# Collaborative Navigation of UAV and UGV Using Vision and LIDAR Sensors

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## ABSTRACT

This paper describes our on-going research efforts toward a collaborative navigation system of an Unmanned Ground Vehicle (UGV) and an Unmanned Aerial Vehicle (UAV). Since the range of sight of a UGV is very limited, the UGV cannot obtain a complete map of its surrounding area to a given destination before it travels if the map information is not provided a priori. Thus, the UGV is not able to generate an optimal path from the source to the destination before its mission. Although a complete map could be provided to the UGV a priori, GPS signals should also be available for the UGV to localize its position in the given map. If the UGV is in a GPS-denied environment, it would be challenging for the UGV to travel to the destination along an optimal path.

In this paper, we utilize a UAV to assist a UGV when complete map information is not provided and/or GPS signals are not available to the UGV. In particular, we present the applied algorithms of image processing and path planning to find an optimal path for the UGV based on the vision data obtained from the UAV. The UGV navigates along the obtained optimal path using its Light Detection and Ranging (LIDAR) sensor.

The collaborative navigation system consists of a UAV, a UGV, and a processing server. The UAV is equipped with a vision camera and a Wi-Fi transmitter, and the UGV is equipped with a LIDAR, an actuator control processor, and a Wi-Fi transmitter. The processing server is designed to process and relay navigation information between the UAV and the UGV. This collaborative navigation system is experimentally validated in an open field with structured paths with an intersection.

## I. INTRODUCTION

An Unmanned Ground Vehicle (UGV) has broad applications such as hazardous search and rescue, and explosive disposal. If a UGV can navigate along an optimal path in GPS-denied environment without provided map information, its application areas could be even wider. A complete map of surrounding area is necessary for a UGV to calculate its optimal path. GPS signals are necessary for the UGV to localize its position within a map. However, the map information or GPS signals are not always available. When this information is not available, an Unmanned Aerial Vehicle (UAV) can assist the UGV by generating necessary map information. In the literature, there are several previous researches on collaboration between a UAV and a UGV.

For example, MacArthur, *et al.* [1] and MacArthur and Crane [2] have researched on state estimation of a UGV using a UAV. This research assumed that GPS is always available. Moseley, *et al.* [3] proposed a method to track a target with collaboration between a UGV and a UAV. However, the method in this paper focused on how the system can track a moving object, and the paper did not consider how the UGV can determine its optimal trajectory to a given destination. A UAV-guided UGV navigation simulator has been developed [4]. However, the algorithms implemented in this simulator were not experimentally validated.

In this paper, we present a collaborative navigation system operating in GPS-denied environment. The system can calculate the optimal trajectory of a UGV from a source to a given destination with the help of a UAV. This system does not require surrounding map information a priori, and the implemented system has been experimentally validated.

In order for the UGV to navigate along the optimal path which is obtained from the UAV, the UGV relies on a Light Detection and Ranging (LIDAR) sensor. Since the LIDAR sensor scans all directions around the UGV, the UGV can detect and avoid obstacles. To the authors' knowledge, a collaborative real-time navigation system using vision and LIDAR sensors on a UAV and a UGV under GPS-denied environment without a priori map information has not been previously studied. In this paper, we demonstrate such a collaborative real-time navigation system.

After describing the architecture of our collaborative navigation system including a UAV, a UGV and a processing server in Section II, we present the system implementation in Section III. The experimental set-up and the field test results are presented in Section IV. Our conclusions are given in Section V.

## II. COLLABORATIVE NAVIGATION SYSTEM ARCHITECTURE

This section presents the software and the hardware architectures of the collaborative navigation system. The system proposed in this paper consists of a UAV part, a UGV part, and a processing server part. Figure 1 shows the diagram of the proposed collaborative system architecture.

