A Proposal for a Parameterized Circulating Vector Field Guidance for Fixed Wing Unmanned Aerial Vehicles

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Garrett S. Clem

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by

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Abstract

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A Proposal for a Parameterized Circulating Vector Field Guidance for Fixed Wing Unmanned Aerial Vehicles (25 pp.)

Directors of Thesis: Dr. Jay Wilhelm and Coadvisor's Full Name

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ACKNOWLEDGMENTS

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1 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) can be used for a multitude of complex tasks such as surveillance, reconnaissance, aerial photography, delivery, and for defense. Accomplishing these tasks require robust and fast execution of three distinct subsystems consisting of navigation, guidance, and control.

1.1 Motivation and Problem Statement

1.2 Methods Overview

1.3 Phases

1.4 Summary of Objectives

- Develop a parameterized circulation method that eliminates the singularity and guides a UAV around an obstacle and to a target. The parametrized circulation term $f(heading, closingvelocity, position, turnrate)$ and would be determined by minimizing a cost.
- Simulate and compare the parametrized circulation with a non parametrized VF guidance for circular and elliptical obstacles
- Emulate fixed wing algorithm with a ground robot to validate simulation results and demonstrate real time VF guidance is achievable with parametrized circulation modification

2 Literature Review

2.1 Literature Review Introduction

2.2 Unmanned Aerial Vehicles

In literature, UAVs generally occupy one of two categories consisting of fixed wing aircraft and multi-rotor aircraft. Fixed wing aircraft can carry a large payload and are ideal for long endurance missions, whereas multi-rotor aircraft are used when hovering or high maneuverability is desired. Both categories of vehicles require navigation, guidance, and control to maintain flight and accomplish their task. These processes are often automated and programmed into flight controllers that are placed on-board the aircraft itself.

- Miniature Aerial Vehicles (Classification, what makes them different then traditional fixed wing UAVs...etc)

- Tasks (path following, waypoint navigation, loitering)

- The autopilots that operate the UAVs do so through several layers of systems known as navigation, guidance, and control NGL

- Path planning - Guidance - Control

- Who (Civilians and military) - Military uses for surveillance, reconnaissance, data transmission - Civilians have found uses such as aerial photography, environmental monitoring, and racing

$$\dot{x} = V\cos(\theta) \tag{2.1}$$

$$\dot{y} = V\sin(\theta) \tag{2.2}$$

2.2.1 Flight Mechanics

- Lift - Thrust - Drag

- Kinematics

Figure 2.1: Fixed Wing UAV

- Dubins equations of motion

- Dynamics

- Need more literature

- Forward velocity constraints, turn rate constraints

- Transition could be the autopilot ensures that the vehicle does not violate these constraints or attempt to

- Autopilot (combination of hardware and software, takes mission objectives and produces necessary actuator output)

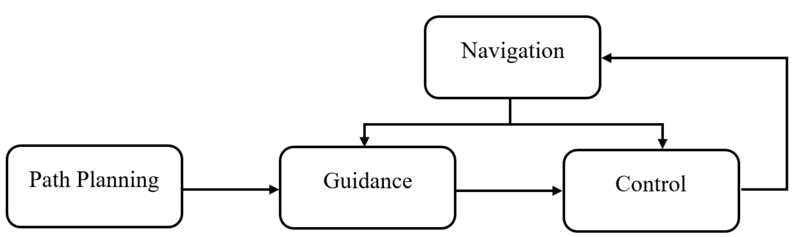


Figure 2.2: Navigation Guidance and Control Flowchart

2.3 Navigation

Before commanding a vehicle to a given task it is paramount that the location of a vehicle with respect to some reference point is known. Measuring, filtering, and estimating the location of a vehicle generally falls under the study of navigation. Commanding a vehicles heading and general operation is provided by a guidance system. Maintaining vehicle stability and reducing any errors is the responsibility of a control system.

Sensor packages containing GPS receivers, barometers, and compasses measure the location and heading of a vehicle. Data is always subject to uncertainty caused by process and measurement noise. Filtering measurements with Kalman filters produce estimates that more accurately represent the location and heading.

2.4 Guidance and Control

Traditional guidance and control are considered separate and independent systems that only exchange the most basic information. High level guidance provides the control system with a commanded heading and velocity to guide the UAV to a path or waypoint designed by the path planner. Low level control accepts the guidance and attempts to drive the state error to zero while maintaining vehicle stability. As more complicated tasks are assigned to UAVs, such as converge and follow a moving path [OAE16] either the guidance or control will become more complicated. The line between guidance and control is starting to become less tangible as the responsibilities of the guidance system becomes more intertwined with control systems.

One notable field of study in robotic guidance is that of vector fields. Each point in the operational space of the robot is assigned a vector of n-dimensions that can represent velocity, acceleration, or any arbitrary state. Vector fields have been shown to be an effective way to guide a UAV to a path and does so with less error and control effort than non-linear guidance, linear quadratic regulator, carrot chasing, and pure pursuit line of sight methods [SSS14]. There are many ways to build a vector field including potential Lagrangian functions [Kha86], Lyapunov navigation functions [EK02][Fre] [Nel05], and integral curves by intersection of surfaces [GPMP09] [GPM+10].

