

TITLE

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ABSTRACT

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LIST OF SYMBOLS

a Previous or Initial Axial Induction Factor (-)

LIST OF ACRONYMS

AoA Angle of Attack

1 INTRODUCTION

1.1 Motivation and Problem Statement

Unmanned Aerial Vehicles (UAVs) are powerful robotic tools used by military and civilian communities alike. Advances in lightweight materials and commercial electronics have increased the range, payload, and reliability of the crafts. Popular applications for UAVs have been military reconnaissance, environmental surveying, aerial photography, and competitive racing. Much research has been conducted in the areas of UAV navigation, guidance, and control to promote the use of UAVs for more complex tasks. Turning high level tasks such as obstacle avoidance and path following into lower level guidance and control efforts has proven to be difficult and there appears to be no one-fits-all solution. Traditional control systems have been adapted for tasks such as following a moving path [1], but prove to be fairly complicated and difficult to implement. Researches have found success in vector field methods for guidance and control. Vector fields provide continuous directional guidance to low-level control systems and have been effective at converging to and following a path of primitives [2], tracking uncertain moving targets [3], and for obstacle avoidance [4]. Several methods have been used in literature to construct vector fields consisting primarily of the Lyapunov method [2] [5] [6] [7] and the intersection of surfaces method [8]. The vector field method allows for obstacle and goal fields to be generated separately and summed to yield a resulting guidance. Determining the weight of each field and the parameters that define circulation and convergence of the vector fields has yet to be investigated. Current field summation has been avoided due to the possibilities for singularities [2], which may be prevented with proper decay and vector field parameter tuning. The method presented in [8] provides a convenient method for building vector fields consisting of convergence, circulation, and time varying terms. **The proposed research**

seeks to provide a goal and obstacle vector field summation strategy that improves circumnavigation around circular and elliptical obstacles.

1.2 Methods Overview

Developing a goal and obstacle vector field summation strategy will be accomplished in three phases. First, singularities described in literature will be reproduced and show qualitatively how adding circulation to an obstacle field promotes circumnavigation. Next, the combination of decay functions and vector field parameters that improve obstacle avoidance will be investigated. Lastly, the modified vector field guidance will be tested on a mobile robot platform operating under the same constraints as a fixed wing will be used to validate the algorithm.

1.3 Phase I

The objective of Phase I is to demonstrate vector field summing singularity and compare strictly repulsive obstacles to circulating obstacles. A resultant vector field with singularities will be produced by summing a strictly repulsive vector field with a goal field of equal weight. Next, it will be shown that singularities can be avoided by adding a non-zero circulation term to the obstacle vector field. A qualitative side-by-side comparison to circulating and non-circulating vector fields are expected to show that adding a non-zero circulation multiplier reduces the impact of singularities and assists in circumnavigating an obstacle.

1.4 Phase II

The objective of Phase II is to Discover what combination of flight parameters has the most positive effect on obstacle avoidance. The simulations from Phase I will be repeated with a modified repulsive vector field that includes a time parametrized circulation term. Commonly used flight parameters such as closing velocity, position, and heading will

be used to form in isolation and in combination to create several scalar time parameterized functions that modify the circulation of the vector field. Decay functions that determine the weight of the goal and obstacle vector fields will be investigated. The combination of vector field convergence and circulation parameters along with the decay functions will be compared by implementing a Dubins vehicle with forward velocity and turning rate constraints.

1.5 Phase III

The objective of Phase III is to Validate parametrized vector field circulation model through mobile robot experiments. The modified vector field with parametrized circulation determined from Phase II will be implemented on a mobile ground robot with scaled forward velocity and turning rate constraints present on fixed wing UAV aircraft.

1.6 Summary of Objectives

Phase I:

- The objective of Phase I is to demonstrate vector field summing singularity and compare strictly repulsive obstacles to circulating obstacles

Phase II:

- The objective of Phase II is to Discover what combination of flight parameters has the most positive effect on obstacle avoidance

Phase III:

- The objective of Phase III is to Validate parametrized vector field circulation model through mobile robot experiments

1.6.1 Deliverables

The objectives listed above are put fourth so that the following deliverable can be presented at the conclusion of the research. **The proposed research seeks to provide a goal and obstacle vector field summation strategy that improves circumnavigation around circular and elliptical obstacles.**

2 LITERATURE REVIEW

2.1 Introduction to Literature Review

The following sections provide a discussion on the literature in regards to the modeling of fixed wing UAVs and the navigation, guidance, and control systems that govern the behavior of the crafts. First, the fixed wing is introduced and a brief discussion on the modeling techniques commonly used for navigation, guidance, and control design. An overview of the structure of autopilots that execute the models is presented. Then, an overview of navigation, guidance, and control is given along with the cutting edge techniques for guidance. (Revisit this section when a rough draft is complete)

