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

A thesis presented to

the faculty of

the Russ College of Engineering and Technology of Ohio University

In partial fulfillment

of the requirements for the degree

Master of Science

Garrett S. Clem

December 2017

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This thesis titled

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

by

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Abstract

CLEM, GARRETT S., M.S., December 2017, Mechanical Engineering

A Proposal for a Parameterized Circulating Vector Field Guidance for Fixed Wing Unmanned Aerial Vehicles (29 pp.)

Director of Thesis: Jay P. Wilhelm

ABSTRACT

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ACKNOWLEDGMENTS

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a Previous or Initial Axial Induction Factor (-)

LIST OF ACRONYMS

AoA Angle of Attack

1 Introduction

1.1 Motivation and Problem Statement

Fixed wing Unmanned Aerial Vehicles are used for long endurance missions such as surveillance that would fatigue pilots or put them in harms way [1]. Missions are typically built using waypoiont navigation and loitering executed by path following [2]. Obstacles are not always known during path planning and once discovered, a new path must be generated. Planning obstacle free and flyable paths takes time and may be impossible to relay to a UAV if communication is not reliable. Guidance that follows mission paths while avoiding obstacles without the need for constant communication with a ground station may be beneficial. Gradient Vector Fields (GVF) produce heading guidance at any point in space by summing together convergence and circulation field components. Each component uses a static scalar weight. Obstacles have been represented as separate repulsive GVFs that are later summed to the path following GVF [Wilhelm, Wambold, Clem]. Static GVF weights do not consider the state of the UAV resulting in sub-optimal guidance. Modifying the GVF convergence and circulation weights to be functions of common UAV states may generate an optimal guidance. **The proposed research seeks to determine GVF weighting functions that construct optimal obstacle avoidance.**

1.2 Methods Overview

The proposed research will be conducted in three phases where singularities will be demonstrated, weighting functions will be investigated, and a developed GVF will be validated on a ground robot simulating a UAV. Phases I and II will be conducted in a simulation environment that combines mission paths and obstacles into a single GVF. Phase III will be conducted with a ground robot simulating a UAV guided by the modified GVF in real-time. Dubins fixed wing constraints will be imposed in simulations and experiments.

1.3 Phase I

Recreate vector fields for circular and elliptical obstacles and demonstrate singularities. A simulation environment will be built that generates GVFs consisting of mission paths and obstacles. Circular and elliptical obstacles will be investigated and the resulting singularities will be characterized. Static weights will be used and the performance of the guidance measured in distance traveled and time of flight.

1.4 Phase II

Investigate GVF weighting functions that influence obstacle avoidance. UAV closing rate, position, and range will be used to develop dynamic GVF weights for convergence and circulation. The modified GVF will be compared against a static and strictly repulsive GVF. Distance traveled and time of flight will be used to compare the modified GVF to the unmodified GVF.

1.5 Phase III

Validate modified GVF model with ground robot experiments. The modified GVF developed in Phase II will be implemented on a differential drive ground robot simulating a fixed wing UAV. Guidance to guide the robot to a path while avoiding static obstacles will be demonstrated.

1.6 Summary of Phases

Each phases consists of a **goal** that will be accomplished by executing *objectives*. Completion of all objectives and phases will result in the final deliverable.

Phase I: Demonstrate Gradient Vector Field Singularities

1. *Build a GVF simulation environment*
2. *Derive GVF for circular and elliptical obstacles*
3. *Identify path and obstacles where singularities are produced*

Phase II: Investigate GVF weighting functions that influence obstacle avoidance

1. *Formulate circulation and convergence weights as functions of UAV state*
2. *Determine combination of GVF weights that produces optimal guidance in simulation*

Phase III: Validate modified GVF model with ground robot experiments

1. *Build differential drive robot*
2. *Build robotic framework to take guidance commands*
3. *Repeat simulations performed in Phase II on ground robot*

Deliverable: Modified GVF optimal guidance for path following and static obstacle avoidance.

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 been used for surveillance and reconnaissance in hostile environments since no on-board pilot is required. Ground stations allow for remote data collection and piloting, keeping soldiers out of harms way. During long endurance missions, operators can easily be changed out when fatigued allowing the UAV to remain in service for many hours beyond what a single pilot could safely handle. Keeping the UAV in service for longer allows more tasks to be accomplished. 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 2.1a. 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 2.1b. 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.