2.4.1 Potential Field

Potential field is a real-time robotic manipulator algorithm that distributes the task of goal seeking and obstacle avoidance among multiple layers of control [Kha86]. The robot's workspace is represented as a gradient potential of attractive and repulsive artificial forces that drive the robot to a desired state. Goals are represented as an attractive force while obstacles provide a repulsive force. The potential field is constructed by modeling the robots motion in terms of Lagrangian mechanics shown in Equation 2.3. The Lagrangian is defined as the difference in kinetic energy $T(x, \dot{x})$ and potential energy $U(x)$ in a system. The goal of the system imparts a potential U_{xd} while obstacles impart a repulsive potential U_o.

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) - \frac{\partial L}{\partial x} = F \tag{2.3}$$

$$L(x, \dot{x}) = T(x, \dot{x}) - U(x) \tag{2.4}$$

$$U_{art}(x) = U_{xd} + U_o(x) \tag{2.5}$$

Potential field has been shown to be successful at driving a robot from an initial state to a goal state while avoiding obstacles by taking the path of least action formed by the gradient. One of the weaknesses of potential field identified early on is the methods susceptibility to local minima, preventing the robot from reaching the desired global minima, or goal state [KB91]. Local minima can be avoided in the potential field method if navigation functions are used [GKM10].

Potential field is useful for point-to-point guidance and control which is often the task of UAVs traveling to waypoints, however it is often desired for a UAV to converge to and follow a path.

2.4.2 Vector Field

Several methods have been developed to generate vector fields that converge to and follow paths. Histogram virtual force field (VFF) breaks the workspace into discrete cells that contain information in regards to the certainty of the presence of an obstacle [BK90] [BK91]. Cells containing an obstacle apply an artificial guidance force away from the cell. Goals apply a global attractive force that drive the robot towards the desired state. The resultant guidance vector for the VFF method is the sum of the contributions of obstacle repulsive cells and the globally attractive goal. Lyapunov and navigation functions have been successfully used to provide guidance for converging to and following a path. Nelson et al. developed a method for generating a vector field that converges to and follows a path for line and circular primitives [Nel05]. Sinks, dead zones, and singularities were avoided when constructing more complex flight paths from the primitives by only allowing a single field to be active at any time. A vector field construction method for curved paths was presented in [Gri06] by extending Nelson's method. Elliptical paths have been generated by from primitives by applying coordinate transformations to the field [Fre].

Vector fields have many advantages to traditional guidance. UAVs often encounter disturbances in the form of wind which can be difficult to plan for. In the event a UAV encounters wind disturbances and is pushed off course, the field will drive the vehicle back on course [dMKB+17]. In addition to path following, vector field has been used to track a moving target in 3D [MTE+16]. When the location of the target is unknown, loitering about an uncertain target can be achieved by building a circular vector field and applying a linear coordinate transformation to form an elliptical loiter based on the uncertainty in targets position estimate [Fre07].

- Following curved paths in a constant wind [Gri06]

Another method for constructing a vector field is by forming integral curves that converge at the intersection of surfaces [GPMP09].

- construct an n-dimensional vector field by forming integral curves that converge at the intersection of surfaces - Field is a result of the sum of 3 terms - Convergence - Circulation - Time varying

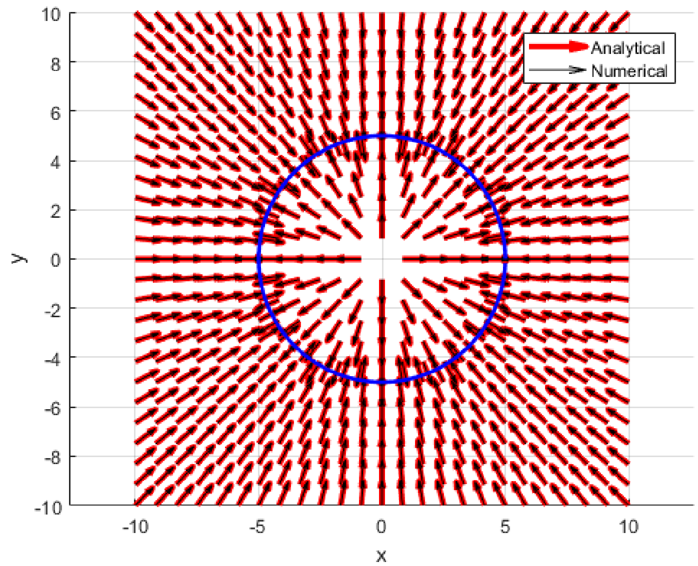
$$\boldsymbol{u} = G\nabla_q V + H \wedge_{i=1} \nabla_q \alpha_i - M(\alpha)^{-1}\boldsymbol{a}(\alpha) \tag{2.6}$$

- Define all variables - u is the resulting 2x1 vector - Gradient - $alpha_i$ is a surface function - Wedge product simplifies to cross product in 2d - G, H, L scalar weighting quantities - The intersection of the surfaces represents a path to converge and follow - Cylinder and plane example

- Cooperative Standoff Tracking of Uncertain moving targets (2007, Frew)
- VF usefulness extended to loitering about an uncertain target
- Lyapunov vector field generation for a circular loiter
- Linear transformation applied to stretch the field into an ellipse shape

2.5 Simulation and Emulation

- As new features and improvements are made to the autopilot software, it is often useful to test the performance of the software in a virtual environment. The process of simulating the autopilot software is called Software in the Loop (SITL).