2.2 Fixed Wing Unmanned Aerial Vehicle

2.2.1 Introduction to Fixed Wing UAV

Fixed wing UAVs have found uses in surveillance, reconnaissance, environmental surveying, aerial photography, and competitive racing. The crafts are well suited to carry out tasks that require long endurance and large payloads. Fixed wing UAVs come in many different sizes and configurations, but can be categorized into large and hand-launched varieties. Large fixed wing UAVs require long stretches of runway to takeoff and land, are gas powered, and can carry large payloads consisting of sensor packages, high resolution cameras, and scientific instrumentation shown in Figure . Hand-launched UAVs can be easily broken down and carried by a single person and are often battery powered. Easily deployed, the hand-launched UAVs take-off by being thrown in a similar way as a javelin shown in Figure 2.2. The smaller form factor makes hand-launched UAVs well suited for short range reconnaissance and for carrying lightweight payloads with low to medium resolution cameras.



Figure 2.1:



Figure 2.2:

Both large and hand-launched UAVs operate under the same basic principle consisting of navigation, guidance, and control depicted in Figure 2.3. The desired path to be flown is passed to a guidance algorithm whose purpose is to produce guidance commands consumable by the low level-control system that puts the UAV on the desired path. Navigation systems are responsible for estimating the state of the UAV to provide feedback to both guidance and control loops. For more detail on NGC systems, refer to section 2.3. Each of the NGC sub systems are typically not evaluated independently and must be integrated into a complete NGC system to evaluate the performance as a whole. The

most common ways to measure the performance of a UAV system are tracking error with respect to the desired path and control effort.

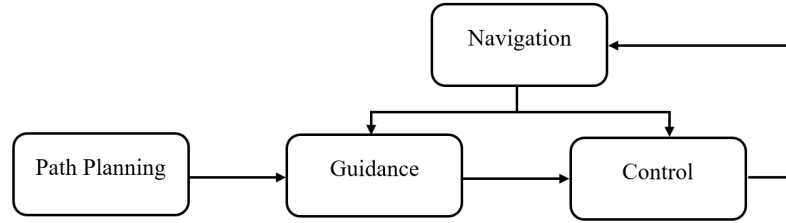


Figure 2.3:

2.2.2 Modeling

The fixed wing UAV is a 6 degree of freedom (DOF) system with four degrees of control consisting of pitch, roll, yaw, and thrust. Change in the control variables is done by actuating the elevator (pitch), ailerons (roll), rudder (yaw), and propeller or jet (thrust). Due to the under actuation and complex non-linear dynamics of the UAV, high fidelity models tend to be high order and non-linear. High order non-linear models can be linearized and simplified to be used in low level control systems to maintain vehicle stability. Beyond the control aspect of UAVs, the high order non-linear models are not always necessary. It is common in literature to simplify complex non-linear dynamics of a fixed wing UAV by implementing a 2D Dubins vehicle model [3] [9] [2] [5] [10]. When simplified kinematics are used when developing navigation and guidance systems, it is assumed that there already exists a low level control loop that maintains vehicle stability and performs according to the kinematic model in Equations 2.1-2.2.

The position of the vehicle at any point in 2D Cartesian space is defined as (x, y) and the velocity of a vehicle in each axis is defined as (\dot{x}, \dot{y}) .

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

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

The position of the vehicle at any point in 2D Cartesian space is defined as (x, y) and the velocity of a vehicle in each axis is defined as (\dot{x}, \dot{y}) . The heading of the vehicle θ is most frequently used as the input $\mathbf{u} = \theta$. To more closely represent the dynamics of a fixed wing, constraints are given to the velocity V and turning rate $\dot{\theta}$.

$$V \geq V_{stall} \quad (2.3)$$

$$-\dot{\theta}_{max} \leq \dot{\theta} \leq \dot{\theta}_{max} \quad (2.4)$$

The devices that are assumed to be in control of the UAV when designing guidance and navigation systems are called autopilots or flight controllers, which will be discussed briefly in the next section.

2.2.3 Autopilot

The autopilot is a software and hardware package that brings navigation, guidance, and control techniques to realization. A typical autopilot system is depicted in Figure 2.4, consisting of a hard shell protecting sensors with numerous input and output connectors for power, communication, and servo actuation. The flight controller is responsible for several major tasks including maintaining vehicle stability, turning high level commands into low level control effort, and recording and transmitting data to ground stations. Autopilots accomplish these tasks by implementing several layers of algorithms consisting of navigation, guidance, and control which will be discussed next. An autopilot is a software and hardware package that executes the NGC systems that allow for complex flight. A typical autopilot system is depicted in Figure 2.4, consisting of a hard shell protecting sensors with numerous input and output connectors for power, communication, and servo actuation. The flight controller is responsible for several major tasks including

maintaining vehicle stability, turning high level commands into low level control effort, and recording and transmitting data to ground stations.

