boundary tracking is to distinguish the water region and the land region. A solution to this problem is based on the difference between the dominant colors of these two regions. In particular, the hue of a pixel is computed from its RGB representation. After the boundary between the water and land regions is detected, a straight line through the boundary of the binary image is fitted, which can be the transformed into a desired heading of the drones.

2) Cooperative tracking by the following the leading drones: The cooperative target tracking problem can be tackled by a Kalman filtering based approach. With the estimated target position, mobile robots are required to move as a flocking group to track the target. The flocking algorithm includes a cohesion control component and a separation control component [16]. These two components constrain the formation of a flock of robots. The cohesion control keeps the robots close enough such that each robot can communicate with at least one neighbor, while the separation control is to avoid collisions between neighbors. A potential function approach is commonly applied to keep robots in a safe distance.

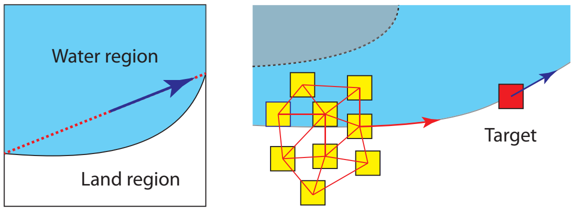

Fig. 3. Field of vision for the target robot (right), cooperative multi-robot target tracking (right)

B. *Target tracking by single drone in the expanding stage*

After every sampling distance, the target will stop from tracking along the edge of the flood zone and be replaced by its the nearest drone from the flock of followers. The original target drone is required to track the propagation of the flood zone in the expanding stage.

The tracking problem can be stated as follows. Design the velocity controller for the drone such that a portion of the edge for the flood zone is always within the drone's field of vision as illustrated in Fig. 4, where the grey and blue areas respectively represent for the flood zone before and after its expansion, and the black squared frame for the drone's field of vision. By regarding the mass center of the flood zone (see Fig. 4) as a target object, the problem above is tackled by constructing velocity tracking algorithm based on the Kalman filter, which can accurately track the movement of the target by adaptive filtering.

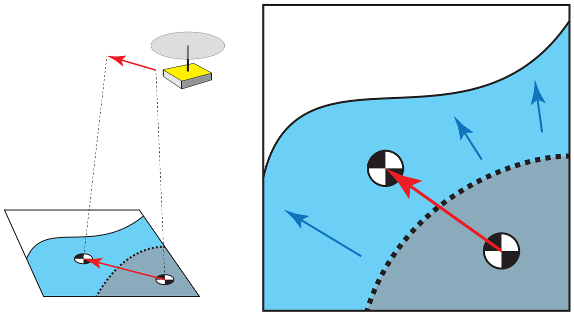

Fig. 4. Tracking problem with a single drone.

Note that this tracking algorithm works only when both the water and the land regions appear in the field of vision of a single drone. When only the land or the water region appears, the algorithm will throw an exception between the movement of the center of mass of the water region cannot be detected. In such a case, the heading of drone will follow the information from its neighbors. Specifically, the desired velocity will be the vector sum of the edge velocities for the propagation of the water region in the neighboring fields of vision.

III. BASIC COMPONENTS OF THE CONTROL SYSTEM

From the statement of tracking problem, three main components of the control system can be identified. This includes the image segmentation, Kalman filtering based target tracking, and the formation control for multiple robots. These components are clarified and reviewed as follows.

A. Image segmentation

The image segmentation problem requires to distinguish the water and land regions from the camera image of a drone, assuming only one continuous boundary between these two regions exists. This problem is dealt with in algorithms outlined in Section II-A1 and Section II-B. Several related works have been proposed [3]–[7] in the literature based on neural networks and extended Kalman filter, for the application on target tracking, road boundary and coastal lines detecting, etc.

B. Kalman filtering based target tracking

This problem requires to track the states of one or multiple target drones by applying Kalman filter. We deal with this problem in the stages described in Section II-A2 and Section II-B. The key of the solution to the tracking problem is the estimation of the state of the target. In the literature, several approaches based on the Kalman filter and its variants, the extended Kalman filter (EFK) and the particle filter. For cooperative target tracking, many works have been proposed in the literature, based on centralized, decentralized, and distributed approaches.