(a) (b)

Figure 2.1: Global Hawk and Hand Launched Fixed Wing UAV

Both large and hand-launched UAVs operate by using path planning, navigation, guidance, and control algorithms depicted in Figure 2.2. Most UAV tasks can be framed as path following problems such as waypoint navigation or loitering. The UAVs path planner is responsible for generating a flyable path from the current state to the desired state while avoiding known obstacles. Guidance systems are responsible for producing guidance commands to the low level controller that guide the UAV towards 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 navigation, guidance, and control systems, refer to section 2.3. Each of the navigation, guidance, and control sub systems are typically not evaluated independently and must be integrated into a complete 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. Next, common UAV modeling techniques will be discussed.

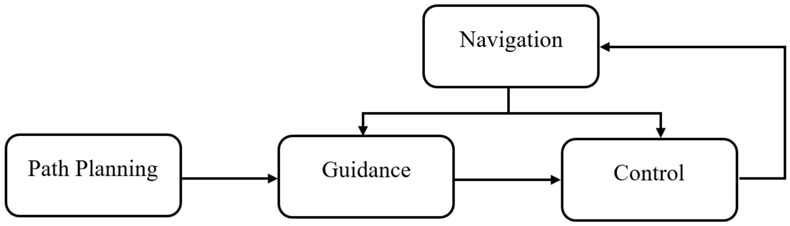


Figure 2.2:

2.2.2 Modeling

Accurate models of fixed wing UAVs tend to be high order, coupled, non-linear systems that can be difficult to solve for. The complexity is due to the fact that a fixed UAV has 6 degrees of freedom with only 4 degrees of control and has non-linear aerodynamic external forces. Models can be linearized and simplified when designing control systems, but still maintain high complexity and require significant effort to implement. 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 [4] [5] [6] [7] [8]. 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 $(\dot{x}, \dot{y})$.

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

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

The heading of the vehicle θ is most frequently used as the input $\boldsymbol{u} = \theta$. To more closely represent the dynamics of a fixed wing, constraints are given to the velocity V and turning rate $\dot{\theta}$.

$$V \geq V_{stall} \tag{2.3}$$

$$-\dot{\theta}_{max} \leq \dot{\theta} \geq \dot{\theta}_{max} \tag{2.4}$$

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 and Ground Station

Autopilots and ground stations work together to configure vehicle settings, exchange high-level mission objectives, and collect data. 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 2.3, consisting of a hard shell protecting sensors with numerous input and output connectors for power, servo actuation, and communication. Major responsibilities for a autopilot are maintaining vehicle stability, turning high level commands into low level control effort, and transmitting data to ground stations.

Figure 2.3: Pixhawk Flight Controller

Ground stations provide an interface for configuring vehicle settings such as cruising velocity and safety protocols. High level mission objectives for waypoint navigation, path following, and loitering are programmed and sent from the ground station to the autopilot. Data collected by the autopilot can also be relayed to the ground station for real time mission updates and for diagnosing problems.

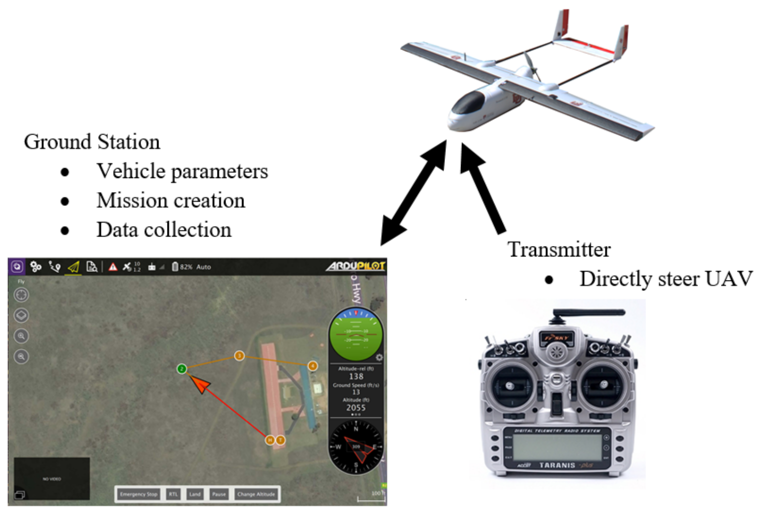


Figure 2.4:

In the event that manual control is required, a transmitter can be used to directly control actuation of the control surfaces on the aircraft. An overview of the autopilot, ground station, and transmitter system is shown in Figure 2.4.