Figure 2.4: Pixhawk Flight Controller

2.3 Navigation, Guidance and Control

2.3.1 Introduction to NGC

Nearly all of the systems that go into an autopilot system for a fixed wing UAV can be put under the category of Navigation, Guidance, or Control (NGC). Traditionally, NGC could be thought of separate but equally important algorithm layers that aid an autopilot in accomplishing a given task. Navigation is the study of measuring and filtering the state of a vehicle. Guidance produces a commanded state based on high level requests from a path planner or user. Control maintains vehicle stability while attempting to achieve the state commanded by the high level guidance system. Lately, the lines between guidance and control have become less clear as the systems become more integrated with each other, resulting in more complex capabilities. Continuing with the convention in literature, navigation will be discussed as a separate unit while guidance and control will be discussed simultaneously. Guidance and control will be discussed as a single system and two commonly researched algorithms, potential and vector field methods, will be discussed.

2.3.2 Navigation

Navigation is the study of measuring the position and attitude of the UAV for the purposes of building guidance and providing feedback for the low level control system. Modern flight controllers contain a package of sensors called an Inertial Measurement Unit (IMU) which consists of a 3-axis accelerometer, gyroscope, compass, and barometer.

The accelerometer and gyroscope are measured to determine the translational and angular acceleration of the craft. The compass measures the heading, and the barometer measures air pressure which is correlated to altitude. GPS is often used to determine the local position of the UAV. One of the major challenges in navigation is the noise and uncertainty in sensor measurements. Filters are used to fuse information and provide more accurate estimates of the vehicles position and rate of change.

2.3.3 Guidance and Control

Guidance and control have traditionally been separate systems, but as the need for UAVs to perform complex tasks increases, so does the complexity of the control systems. A common high level request provided to a UAV is to follow an arbitrary path which can be done with traditional controls [11]. A control system for following a moving path was developed in [1], which was successful at reducing the tracking error in simulation and real flight tests. To accomplish path following of a mobile path, the control law becomes complex and less intuitive.

Instead of relying on complex control laws, there has been much research on methods that combine guidance and control. Two categories will be discussed consisting of potential field and vector field methods. In literature, the two methods have been seen used interchangeably. In the work presented, potential field is in reference to a gradient potential converging to a local minimum while vector field is in reference to a space of vectors whose integral lines converge and follow a path. It can be argued that vector fields are essentially a potential field, but for organizational purposes, they will be referred to as completely different methods.

2.3.4 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 [12]. 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 2.5. 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 .

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{x}} \right) - \frac{\partial L}{\partial x} = F \quad (2.5)$$

$$L(x, \dot{x}) = T(x, \dot{x}) - U(x) \quad (2.6)$$

$$U_{art}(x) = U_{xd} + U_o(x) \quad (2.7)$$

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 [13]. Local minima can be avoided in the potential field method if navigation functions are used [14].

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.

2.3.5 Vector Field

Introduction to 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 [15] [16]. 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 [2]. 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 [5] by extending Nelson's method. Elliptical paths have been generated by from primitives by applying coordinate transformations to the field [7].

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 [17]. In addition to path following, vector field has been used to track a moving target in 3D [18]. 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 [6].

- Following curved paths in a constant wind [5]

Another method for constructing a vector field is by forming integral curves that converge at the intersection of surfaces [8].

- 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

$$\mathbf{u} = G\nabla_q V + H \wedge_{i=1} \nabla_q \alpha_i - M(\alpha)^{-1} \mathbf{a}(\alpha) \quad (2.8)$$

- Define all variables - \mathbf{u} is the resulting 2x1 vector - Gradient - α_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

