Collaborative Control of Ground and Aero Vehicles

ECE 445
Design Document

Team 19
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1 Introduction

1.1 Problem and Solution Overview

Autonomous delivery over drone networks has become one of the new trends which can save a tremendous amount of labor. However, it is very difficult to scale up development due to the increasing likelihood of collision between multi-rotor drones and ground vehicles, especially when carrying payload. To actually have such a system deployed in big cities, we could take advantage of the large ground vehicle network which already exists with rideshare companies like Uber and Lyft as well as public transportation networks such as buses and mailing / delivery services. The roof of an automobile has plenty of space to hold packages and a drone network can optimize for flight time and efficiency while having minimal interference with the automobile's route. While this can dramatically increase delivery coverage and efficiency, the problem of safely docking a drone onto ground vehicles in motion remains quite challenging.

We aim at to prove the mentioned idea in the lab environment by implementing a decentralized multi-agent control system that automatically synchronizes a drone with an in-motion ground vehicle when in close proximity. As a proof of concepts, the project takes the assumptions that vehicle states (such as its position and orientation) can be accurately estimated. The infrastructure of the lab, drone and ground vehicle will be provided by the support of our generous sponsor Professor Naira Hovakimyan. We will achieve the synchronized motion through a collaborative peer-to-peer control scheme. More specifically, the ground vehicle will estimate its own trajectory several seconds into the future, and will periodically send the trajectory to the drone. Since the drone cannot acquire absolute position read from the motion capture system, the ground vehicle is also in charge of estimating the drone's poses (through motion capture). The drone will then optimize its current control to track this future trajectory.

1.2 Visual Aid

As shown in Figure 1, we will design a collaborative control system so that the drone accurately tracks the predicted trajectory of the ground vehicle in real-time. After taking off from random initial conditions, the drone will fly toward the ground vehicle and stabilize into a certain proximity range with respect to the ground vehicle. The problem of dynamic estimation is achieved through Vicon, an indoor motion capture system. In addition, we will also design a standalone alignment indicator that runs on board the ground vehicle. This is built with a custom-made LED matrix which can indicate the quality of the spatial alignment between the two vehicles. This hardware will display an overall color of green to indicate a good alignment, and red for a bad alignment. It also estimates the relative poses between the ground vehicle and the drone and displays such relative displacement through LED patterns. As shown in Figure 2, the circle represents the position of the drone relative to the ground vehicle's heading. The overlapping between the circle and the center square indicates a good alignment situation.

