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.

$$\chi^d(d) = \gamma - \frac{\pi}{2} - \tan^{-1}\left(k\frac{d-r}{r}\right) \tag{2}$$
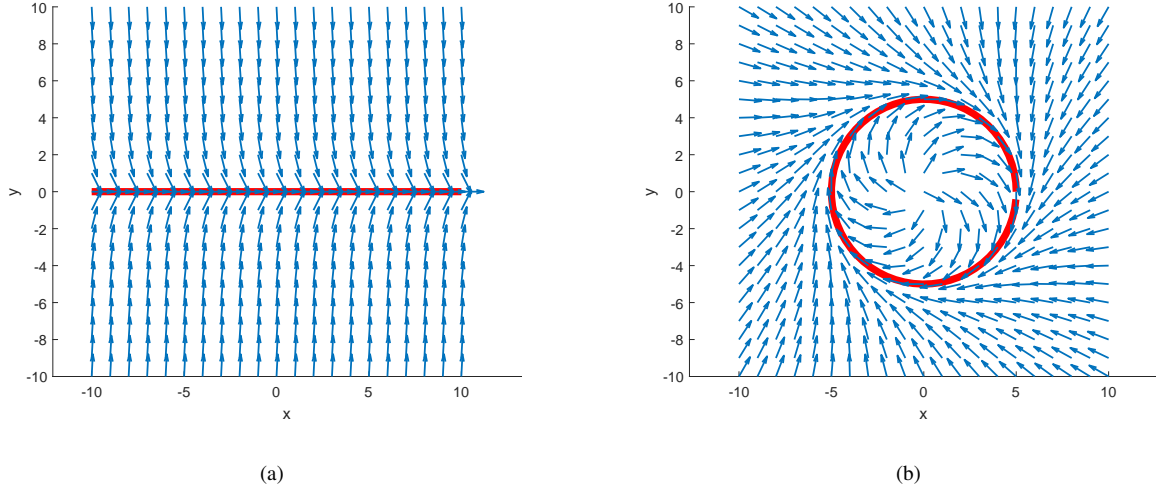
Fig. 2   Vector field converging and following a) straight path b) circular path

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 Gonvalves Vector Field (GVF) method produces a similar field, however has several advantages over LVFs. GVF produces an n-dimensional vector field that converges and circulates to both static and time varying paths. Additionally, convergence, circulation, and time-varying terms that make up the GVF are decoupled from each other allowing for easy weighting of the total field. GVFs converge and circulate at the intersection, or level set, of $n - 1$ dimensional implicit surfaces ($\alpha_i : \mathbb{R}^n \rightarrow \mathbb{R} | i = 1, ..., n - 1$). The integral lines of the field are guaranteed to converge and circulate the level set when two conditions are met: 1) they are positive definite and 2) have bounded derivatives. Consider the space with dimensions in set **q**:

$$\mathbf{q} = \left[x_1, x_2, ..., x_n \right] \tag{3}$$

The total vector field $\overrightarrow{V}$ is calculated by:

$$\overrightarrow{V} = G\nabla V + H \wedge_{i=1}^{n-1} \nabla_q \alpha_i - LM(\alpha)^{-1} a(\alpha) \tag{4}$$

or in component form:

$$\vec{V} = \vec{V}_{conv} + \vec{V}_{circ} + \vec{V}_{tv} \tag{5}$$

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where $\vec{V}_{conv}$ produces vectors perpendicular to the path, $\vec{V}_{circ}$ produces vectors parallel to the path, and $\vec{V}_{tv}$ is a feed-forward term that produces vectors accounting for a time varying path.

Convergence is calculated by:

$$\vec{V}_{conv} = G\nabla V \tag{6}$$

where scalar G is multiplied by the gradient of the definite potential function V:

$$V = -\sqrt{\alpha_1{}^2 + \alpha_2{}^2} \tag{7}$$

Circulation is calculated by taking the wedge product of the gradient:

$$\vec{V}_{circ} = \wedge_{i=1}^{n-1} \nabla_q \alpha_i \tag{8}$$

In the case of ($n = 3$) the wedge product simplifies as the cross product:

$$\vec{V}_{circ} = \nabla_q \alpha_1 \times \nabla_q \alpha_2 \tag{9}$$
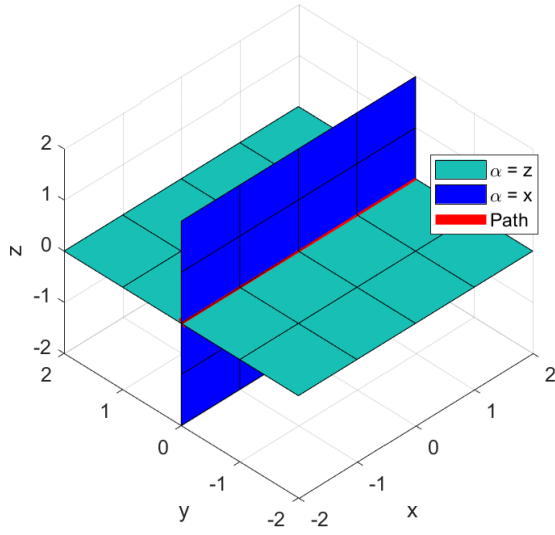
The feed-forward time-varying component is calculated by:

$$\vec{V}_{tv} = M^{-1} a \tag{10}$$

where,

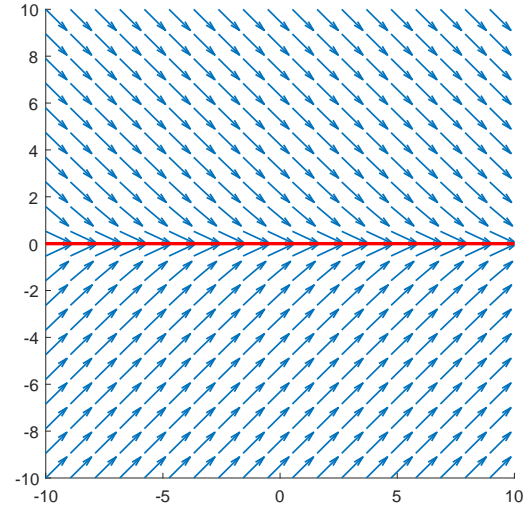$$M = \begin{bmatrix} \nabla \alpha_1^T \\ \nabla \alpha_2^T \\ (\nabla \alpha_1 \times \nabla \alpha_2)^T \end{bmatrix} \tag{11}$$

$$a = \begin{bmatrix} \frac{\partial \alpha_1}{\partial t} & \frac{\partial \alpha_2}{\partial t} & 0 \end{bmatrix}^T \tag{12}$$

Intersecting two flat planes ($\alpha_1 = z, \alpha_2 = x$) produces a GVF that converges and circulates a straight path, shown in Figure (). A circular path can be produced by intersecting a plane and a cylinder ($\alpha_1 = z, \alpha_2 = x^2 + y^2 - r^2$).
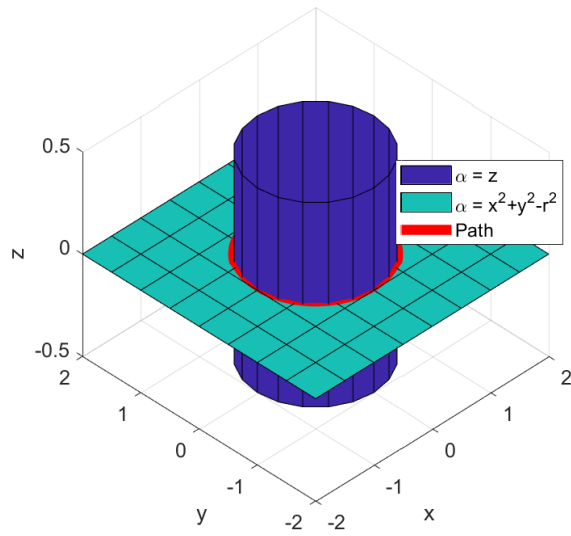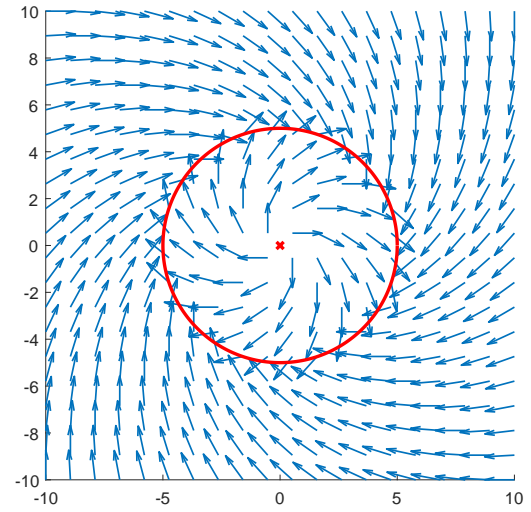
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Fig. 3   GVF converging and circulating straight path

Fig. 4   GVF converging and circulating circular path

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.

III. Conclusion

Appendix

Acknowledgments

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