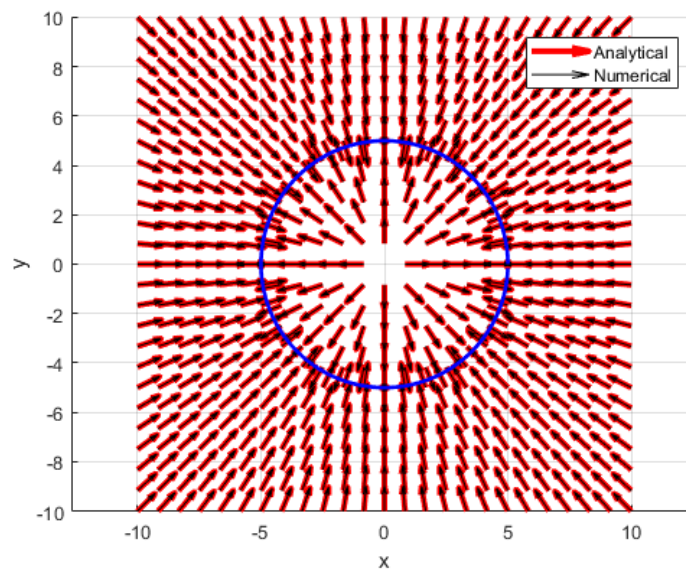


Figure 2.5: Convergence

- 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

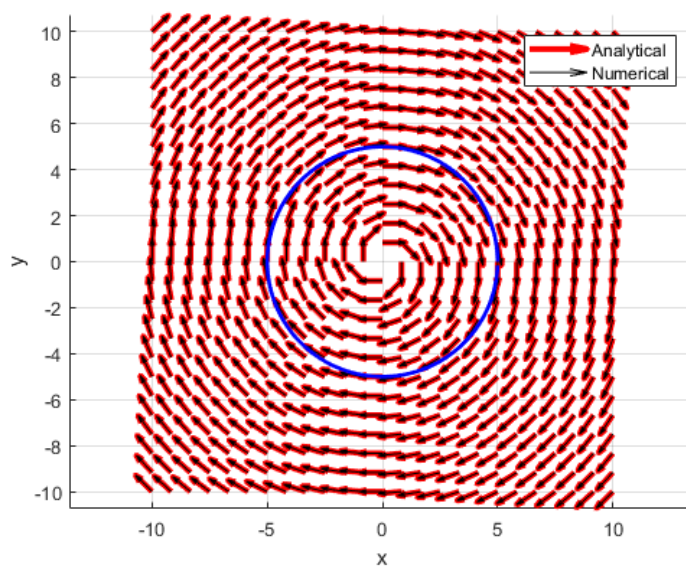


Figure 2.6: Circulation

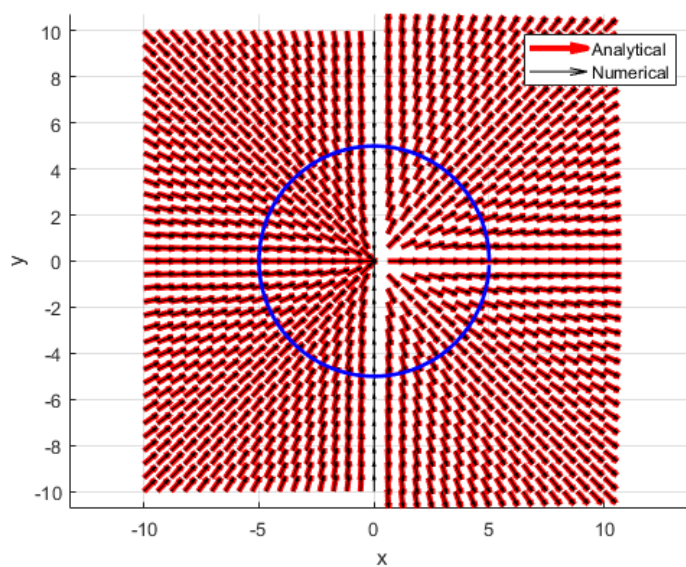


Figure 2.7: Time Varying

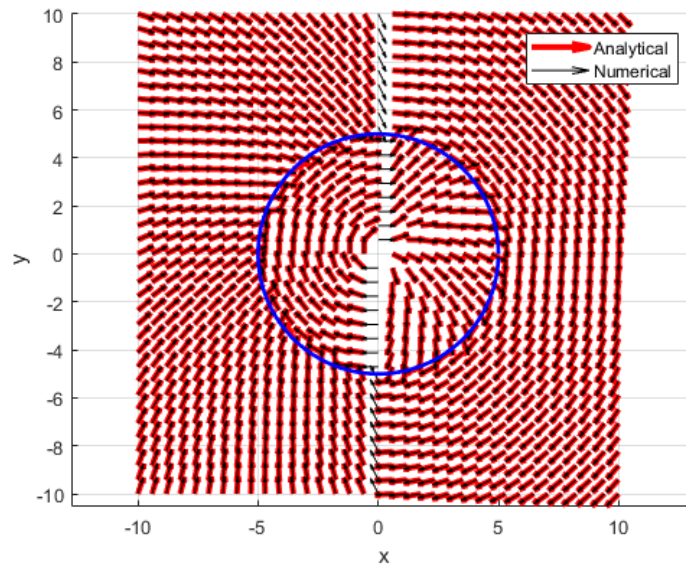


Figure 2.8: Total Field

- Linear transformation applied to stretch the field into an ellipse shape

2.4 Literature Review Summary

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