Vector field path following and obstacle avoidance singularity mitigation via look-ahead flight envelope

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ABSTRACT

Problem Statement

Unmanned Aerial Vehicles (UAVs) conventially navigate a series of off-line generated and initially obstacle free waypoints that may have to be re-planned when encountering a previously unknown obstacle. Re-planning waypoints could be avoided by implementing a path following and obstacle avoidance vector field guidance. Guidance to converge and follow a pre-planned path is produced by an attractive vector field while obstacles are represented by a repulsive vector field. Summing together attractive goal and repulsive obstacle fields produce a guidance for tracking a pre-planned path while avoiding unplanned obstacles. Small regions of null guidance, called singularities, may be produced when summing attractive and repulsive fields together.

Method for path following, obstacle avoidance, and detection / mitigation of vector field singularities for UAVs etc

Motivation

- Conventional waypoint guidance relies on a pre-planned, flyable, and obstacle free path
- Obstacles unaccounted for during planning may require a re-plan which may require communication with a ground station

Background

- Vector field guidance for path following has been shown to be both robust in the presence of external disturbances and produce low cross track error flight
- Obstacles can be represented as repulsive fields and summed with attractive fields to produce an obstacle avoidance guidance
- Summing vector field guidance my produce singularities, resulting in no guidance
- Repulsive fields currently provide no additional information on how to go around obstacle

Contribution

- Method for compensating for singularities that may be experienced (Lookahead or fast detection)

I. Nomenclature

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VF = Vector Field

II. Introduction

Unmanned Aerial Vehicles are pilotless aircraft used by military, police, and civilian communities for tasks such as reconnaissance, damage assessment, natural disaster surveying, and target tracking [1, 2]. Tasks can be performed by a single UAV or with a team of other air, ground, or marine vehicles [3–5]. Autonomous vehicle missions are typically accomplished by navigating a series of waypoints [1] or following a path [6]. Waypoints are conventionally generated off-line at a ground station and relayed over radio to the UAVs autopilot. The on-board guidance directs the UAV towards the current active waypoint. Once the UAV has reached a pre-defined distance from the waypoint, the UAV is directed to the next waypoint. An example of a UAV following waypoint guidance while avoiding an obstacle is shown in Figure 1

Fig. 1 UAV path from waypoint guidance

During waypoint navigation the UAV may encounter obstacles or environmental changes that would require a new set of obstacle free waypoints to be generated. For highly uncertain or dynamic environments, there may have to be frequent updates which increases the communication overhead of the autopilot. Additionally, if communication is lost or the path is not updated rapidly enough the UAV may fail to avoid obstacles completely.

Obstacle free paths in static and dynamic environments have been generated with the potential field method, which models a robot's workspace as a gradient of artificial attractive and repulsive forces [7]. Potential field combines path planning, trajectory planning, and control [8] into a single system making it an attractive solution for robotic systems. Paths can be generated by placing a point mass at an initially high potential and allowing it to descend the gradient until the point reaches the goal, located at a global minimum potential. Obstacles provide a limited repulsive force, pushing the mass away from the obstacle. Major drawbacks to potential field were identified in [9] consisting of local minimum and oscillations in corridors. The local minimum problem occurs when closely spaced obstacle's potential combine to produce a well on the descent gradient where a pre-mature stable point is found. Proposed solutions to local minimum include object clustering and virtual waypoint method [10], virtual escaping route [11], and use of navigation functions [12]. Oscillations in potential field were studied in [13], and [14].The potential field method converges to a singular point which is not possible for fixed wing aircraft. Similar to conventional waypoint guidance, the active goal point would change as a function of proximity, however for certain UAV applications such as following a curved ground track or surveying it may be beneficial to follow an explicit path.

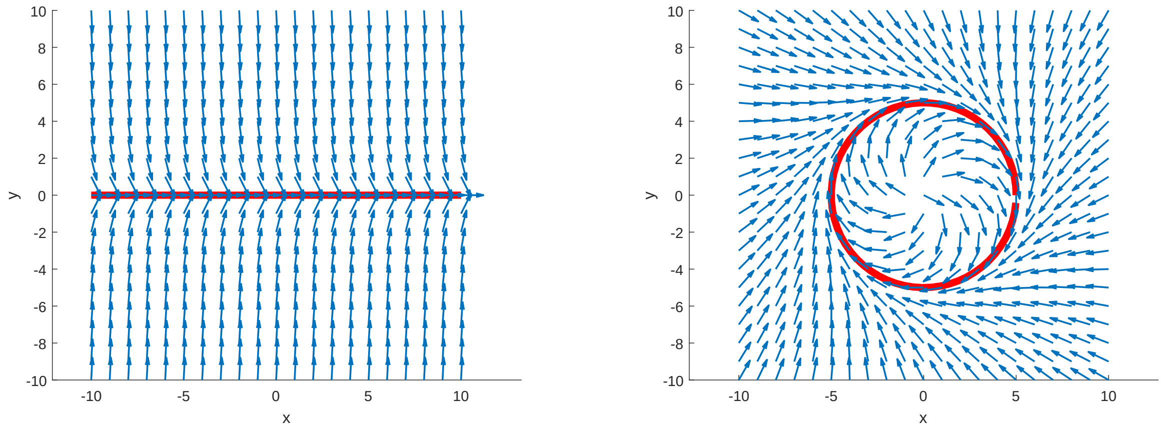
Such path following can be accomplished with vector fields which produce a heading guidance that asymptotically converges and circulates a path. A comparison between vector field and waypoint guidance techniques was presented in [15] where each method was evaluated based on its complexity, robustness, and accuracy. Vector field produced guidance that was both robust to external wind disturbances while maintaining a low cross track error.