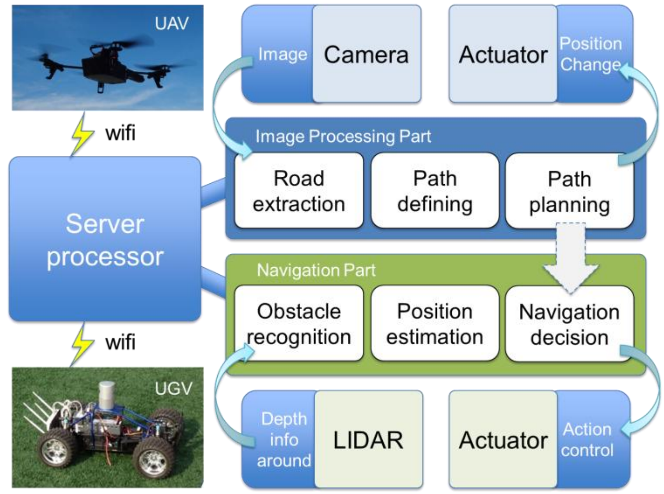


Figure 1. Architecture of the collaborative navigation system

### A. UAV

A Parrot AR Drone 2.0 which is a commercial quad-rotor product is utilized as a UAV platform. The AR Drone consists of an embedded controller, actuators, and sensors such as an ultrasound sensor, an inertial sensor, and two vision sensors. From the ultrasound sensor, the flying altitude of the UAV can be obtained, and from the inertial sensor, the tilting angle of the UAV are measured. With the vision sensor, ground image data can be acquired. The mission of the UAV is to obtain a regional map for the UGV navigation. When the connection between the UAV and the server processor is established, maneuvering commands are sent to the UAV via UDP protocol. Information of the UAV such as its status, flying altitude, tilting angle, and speed is sent to the processing server at the same time. A video stream is also sent to the processing server via UDP protocol from the UAV. After the processing server receives the packets which contain the information of the UAV and video stream, it saves the raw images of the region. The communication part between the server and the UAV is implemented in C++ language.

### B. UGV

The UGV consists of four parts (Figure 2): a sensor part, a controller part, an actuator part, and a communication part. A LIDAR sensor is used to recognize obstacles and estimate the position of the UGV. The distance data sets obtained from the LIDAR sensor are processed. Two DC motors connected to the UGV's wheel and steering are controlled by pulse-width-modulated signals generated by the NI Compact-Rio controller. A Wi-Fi router is equipped on the UGV for the communication between the UGV and the processing server. The processing server generates maneuvering commands for the UGV to navigate along the optimal path using data such as waypoints, heading angles and localization information.

### C. PROCESSING SERVER

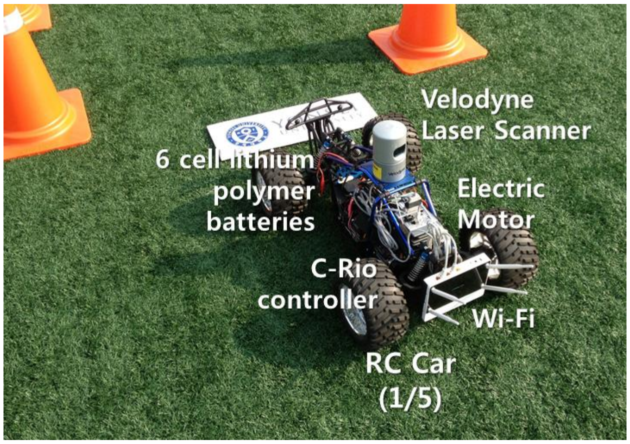


Figure 2. Components of UGV

The information including the road features and the optimal path can be sent directly from the UAV to the UGV. However, there are cost issues to equip the processing part on the UAV. Thus, in this research, we decided to utilize a separate processing server, and unprocessed raw images are sent to the server from the UAV. The processing server performs two processing parts. One is the image processing part and the other is the navigation processing part. Each part has three processing steps.

In the image processing part, the processing server extracts the road information from the obtained image from the UAV. Then, the server computes all possible paths for the UGV to the destination. Finally, the server determines the optimal path using a shortest path algorithm. These three steps are repeated while the UGV and the UAV operate.

The navigation processing part consists of an obstacle recognition step, a position estimation step, and a navigation decision step. The optimal path obtained from the image processing part is utilized in the navigation decision step. We have developed control protocol via Wi-Fi to get the image from the UAV, and maneuvering command is sent to the UGV through Wi-Fi as well.

## III. IMPLEMENTATION OF THE COLLABORATIVE NAVIGATION SYSTEM

To implement collaborative navigation system, three steps are required: map image acquisition, image processing, and navigation. Map image acquisition step is performed by the UAV. Image processing step and navigation step are performed by the processing server and the UGV, respectively.

### A. MAP IMAGE ACQUISITION

To obtain an optimal path for the UGV, a regional map which contains all possible paths is required. However, because the UGV has a limited range of sight, it is impossible for the UGV to find all possible paths to the destination without a given regional map information. For this reason, we propose a collaborative navigation system with a UAV to assist the UGV. Specifically, the UAV takes an image of the whole region with its vision sensor. The image should contain a whole regional image with all possible routes for the UGV. Since the quality of a generated map based on the raw image depends on the resolution of the image, the maximum image size of the camera, 1280 x 768, is utilized.