1) Centralized approach: For the target tracking problem, several works [8]–[10] have been proposed in the literature based on the centralized approach. In a centralized approach, the measurements from the sensor nodes of multiple agents are sent to a central processor in which global estimates are computed.

2) Decentralized approach: Different form the centralized approach, the decentralized approach does not require all sensor nodes to evaluate the overall state. The estimate computations can be decentralized to the sensor nodes of multiple agents and the local estimates are communicated between two or more nodes using an algorithm to get the estimates of the global state. The decentralized approach is suitable for large scale systems as shown in the literature [11]–[13].

3) Distributed approach: The advantage of the distributed approach is that the estimates in all sensor nodes will converge to the centralized Kalman filter. In the literature, [14]–[16] have been proposed for the the estimation of target's state based on distributed Kalman filter (DFK). In these algorithms, multiple measurements and their covariance matrices in the information form of DKF can be expressed as the sum of measurements and covariance matrices of individual sensors.

C. Formation control for multiple robots

The formation control problem requires a flock of drones moving cohesively such that a single drone can communicate with at least one neighbor while keeping a distance from each other for the avoidance of collision. This problem appears in the stages described in Section II-A1 and Section II-A2.

The formation control methods can be classified into the following main types: the position-based control, the displacement-based control, the distance-based control, and the flocking-based control. A detailed review of the formation control techniques can be found in [34].

1) Position-based control: In the position-based control, each agent knows its absolute position with respect to a global coordinate system. The desired formation of multiple agents is achieved by tracking the position of each agent. It can be achieved without any interactions among the agents under ideal conditions. Many approaches applying the position-based control [17]–[20] have been proposed in the literature.

2) Displacement-based control: The displacement-based control have been utilized in many works proposed [21]–[24] in the literature. In the displacement-based control, it is assumed that the majority of agents cannot sence their absolute positions. Instead, they know the relative positions of, or displacement from, their neighbors with respect to a global coordinate system. By controlling these distances, a desired formation of multiple agents can be achieved.

3) Distance-based control: For the formation control of multiple agents, many authors considered the distance-based methods [25]–[28]. In distance-based formation control, agents can sense the relative positions of their neighboring agents with respect to their local coordinate systems. They actively control inter-agent distances to achieve their desired formation, which is specified by the desired values for distances between any pair of agents. Different from the position-based and displacement-based control, the distance-based control requires less global information.

4) Flocking-based control: The flocking-based control relies on relatively simple interactions among individuals. An agent model was first constructed [29] based on the following three basic rules: cohesion (stay close to nearby neighbors), separation (avoid collisions with nearby neighbors), and alignment (match velocity with nearby neighbors). As extensions of [29], many control laws [30]–[33] have been proposed in the literature to achieve collective behaviors. In these works, the cohesion and the separation rules have been usually implemented by means of a potential function of inter-agent distances, and the alignment rule has been implemented by means of velocity consensus of agents.

IV. SOFTWARE TOOLS FOR THE INITIAL VERIFICATION

The verification of the control strategies and disaster coverage algorithms is an ongoing research work aimed at the development of a simulator in ROS/Gazebo programming environment. The simulation framework admits the inclusion of aerial and ground types of mobile robots for testing typical scenarios of monitoring the disaster area. The structural design of the software architecture includes the core part, the graphical rendering, the physical simulation engine, the user interface for online correction.

In the current implementation (alpha-version of the simulator), we employ only simple thematic maps of the environment. The multiple UAV's are modeled with the use of Hector quadrotor package [35], which is a collection of ROS stacks that supply several tools to simulate and interact with the robots, and its extension to multiple quadrotors [36]. The expandable disaster area is modeled by a swarm of mobile robots on a flat surface connected into polygonal structures with edges corresponding to the boundaries of the disaster area.

V. CONCLUSIONS

Formalization of a practical scenario of using multiple aerial robots for monitoring an expanding area, which is a part of an operational framework and a global information system for real-time management of flood disasters caused by torrential rains, has been considered in this paper. Two typical problems of the optimal information coverage, represented by caging the disaster area and tracking its dynamic expansion have been outlined and sketched. Three basic component of the minimal configuration of the control system—the image segmentation, Kalman filtering-based tracking, and distributed formation control—were identified and reviewed.

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