The two most prominent methods for generating vector fields in literature consist of the Lyapunov [16–21] and Goncalves [22–25] method. Lyapunov vector fields for converging and following straight and circular paths were described in [16]. For converging and following a straight path, a guidance vector χ^d is determined in Equation 1, where χ^∞ is the course approach angle, y is the lateral distance to the path, and k is a positive constant that determines the rate of transition between convergence and following. An example of a Lyapunov vector field converging and following a straight line is shown in Figure 2a.

$$\chi^d(y) = -\chi^\infty \frac{2}{\pi} \tan^{-1}(ky) \tag{1}$$

For converging and following a circular path, a guidance vector χ^d is determined in Equation 2, where γ is the UAVs angular position with respect to the circle, r is the paths radius, d is the distance from the circles center, and k is a positive constant that determines the transition behavior. An example of a Lyapunov vector field for converging and following a circular 2b.

$$\chi^d(d) = \gamma - \frac{\pi}{2} - \tan^{-1}\left(k\frac{d-r}{r}\right) \tag{2}$$



(a) (b)

Fig. 2 Vector field converging and following a) straight path b) circular path

Straight and circular path vector fields can be selectively activated throughout flight to form more complex paths, shown in [16–18, 26]. Lyapunov vector field for curved path following was presented in [21] which may allow for more complex paths and eliminates the need to switch between vector fields.

The Goncalves method produces an n-dimensional vector field that converges and circulates a static or time-varying path defined by *(n-1)* implicit surfaces ($\alpha_i : \mathbb{R}^n \rightarrow \mathbb{R} | i = 1, ..., n-1$). The surface functions can represent any shape as long as they satisfy the two conditions that 1) they are positive definite and 2) have bounded derivatives. Consider the space with dimensions in set **q**:

$$\mathbf{q} = \begin{bmatrix} x_1, x_2, ..., x_n \end{bmatrix} \tag{3}$$

The vector field can be calculated by the sum of three terms consisting of a convergence $\vec{v}_{conv}$, circulation $\vec{v}_{circ}$, and time-varying $\vec{v}_{tv}$ term.

$$\vec{v} = \vec{v}_{conv} + \vec{v}_{circ} + \vec{v}_{tv} \tag{4}$$

Convergence is calculated by:

$$\vec{v}_{conv} = \sum_{i=1}^{n-1} \alpha_i \nabla_q \alpha_i \tag{5}$$

Circulation:

$$\vec{v}_{circ} = \wedge_{i=1}^{n-1} \nabla_q \alpha_i \tag{6}$$

$$\vec{v}_{circ} = \nabla_q \alpha_1 \times \nabla_q \alpha_2 \tag{7}$$

The time-varying component is calculated by:

$$\vec{v}_{tv} = M^{-1} a \tag{8}$$

$$M = \begin{bmatrix} \nabla \alpha_1^T \\ \nabla \alpha_2^T \\ (\nabla \alpha_1 \times \nabla \alpha_2)^T \end{bmatrix} \tag{9}$$

$$a = \begin{bmatrix} \frac{\partial \alpha_1}{\partial t} & \frac{\partial \alpha_2}{\partial t} & 0 \end{bmatrix}^T \tag{10}$$

The standoff tracking scenario presented in [Wilhelm] tasked a fixed wing UAV with loitering around a moving ground target while adding obstacle avoidance constraints. A circular attractive vector field was attached to a moving ground target. Repulsive vector fields centered at the obstacles and weighted by hyperbolic tangent decay functions were summed with the attractive circular field to produce a target loitering and obstacle avoidance guidance. The performance of Lyapunov [19] and gradient vector field [22–24] were compared for their cross track error with respect to the loiter circle. Gradient vector field had favorable performance due to compensation for a time-varying vector field. The gradient vector field technique also has the benefit of decoupled weighting parameters for convergence, circulation, and time-varying terms, allowing for easy modification of field behavior.

Decay functions for avoidance fields were investigated in [Zhu] for obstacles present on a straight path. When summing attractive and repulsive vector fields there is the possibility of guidance singularities, where magnitude and direction are equal and opposite. The presence of singularities were not addressed in [Wilhelm] and [Zhu], mentioned briefly in [16] and observed in [27]. For fixed wing UAVs the lack of guidance may prevent the UAV from avoiding an obstacle, while multi-rotor UAVs may end up in a trap situation. Singularities may be present at any location where a goal field and obstacle field are of equal strength.

