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

VF = Vector Field

II. Introduction

- Introduction / literature review

Unmanned Aerial Vehicles typically move through the environment by navigating a series of pre-planned and off-line generated waypoints. An on-board guidance system typically generates a desired heading based on the current active waypoint and the current position of the UAV. Once the UAV breaches the radius of the waypoint, guidance transitions to the proceeding waypoint. During waypoint navigation the UAV may encounter a previously unknown obstacle or change in the environment which may require a new obstacle free series of waypoints be generated. Dynamic environments may require frequent waypoint re-planning which may be difficult or impossible if communication with the ground station responsible for waypoint generation is lost.

(More information on path planning)

Potential field models a robot's workspace as a gradient potential of attractive and repulsive artificial forces [k].

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— Path planning and waypoint navigation —-

- Path that meets mission requirements - Conventionally build from straight lines connecting waypoints - Guidance algorithm direct the UAV towards the waypoint and switches once within a pre-determined range to the next waypoint

- The UAV is not guaranteed to follow the path connecting waypoints perfectly, therefore more detailed paths require a more dense clustering of waypoints

[Figure] - Sketch of waypoints, UAV following waypoints, Obstacle with waypoints placed closely together to form path around obstacle

- Transition into potential field methods

— Potential Field Methods —-

Potential field combines path planning, trajectory planning, and control into a single process [] and is based on the principle of artificial attractive and repulsive forces [katib]. A robot at an initially high potential is pulled towards a goal located at a globally minimum potential while being repelled by obstacles in close proximity by repulsive forces. Major drawbacks to potential field were pointed out in [k and b] consisting of local minimum and oscillations in corridors. The local minima problem occurs when closely spaced obstacles potential combine to produce a well on the descent gradient where a pre-mature stable point is found.

- Potential field is a method based on a gradient descent - Start at a high potential - End in a stable low potential - Obstacle represented by high potentials

- Potential field combines path planning, trajectory planning, and control into a single process - pointed out in []

- And has been used as the means for path planning in - List potential field papers

- Major drawbacks to potential field is the likely encounter of local minima, oscilations, etc [KandB]. - Solutions to local minima

- Object clustering (thesis document) - Navigation functions (thesis document)

and oscillations - Tang (Novel potential field method) - Li (An Efficient Improved APF based regression search method for robot path planning)

- The potential field methods discussed converge to a singular point which is not possible for fixed wing aircraft. The potential field could be calculated for each waypoint, however for certain UAV applications such as following a curved ground track or surveying it may be beneficial to follow an explicit path.

— 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