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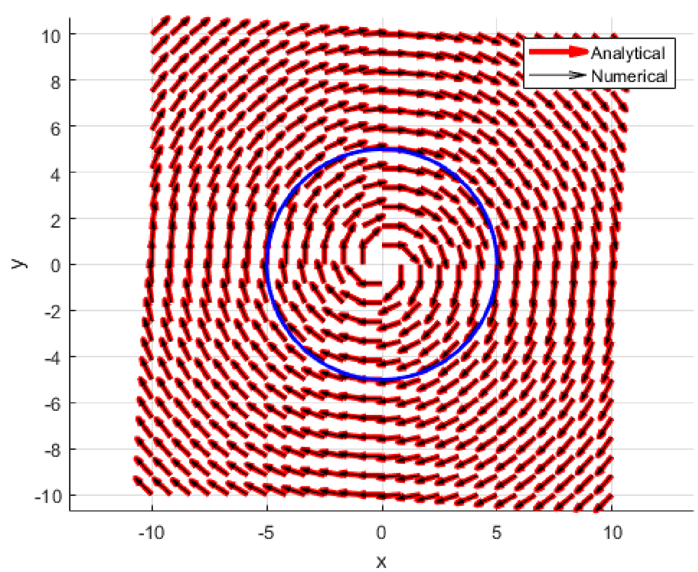

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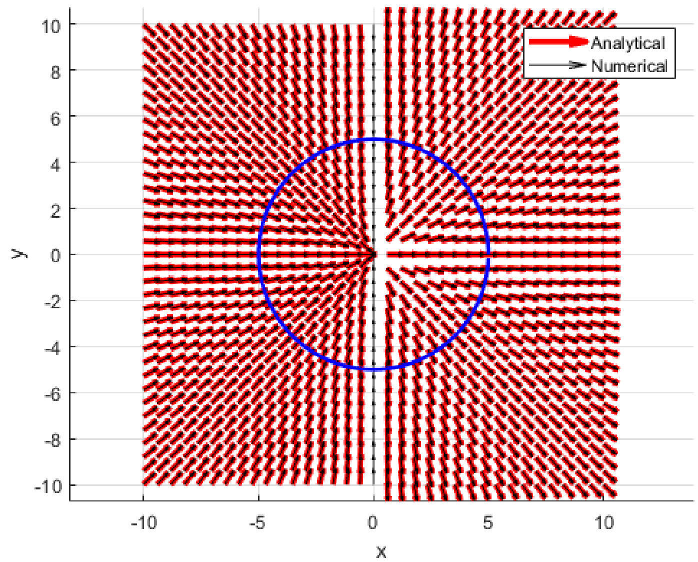

Figure 2.5:

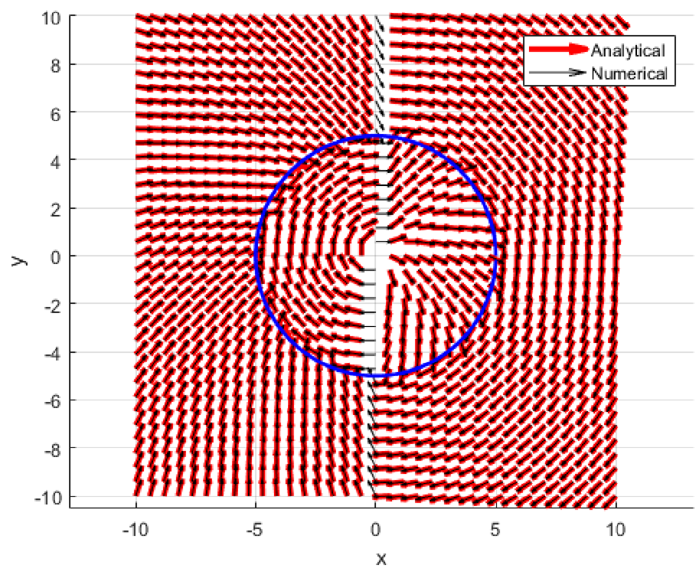

Figure 2.6:

An additional testbed for new navigation, guidance, and control algorithms is the method of emulation. Emulation is the process of mimicking the kinematics of a complex dynamic system on a simplified system. Fixed wing UAV emulation has been observed in [LDN+14], [RMSB07], and [LEBD16].

2.6 Literature Review Summary

3 METHODOLOGY

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Appendix: An Appendix

A.1 A Section in the Appendix