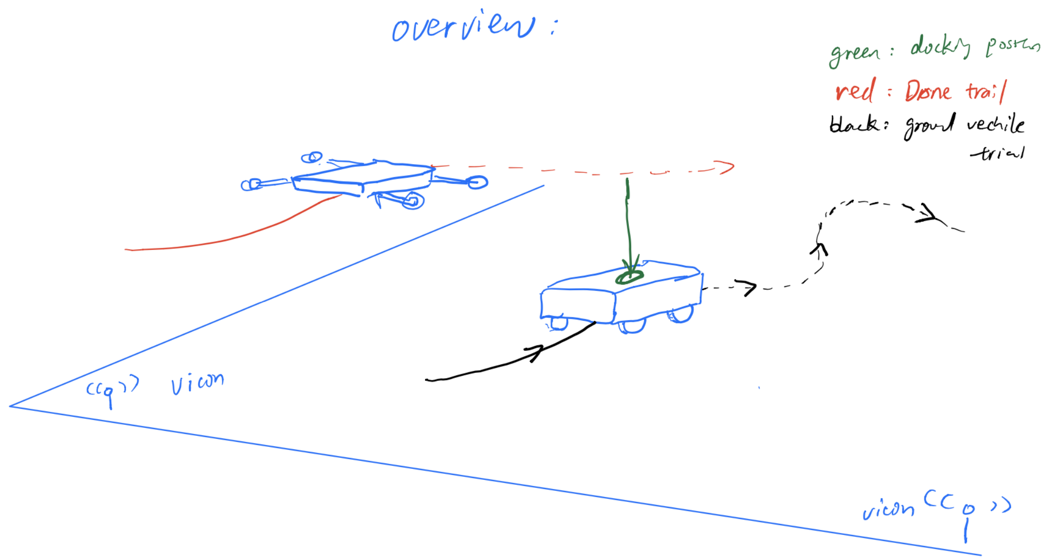
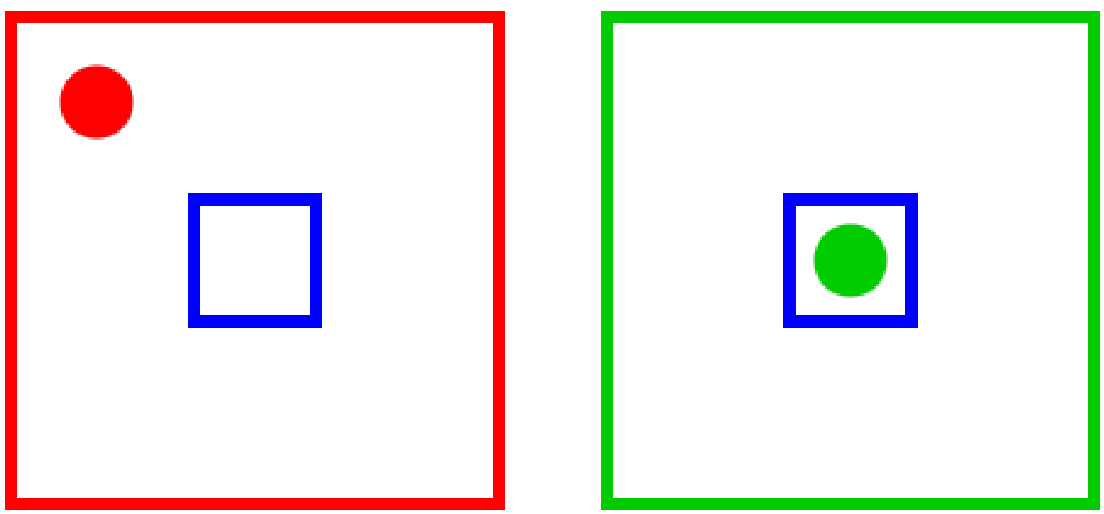


Figure 1: Overall Design Illustration



(a) Bad Alignment (b) Good Alignment

Figure 2: Alignment Indicator Illustration

1.3 High-Level Requirements

The following requirements are all meant to be met under lab environment:

- The elapsed time between our aerial vehicle taking off and reaching the synchronous state (The drone could moving with the vehicle at the same speed. More details stated below) with our ground vehicle is no more than **20 seconds**.

- The spacial proximity error, at synchronous state, between two vehicles is within a circle with **a radius of 30 centimeters**, centered at the spacial center of our GV.
- The LED indicator on our GV continuously reflects the spacial error between two vehicles with a delay of no more than **one second**.

2 Design

Block Diagram See Figure 3.