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, filtering, and estimating 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 heading, and the barometer measures air pressure which is correlated to altitude. IMUs are best for determining the attitude of a UAV but are not used to determine local position due to high noise levels and susceptibility to drift. GPS or motion capture are commonly used to determine local position of a 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. A popular method for filtering and estimating navigation data is done through some variety of a Kalman filter which is a recursive probability method that provides an improved estimation as more information becomes available. The estimates determined by the navigation system are passed to guidance and control systems.

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 [9]. A control system for following a moving path was developed in [10], 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 was first introduced as a real-time robotic manipulator algorithm for obstacle avoidance [11]. The potential field algorithm represents a robots workspace as a gradient potential of attractive and repulsive artificial forces that drive the robot to a desired goal. Goals are given the lowest potential and act as attractive forces. Obstacles have high potential and act as repulsive forces. A simple example is depicted in Figure 2.5 consisting of an initial state, a goal, and a single obstacle. The initial state of the robot is at the edge of a gradient where the potential is maximum. In the lowest part of the gradient a goal exists at the global minimum. Obstacles are added to the potential field, but have limited effect due to a decay function.

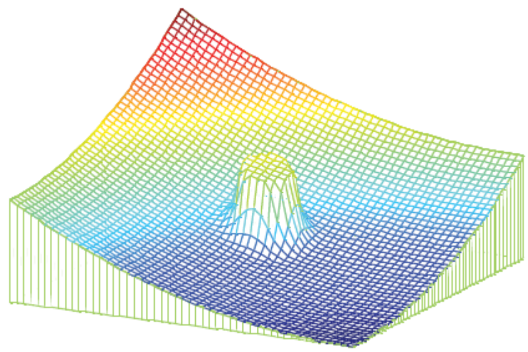
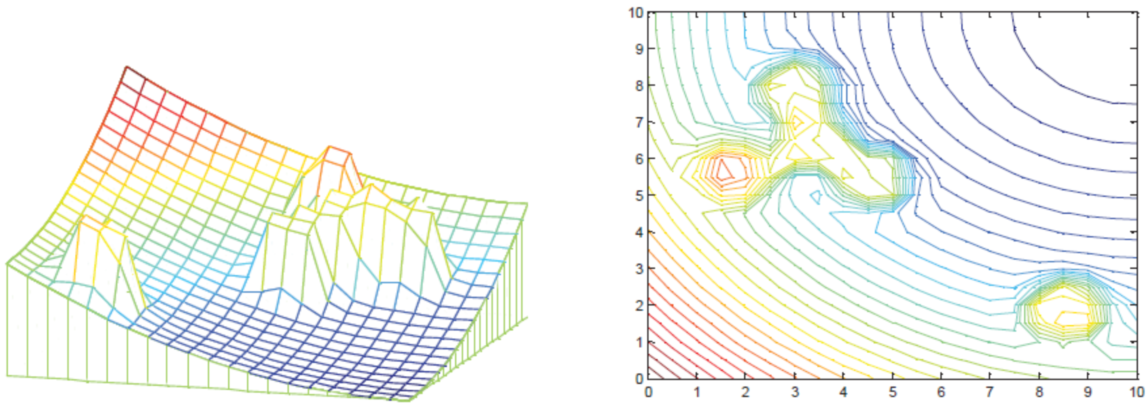


Figure 2.5: Single Obstacle Potential Field Gradient [12]

Potential field is unique in that path planning, trajectory planning, and control are lumped into a single system [13]. Transition from an initial state to a goal state traditionally occurred by executing three steps consisting of path planning, trajectory planning, and control. Path planning dealt with finding an obstacle free path from an initial state to a goal state. Trajectory planning time parametrized the obstacle free path with some high level vehicle constraints considered. Lastly, control attempts to reduce the tracking error with respect to the reference trajectory. Combining the three motion planning steps into a single algorithm has been shown to be computational inexpensive [14].