— Transition to Vector Field —- - Such path following can be accomplished with vector fields which are a continuous source of guidance for converge to and following paths.

— Start of VF —

- Sujit compared vector field guidance to other guidance laws in [] and found that - robust against wind disturbances - Low cross track error

- VF produced for straight line and circular arc primitives in [Nelson] - Method expanded in [Griffiths] for VF following curved paths - Circular fields modified for standoff tracking in - frew - another - Wilehlm

- Standoff tracking of a moving ground target while avoiding obstacles was presented in [Wilhelm] - Fixed wing UAV tasked with tracking a moving ground target - Circular attractive vector field guided UAV to track ground target while compensating for ground target velocity - Repulsive vector field centered at obstacles and weighted by a hyperbolic tangent decay function - Fields summed together to produce a combined guidance - Two methods compared, Lyapunov and Goncalves - Goncalves lower tracking error due to accounting for time varying nature of target

- Activation / decay functions for obstacles were investigated in [Zhu]

- Singularities produced when summing together attractive and repulsive fields - mentioned in [nelson] "deadzones, sinks, singularities" - Observed in Panagou - Expected at any VF location where an attractive field and obstacle field are of equal strength

- VF use existing path planning methods to generate a guidance that minimizes distance to a path while also avoiding obstacles and singularities in obstacle fields —- Final Contribution —-

- UAS consists of vehicle, autopilot, ground station, radios
- Missions typically pre-planned on ground station where flyable and obstacle free paths can be generated. (Figure of conventional waypoints)
- Waypoints are sent to the autopilot over a radio and received and interpreted by the vehicles autopilot
- Autopilot responsible for navigating waypoints while maintaining vehicle stability
- Due to turn rate constraints or external disturbances, a vehicle may not follow the path perfectly where it may encounter an obstacle previously planned for
- Demonstrate the above with dubins
  - Introduce dubins as a way to approximate a UAVs dynamics, assume control working (cite)
  - Equations
  - Demonstrate Dubin's UAV not perfectly following path
  - Demonstrate Dubin's with wind not following path
- Reduced error for straight line and circular path following has been achieved by using vector field guidance (sujit)
- Continuous vectors that asymptotically converge and follow straight and circular paths are both robust and produce guidance that results in low cross track error
- Lyapunov VF primitives introduced (Nelson). Nelson stitched together primitives to produce complex paths

similar to navigating waypoints

- Curved path vector field was introduced in (griffiths)
- Goncalves VF
  - Path of any shape
  - Accounts for TV nature of paths
  - Field is produced by summing convergence and circulation terms that are easily accessable
  - Integral lines guaranteed to converge
- Obstacles considered in standoff tracking scenario Wilhelm
  - TV field loiter around moving ground target
  - obstacles represented by repulsive field
  - Did not consider or identify singularities present in summed fields
  - Singularities are small regions or wells of no guidance where UAV may be trapped
  - No information on how to go around obstacle
  - Field used as a high level specification for avoidance
  - Hyperbolic activation function
- Activation functions of obstacle avoidance investigated in Zhu
- Determining VF parameters that influence performance and singularity location

III. Methodology

A. Singularity Detection

- Present VF equations for straight path following
- Present VF equations for circular obstacle and obstacle definitions
  - Repulsion, small 'path' radius
  - Decay function
  - No circulation versus circulation (side by side figure)
- Sum fields together and show stages of normalization
- Identify pre normalization singularity
  - Surface plot (x,y,magnitude)
  - Identify undefined region and singularity (Evaluating entire space)
  - Find minimum of guidance function by evaluating several initial conditions
  - Method for finding all singularities as a reference to future look-ahead methods
- Look-ahead and singularity detection

- Location of all singularities not important if UAV is not going to encounter them
- Introduce UAV flight envelope
- Time, turn rate, constant velocity, produces possible locations of UAV
- Evaluate ICs on flight envelope when near obstacle

B. Modifying VF to avoid singularities

- Cause and location of singularities
  - Adding circulation to the repulsive obstacle field reduces /removes singularity
  - Singularities will occur where both fields have equal strength
  - Prediction of singularity location based on decay function
- Side by side repulsion and repulsion+circ singularity locations
- Singularity detected, modify field to remove singularity from flight envelope
- Objective function is:
  - Avoid obstacle
  - Avoid singularities
  - Minimize deviation from path

IV. Simulation

- Dubins UAV following a pre-planned straight path
- Obstacle encountered
- A guidance solution must be determined that:
  - Determines location of singularities if present (inside flight envelope)
  - Solve VF parameters to remove / mitigate singularities
  - Solve VF parameters that result in guidance that minimize error from path
- Various UAV speeds
- Worse case scenario presented (on path)
- Multiple obstacles on path (sequential)
- Compare non-modified guidance with modified guidance
  - Deviation from path
  - Yes/no obstacle avoided
  - singularity avoided in flight envelope

V. Conclusion

Appendix

Acknowledgments

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