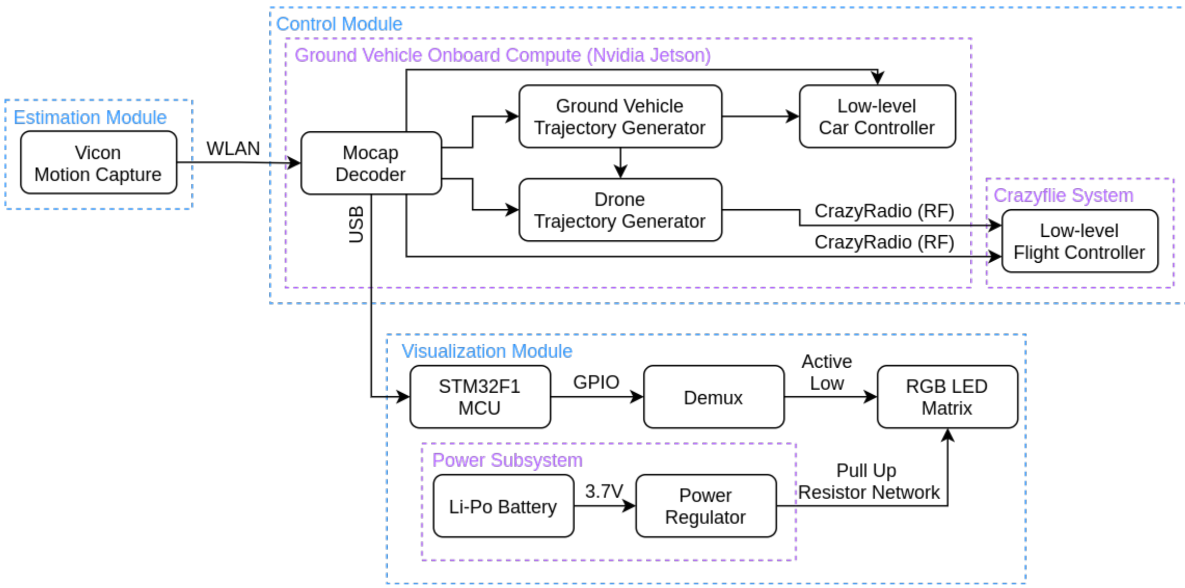


Figure 3: Block Diagram

Physical Design See Figure 4.

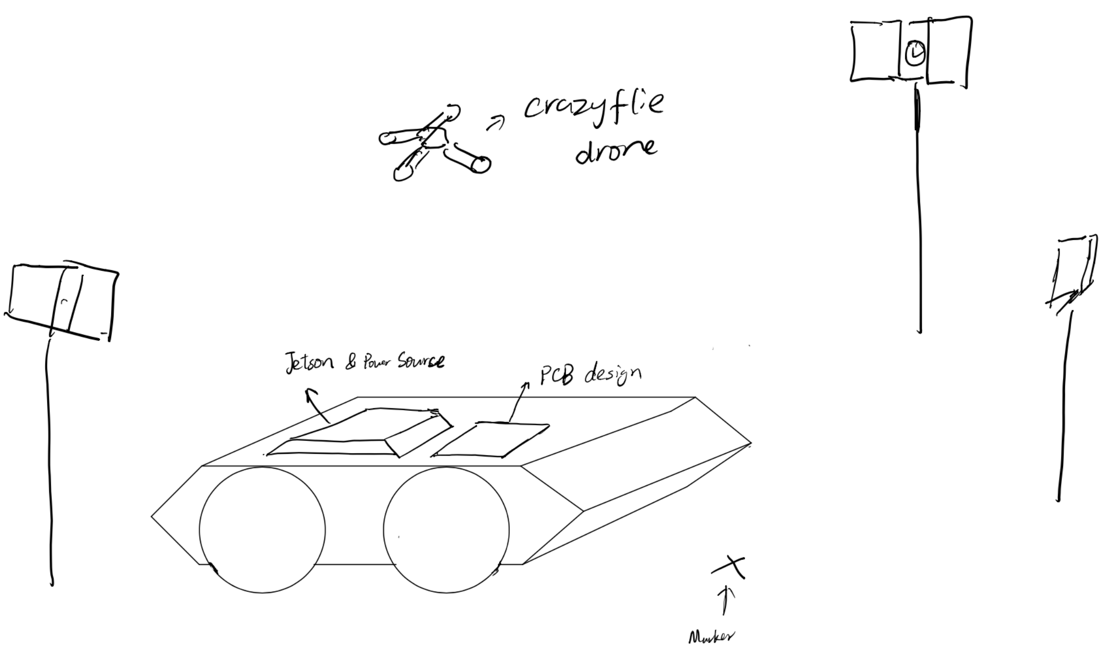


Figure 4: Physical Design

2.1 Estimation Module

The Vicon motion capture system is a commercialized indoor localization system that takes advantage of multi-view high-speed imaging technologies. To configure it properly, we will need to install reflective markers to both ground and aero vehicles and calibrate their extrinsic poses before using the localization data coming from the system. The requirement for this module is to successfully capture the calibrated poses of the two robots with the Vicon system.

Vicon Motion Capture Vicon system uses high-speed cameras deployed around the lab to capture the motion of objects and collect the raw data.

2.2 Control Module

This module is in charge of stabilizing both the ground vehicle and the drone. The overall requirement for this module is to achieve synchronous motion between the drone and the vehicle within certain proximity range.

2.2.1 Ground Vehicle Onboard Compute System

This system is in charge for handling multiple software tasks including algorithms computation and message dispatching. It must accomplish the following tasks:

- Read in and decode the location and orientation of both robots coming from the motion capture system.
- Pre-plan a feasible and safe trajectory for the ground vehicle.
- Control the ground vehicle to follow the pre-generated trajectory.
- Generate feasible and safe trajectory for the drone based on the local ground vehicle trajectory.
- Send serialized messages including trajectory and mocap data to the drone.