Once the UAV receives commands to take off, it flies using four propeller attached on four legs. Every communication packet from the UAV contains the UAV's status information. This status information contains altitude, velocity, and remaining battery gauge. Because an image does not have any information regarding a compression ratio, we utilize the altitude and tilting angle of the UAV to calculate an actual width and height of the map obtained from the image. While the UAV transmits its information regarding height, width, and internal status, it also sends image data. However, because the size of the image data is large, the UAV compresses images using H.264 codec. With this codec, only differentiated image data are sent through the network. Hence, the data size which transmitted to the processing server is highly decreased. Once the processing server, which is a laptop computer, receives the data through Wi-Fi network, it decodes compressed image and continues into the next procedure, image processing.

### B. MAP IMAGE PROCESSING

The main objective of the image processing part is to extract road features from the video stream, which is not given to the UGV a priori. In order to define roads in the open field for our experiment, about 40 heavy cones are used. A white polystyrene box is utilized to indicate a destination.

Once the destination is specified, the system we proposed in this paper operates autonomously. The algorithm extracts road marks from the acquired map image, defines paths, and plans the path for the UGV, sequentially. This system can detect the position of the UGV and all surroundings. Thus, the UGV can start its mission from any point within the area.

*Road Mark Extraction*

For the image processing part, we developed an object recognition algorithm. In order to recognize objects, several image filters are used to discard artifacts included in the raw image data. First, a three-channel image (RGB) is converted to three one-channel images (R, G, and B). Then, the color scale values less than a certain threshold value (i.e., $R_{th}$, $G_{th}$, and $B_{th}$) of each one-channel image are discarded. Since we noticed that the artifacts are mostly generated around heavy cones, a morphological operation is applied to reduce noises.

After the R, G, and B images are converted into a black and white image, the heavy cones which used as a road marks in the open field are extracted. In order to reduce computational expenses without significant loss of performance, only midpoints of each heavy-cone contour are considered.

*Defining Paths*

In this step, we determine areas that the UGV can moves in the map. In order to define paths, the artificial walls need to be detected. The size of the UGV is 40cm in width, 50cm in depth, and 40cm in height including the LIDAR sensor. Thus, the UGV cannot pass through a pair of heavy-cones located closer than 50cm. From the center of the road marks detected in the previous step and the scaling ratio of the image (which we will discuss in the navigation part), distances between heavy cones can be calculated.

A pair of heavy cones that are close enough to block the UGV to pass through can be classified as an artificial wall. And a pair of heavy cones that are separated enough to allow the UGV to pass through is defined as a road. By connecting the heavy cone pairs which are classified as walls, we can draw the walls on the image as Figure 3 (b).

After generating artificial walls, the possible paths have to be defined. First, the center points of the road can be obtained by selecting two heavy cones which are on the opposite walls and finding their midpoint. All center points of the road are shown in Figure 3 (c) with blue cross marks, and they are considered as candidates of the UGV's way-points.

In practical driving of the UGV, the range of its steering angle is limited. The candidates of the way-points in Figure 3 (c) are closely located. Thus, if the UGV tries to follow all candidates we obtained, the steering angle would be changed too rapidly and the maneuvering path would not be smooth. In order to leave only the points that the UGV should follow, some close points are excluded. After eliminating the close points, the smoothed way-points are obtained as blue circles in Figure 3 (d).

*Planning a Path*

In the next step, the possible paths obtained from the midpoints of the road are utilized to calculate the shortest path to the destination. As a shortest path planning algorithm, Dijkstra's algorithm is considered. Dijkstra's algorithm calculates an optimal path based on the sum of weights from a departing node to a destination node. We assume that points in the map are matched to nodes in Dijkstra's algorithm, and distances between the points are matched to the weights of the nodes.

Applying the algorithm to the points in the map, the shortest path is obtained as the magenta line in the Figure 3 (e). The points on the shortest path are the way-points that the UGV should follow. The distances and direction angles between the way-points are calculated and sent to the UGV. Then, the UGV accelerates and steers based on the information of distances, direction angles, and relative positions sent from the processing server.