As pointed out in [15], robots using potential field are susceptible to local minimum. Encountering a local minimum prevents the robot from continuing down the gradient and into the global minimum because equilibrium has been reached prematurely. Figure 2.6 demonstrates local minimum by adding several obstacles into a goal field. Several methods have been developed to mitigate the effects of local minimums as pointed out in [14] through the use of navigation functions. Local minimum produced as a result of closely spaced obstacles as shown in Figure 2.6 have been addressed by grouping obstacles together into a cluster [12].



(a) (b)

Figure 2.6: Potential Field Local Minimum [12]

Several methods have been developed to mitigate the effects of local minimums as pointed out in [14] through the use of navigation functions. Local minimum produced as a result of closely spaced obstacles as shown in Figure 2.6 have been addressed by grouping obstacles together into a cluster [12]. Grouping obstacles addresses the risk of local minima before forming the potential field. If local minima are encountered after the field is generated, additional forces can be applied to push the robot away from the local minima.

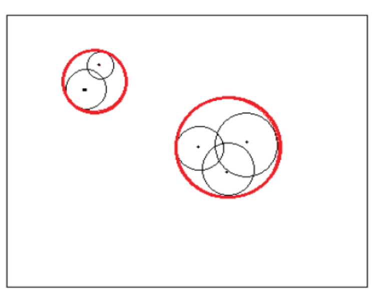


Figure 2.7: Obstacle Clustering [12]

Potential fields ability to avoid obstacles and combine path planning, trajectory planning, and control into a single system while being computationally inexpensive makes it an attractive option for many robotic systems. Fixed wing UAVs must maintain a minimum forward velocity and cannot converge to a single point, making potential field difficult to implement.

2.3.5 Vector Field

Converging and following a path instead of a point is more applicable to fixed wing UAVs and has been accomplished through the use of vector fields which will be discussed next.

Path following

Vector field is a continuous guidance technique that provides heading commands that asymptotically converges and follows a path.

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 [6]. 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 [7] by extending Nelson's method. Elliptical paths have been generated by from primitives by applying coordinate transformations to the field [17].

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 [18]. In addition to path following, vector field has been used to track a moving target in 3D [19]. 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 [20].

- Following curved paths in a constant wind [7]

Another method for constructing a vector field is by forming integral curves that converge at the intersection of surfaces [3].

- 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

$$\boldsymbol{u} = G\nabla_q V + H \wedge_{i=1} \nabla_q \alpha_i - M(\alpha)^{-1}\boldsymbol{a}(\alpha) \tag{2.5}$$