Mocap Decoder Vicon decoder takes the raw data collected by motion capture and calculates the corresponding positions and orientations of the ground vehicle and the drone. It then broadcasts the calculated results to different subsystems through Wireless Local Area Network (WLAN).

Ground Vehicle Trajectory Generator (GVTG) GVTG generates a pre-programmed trajectory that will be passed on to the low-level car controller. GVTG will be deployed on the Nvidia Jetson microprocessor.

Low-Level Car Controller Controls the movement of the ground vehicle and ensure its following of the trajectory.

Drone Trajectory Generator (DTG) Similar to GVTG, DTG generates a pre-programmed trajectory that will be passed on to the low-level flight controller on the drone's micro controller. However, due to the possible delays along the communication pipeline, DTG also needs to predict the ground vehicle's possible position and orientation within the next 2 seconds. DTG will also be deployed on Nvidia Jetson microprocessor.

2.2.2 Crazyflie System

Crazyflie is a commercialized product for nano-drone development. The requirement for this subsystem is to develop add-on firmware that can successfully decode the external measurement and trajectories data sent from the ground vehicle, and integrate those information into their already implemented low-level controllers.

Low-Level Flight Controller Controls the movement of the drone and ensures its following of the trajectory.

2.3 Visualization Module

2.3.1 Power Subsystem

Power subsystem must be able to support a stable 3.6V voltage and 2A current.

Power Regulator Use correct resistors and capacitors to maintain the voltage of the power source to our designed value. Exact values of the resistors and capacitors remained to be decided.

Li-Po Battery One cell Li-Po battery used for power source.

2.3.2 Overall

The visualization module must be able to communicate with the Mocap system and correctly display the correctness and quality of the synchronization by displaying the position of the drone and its relative position to the target platform.

STM32F1 Used as the interface with Mocap Decoder using USB port. It is also in charge of controlling the behaviors of the LED matrix.

Demux Used to decode the control signals sent by the MCU and convert them into signals that could be read by the matrix.

RGB LED Matrix Used to indicate the quality of the synchronization between the ground vehicle and the drone. The matrix will mainly display the position of the drone and landing position/range of the drone. The LED light box within the matrix will remain red when the synchronization has not been achieved. Once the synchronization has been achieved, the light box will turn to green.

2.4 Schematics

2.5 Board Layout

2.6 Tolerance Analysis

The most important parameter within our design is the proximity range between the ground vehicle and the drone. This proximity number is critical, because we need a safe range for the drone to land safely onto the vehicle without missing. We decided to set the proximity range to 20cm when the speed of the drone is 2m/s. The detailed explanation is listed below:

Since the Vicon system within the lab works with a frequency of 100 HZ (meaning it takes 100 pictures per second), we can conclude that the time period between two pictures is 0.01s. During this period of time, the drone relies completely on its own on-board feedback controller to keep it on the right track. The controller is equipped with a Kalman filter to defend against any potential disturbance. For the worst case scenario, we assume the filter is failed completely, and the drift that happens between 0.01s is

$$0.01 * 2 = 0.02m = 2cm$$

However, since in the real experiments, there will be delays within communication and feedback controller, we set the proximity range to a larger value (20cm). This number is also allowed since the length of our vehicle is around 50 cm and the length of the drone is about 7 cm, hence the 20cm difference will still make enough space for the drone to land safely.

3 Cost and Schedule

3.1 Cost Analysis

3.1.1 Material Bill

Aside from basic lab infrastructures (the ground vehicle, the drone and the Vicon system), our parts and manufacturing costs for the prototype are listed below:

3.1.2 Labor Cost

Our fixed development cost is estimated to be $40/hour, 10 hours/week for three people. This semester is 16 weeks long, therefore our total cost for development is:

$$3 * 40 * 10 * 16 = 19200$$

3.2 Schedule

Week	Task	Responsibility
3/1	Design Document Check	ALL
	Finalize Design Document	ALL
	Prepare DDC presentation	ALL
3/8	Design Review sign up	ALL
	Getting access to the lab	ALL
	Set up environment for Vicon, establish an object for the drone	Alvin
	Set up environment for Jetson on the vehicle and enable basic remote control for it	Alivin, Jialing
3/15	Teamwork Evaluation	ALL
	First Round PCB Order	ALL
	Finalize PCB design and schematics	Alvin, Jialiang
	Upload and order PCB	Mingda
	Soldering Assignment	ALL
	Simulation Assignment	ALL