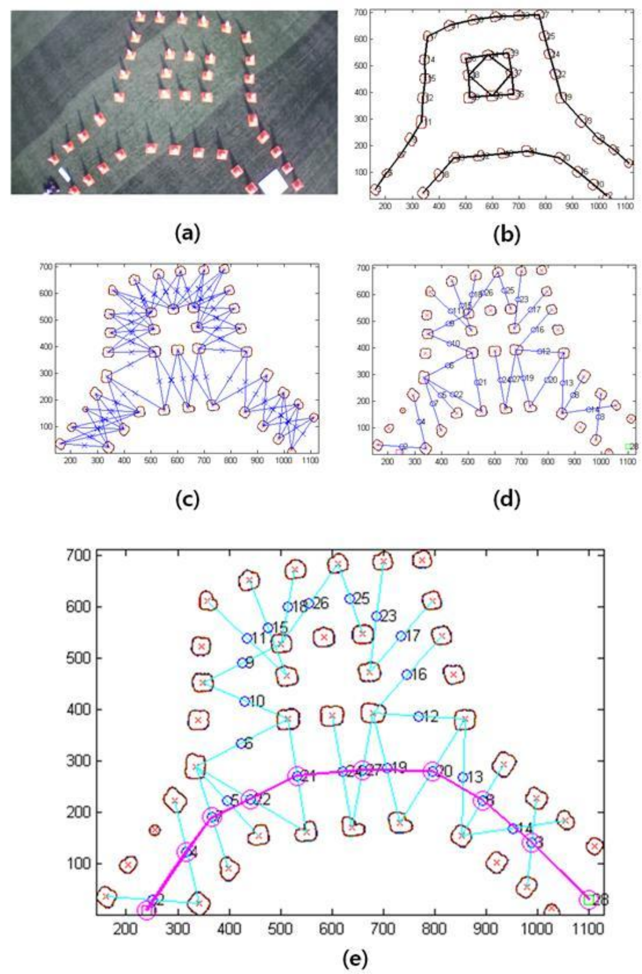

Figure 3. (a) Raw image of the open field obtained by the UAV
(b) Detection of heavy cones and estimation of artificial walls
(c) Marked center points of the road
(d) Smoothed center points of the road
(e) Obtained shortest path for the UGV

### C. NAVIGATION

The 3D laser scanner installed on the UGV continuously gathers three-dimensional point-based depth information around the vehicle. The Iterative-End-Point-Fit (IEPF) algorithm is used to retrieve feature-based obstacle information from the point-based depth information. Once the feature-based obstacle information around the vehicle is acquired, it is compared to the local map information received from the UAV. Based on this comparison, the server can estimate the position of the UGV within the local map. After calculating the shortest path with the image from the UAV, we need to send the control commands to the UGV to follow the path.

Prior to sending maneuvering commands to the UGV, the real-scale distances in the map should be estimated.

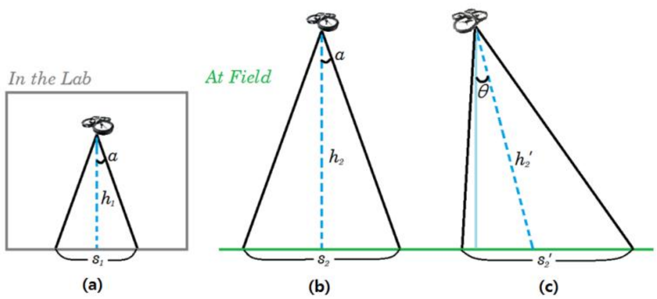


Figure 4. (a) Concept of pre-experiment to get the reference data in laboratory
(b) Concept of sight range at open field
(c) Concept of sight range considering the tilt angle (θ)

To get scale information from the image, pre-experiment in the laboratory is needed. The UAV can measure its flying altitude and the angles of yaw, pitch and roll. As we fly the UAV at 1 meter altitude (h1), we can measure the horizontal ground range s1 as Figure 4 (a). Therefore, we can obtain the viewing angle α of the UAV camera in an arctangent relationship.