- 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

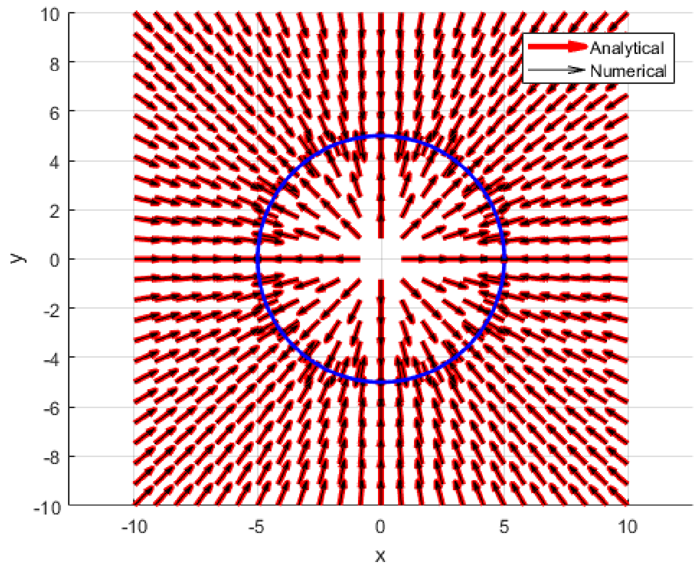


Figure 2.8: Convergence

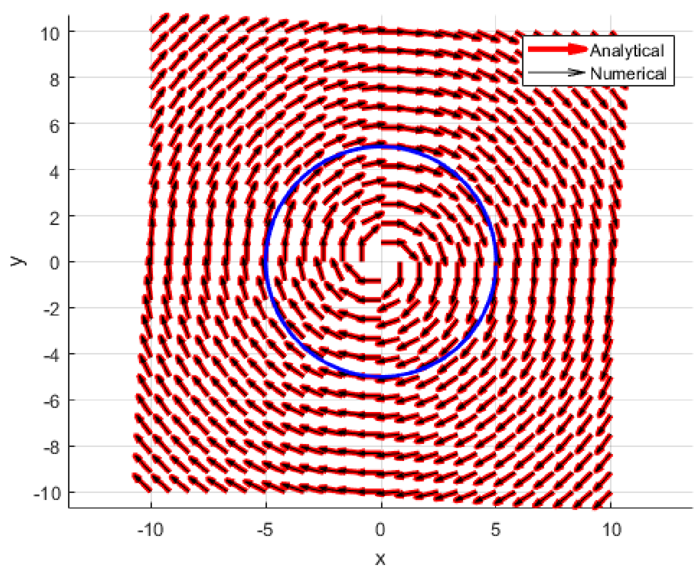


Figure 2.9: Circulation

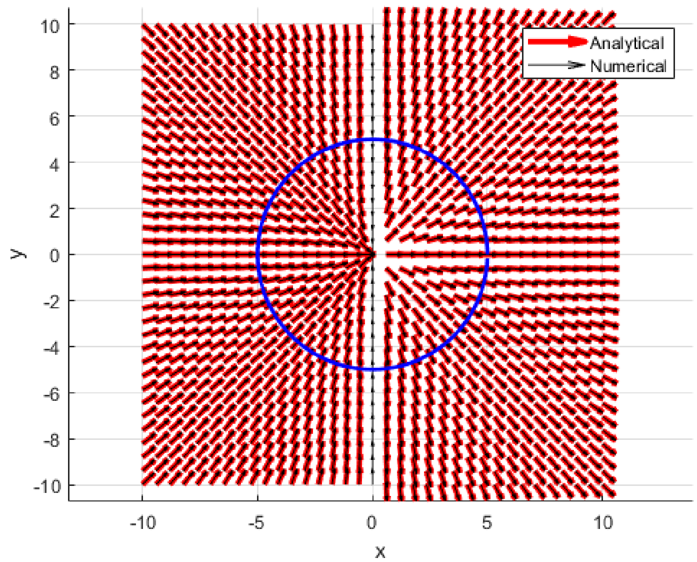


Figure 2.10: Time Varying

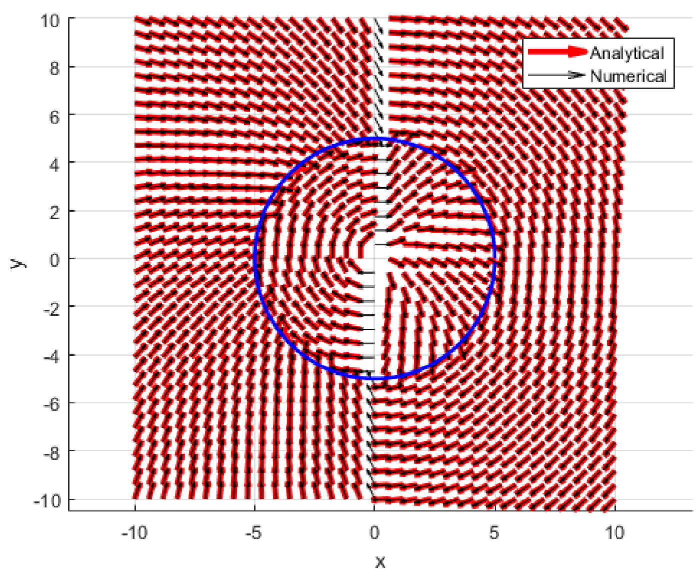


Figure 2.11: Total Field

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

2.4 Literature Review Summary

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