3/22	Second Round PCB Order	ALL
	Control algorithm for the vehicle	Alvin, Jialiang
	Control algorithm for the drone	Alvin, Mingda
	Soldering PCB components and integrate it onto the vehicle	Jialiang
3/29	Optimize control algorithms for docking	Alvin, Mingda
	Implement and verify different LED patterns	Jialiang, Mingda
4/5	Individual Progress Report	ALL
	Debug	ALL
4/12	Debug	ALL
	Prepare Slides for Demo	Jialiang, Mingda
4/19	Mock Demo	ALL
	Finalize Demo details	ALL
4/26	Demonstration & Mock Presentation	ALL
5/3	Presentation	ALL
	Final Papers	ALL

4 Ethics and Safety

Although our project by itself casts little to no ethics or safety concerns because it is in a lab environment with comprehensive safety measures, as a proof of idea, it may raise the following issues:

- **Conflicts of Interests:** The successful deployment of such networks may significantly reduce the needs for labors in relevant industries, taking jobs from workers, and causing conflicts between companies and workers / unions. Such consequences could go against #3 of the IEEE Code of Ethics "to avoid real or perceived conflicts of interest whenever possible, and to disclose them to affected parties when they do exist." [1] We currently do not have a solution for this and consider it far beyond our control.

- **Possible Unlawful Misuse:** Such a autonomous delivery system might offer more vacant for smuggling, taking advantage of the unsupervised time before the packages reaching the destinations, whereas increasing the difficulty for tracking such crimes. Such consequences, together with the next two in the list, would go against #1 of the IEEE Code of Ethics "to hold paramount the safety, health, and welfare of the public, to strive to comply with ethical design and sustainable development practices, to protect the privacy of others, and to disclose promptly factors that might endanger the public or the environment." [1] To avoid such unlawful activities and minimize their damage, recording every delivery specifications and detecting for contraband before the package is sent into the autonomous system is recommend.

- **Potential Hazard to Public Safety:** Aerial vehicles might cause serious secondary injuries under potential misbehavior of the ground vehicles since the drone can cause heavy impact and consequent explosion under high speed. UAV-related incidents are not unusual in today's society as shown by [2]. These experiments [3] suggest the serious aftermaths. In response, we should advocate that drivers to drive safely or use reliable auto vehicle systems to minimize the possibility of accidents as well as to build a emergent evasion response for the drones.

- **Privacy Concern:** In industries, the cyber-security measurement at ending terminals such as the drones could be overlooked. A breach can cause serious violation to public privacy. Potential misuse includes stalking and leaking private information. To protect the civic privacy, the whole system should be protected by reliable hardware / software security such that it is maintained and examined periodically.

With aforementioned concerns, some positive aspects are listed below:

- **Productivity:** Without doubt, autonomous delivery systems could tremendously increase the productivity. This benefit and the next point, help us to develop #1 of the IEEE Code of Ethics [1].

- **Service and User Experience:** Without human intervention, the delivery systems would avoid much mistakes of express and significantly improve the user experience.

- **Social Progress:** The wide use of such a system could push the progress of our society in many aspects, such as productivity, economy, legislation, cyber-security, and so on. This complies with #2 of the IEEE Code of Ethics "to improve the understanding by individuals and society of the capabilities and societal implications of conventional and emerging technologies, including intelligent systems." [1]

References

[1] IEEE, "Ieee code of ethics." https://www.ieee.org/about/corporate/governance/p7-8.html. Accessed: 2021-02-18.

[2] "List of uav-related incidents." https://en.wikipedia.org/wiki/List_of_UAV-related_incidents, Dec 2020. Accessed: 2021-02-18.

[3] E. Tegler, "What happens when a drone crashes into your face?." https://www.popularmechanics.com/flight/drones/a28774546/drone-head-collision/, Aug 2019. Accessed: 2021-02-18.