$$\alpha = tan^{-1}(\frac{s_1}{2h_1})$$

Also, in the experiment at the open field, the flying altitude of the UAV (h2) is continually measured. With h2 and α, the scale ratio can be calculated as the shown below:

$$scale\ ratio\ \mathrm{R} = \frac{S_1}{S_2} = \frac{s_1}{2h_2 \tan\alpha}$$

When the UAV flies to acquire images in the field, yaw, pitch and roll angles are existed. In an ideal case, all angles should be zero to obtain an accurate scale ratio. However in reality, the angles are not always zero because of the movement of the UAV and other external influences such as wind. Yaw angle does not affect to the scale ratio but the pitch and roll angles make a tilting angle θ as shown in the Figure 4 (c). The UAV measures its altitude with a SONAR sensor. The SONAR sensor generates an ultrasonic wave and detects the Time of Arrival (TOA) of the reflected wave to measure its altitude. Thus, the altitude measurement is changed from h2 to h2' when θ is not zero (refer the Figure 4 (c)). By mathematical calculation,

$$s_2' = h_2' \cos\theta \tan(\alpha+\theta) + \ h_2' cos\theta \tan(\alpha-\theta)$$
$$= 2h_2' \frac{(\sin 2\alpha \cos\theta)}{(\cos 2\alpha + \cos 2\theta)}$$

Therefore, the scale ratio R concerning the θ is,

$$scale\ ratio\ \mathrm{R} = \frac{s_1}{s_2'} = \frac{s_1}{2h_2' \frac{(\sin 2\alpha \cos\theta)}{(\cos 2\alpha + \cos 2\theta)}}$$

This equation can also be used in the case of θ is zero. As discussed previously, s1 and α are measured values in the pre-experiment. Therefore scale ratio can be calculated only with the information of altitude h2' and tilting angle θ. Using this scale ratio, the real-scale distance can be calculated from the pixel-scale length on the image obtained by the UAV.

In previous steps, with the way-points of the shortest path, distance and heading angle to next way-point are calculated in pixel scales. By multiplying the scale ratio to the distances in pixel, the real-scale distances are obtained. Finally, the converted maneuvering commands are sent to the UGV.

In order to simplify the maneuver of the UGV, steering control model is considered. If the vehicle is under a low speed, some forces such as tire-slip, cornering force, and air resistance, etc. can be disregarded.

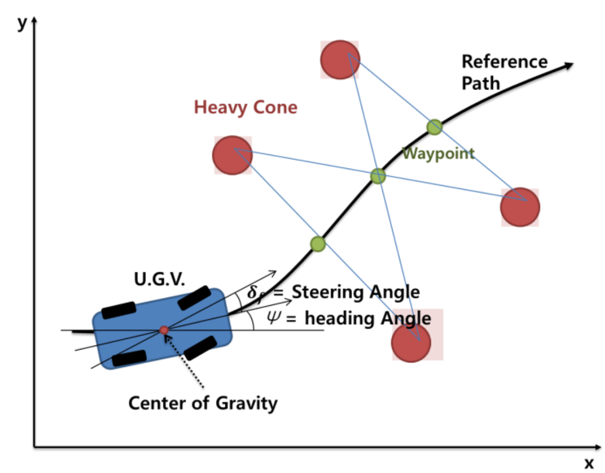


Figure 5. The implementation of steering control of UGV

## IV. EXPERIMENT RESULT

This section presents the experiment of the collaborative navigation system based on the vision and LIDAR sensors.

### A. EXPERIMENTAL SET-UP

Figure 6. Experimental site at the open field

The experiment is performed at an open field. In order to define roads in our experiment, about 40 heavy cones are used (Figure 6). There are two intersections in this set-up. A white polystyrene box is utilized to indicate the destination.

In order to test the implemented collaborative system, we used a processing server with a quad-core processor to improve the processing speed, especially for the image acquisition and processing parts. Following languages are used to implement the system: C++ for the UAV control, Matlab for image processing and path finding algorithms, and Labview for vehicle control.

### B. EXPERIMENT

The first step of our experiment is to acquire an image of the entire region. Once our application is executed, the application begins to maneuver the UAV and gathers the regional image from the UAV.

Once an image from the UAV is acquired, Matlab codes perform the image processing to extract roads information, possible paths, and way-points along an optimal path. Finally, the distances to the intersection and directions are calculated properly, and it is demonstrated that the UGV travels to the specified destination along the optimal path. In conclusion, the proposed method for the collaborative system is properly designed, implemented, and tested.

## V. CONCLUSION

In this paper, a collaborative real-time navigation system of a UAV and a UGV is proposed and developed to navigate under an unusual environment. The assumed environment is that the UGV does not have a regional map information prior to the mission, and GPS signals are unavailable due to high-power jamming.

A small-scale field test is performed with significant engineering efforts. The UAV and the UGV are modified to host necessary equipment such as Compact-Rio, 3D LIDAR, and Wi-Fi router. Algorithms for vision processing, obstacle detection, and autonomous driving are implemented in C++, Matlab, and Labview languages.

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