Rendezvous Mission Risk Reduction Through Passive Safety Analysis

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Outline

Introduction

Funding for this research has been provided by NASA JPL for support of the **Ne**xt **M**ars **O**rbiter (NeMO) mission for Mars sample return terminal rendezvous.

Rendezvous History

Dozens of spacecraft have performed orbital rendezvous.
Three have experienced failures.

Gemini	Apollo	Soyuz	STS
ETS-VII	Progress	XSS-10	Rosetta
DART	SPHERES	Orbital Express	ATV
HTV	PRISMA	Dragon	ANGELS
AeroCube-7b/c	Cygnus	Dream Chaser*	CPOD*

**Spacecraft have been built but not flown*

Current State

An increasing number of missions require orbital rendezvous.

- Satellite servicing
- Active debris mitigation
- In-space manufacturing
- Cargo & crew resupply
- **Sample capture**

Problem

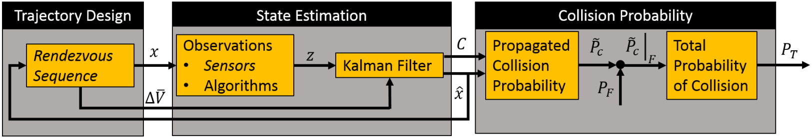
Evaluating the probability of collision of rendezvous mission concepts provides four immediate and important applications

A passive safety analysis allows mission designers and project managers to:

- **Evaluate and compare of mission design concepts**
- Determine of fault protection abort response types
- Create of hardware reliability requirements
- Balance mission risk against mission cost

Calculating Rendezvous Collision Probability

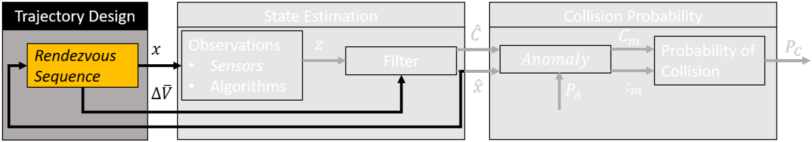
The total collision probability for a rendezvous mission involves an understanding of trajectory design, state estimation, and collision probability calculations



x	True state	$\tilde{P}_c(t_j)$	Propagated probability of collision
z	Observed state	P_F	Probability of fault occurring
$\hat{x}$	Estimated state	P_T	Total probability of collision
C	Estimate covariance	$\Delta\bar{V}$	Planned maneuver

Dynamics Model

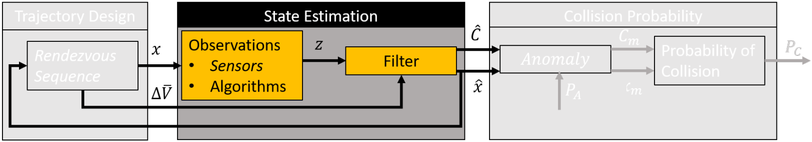
The chosen trajectory determines the nominal relative position and velocity from the target vehicle



x	True state	$\Delta\bar{V}$	Planned maneuver

State Estimation

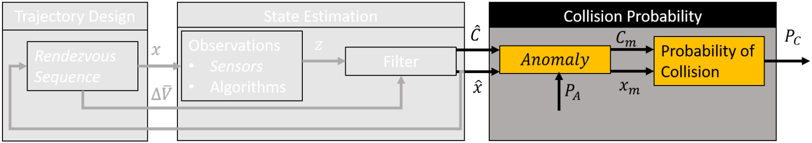
State Estimation methods affect the state uncertainty and the distribution of potential trajectories following a fault



x	True state	$\Delta\bar{V}$	Planned maneuver
z	State observation	$\hat{x}$	State Estimate
C	Estimate covariance		

Probability of Collision

The method chosen to calculate the probability of collision can affect the final value and alter the perceived level of mission risk.



$\hat{x}$	Estimated state	P_{ct}	Passively Safe probability of collision
C	Estimate covariance	P_F	Probability of fault occurring
		P_T	Total probability of collision

Propagated Collision Probability

The probability of collision for a given trajectory can be approximated by a single covariance at the point of maximum instantaneous collision probability.

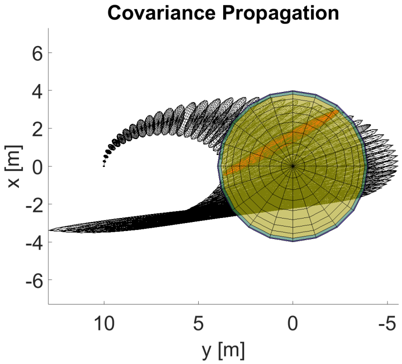


Figure 1: Trajectory beginning at 10m showing the expansion of the covariance along the trajectory.

Total Probability

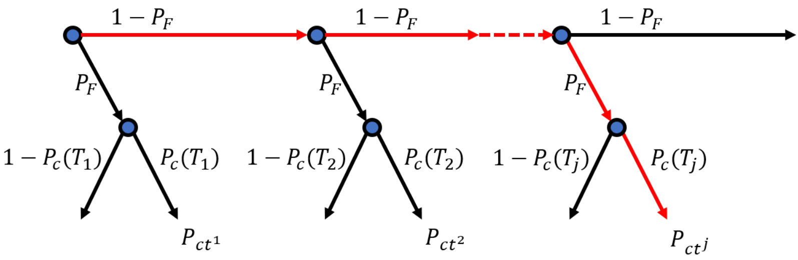


Figure 2: Collision probability tree highlighting an example fault at time t^j

$$\tilde{P}_c(t_j)|_F = P_F P_c(t_j)(1 - P_F)^{(j-1)}$$

$$P_T = 1 - \Pi_{j=1}^{n}(1 - \tilde{P}_c(t_j)|_F)$$

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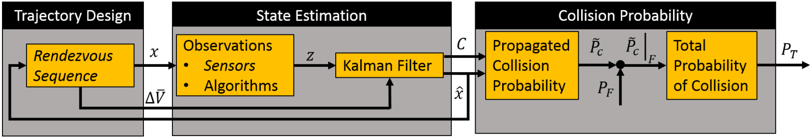

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Baseline Rendezvous Trajectories

Common rendezvous trajectories are [1]:

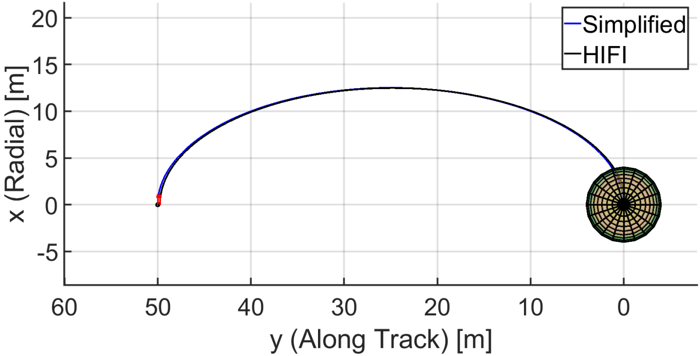
- Ballistic trajectory
- Two-phase approach
  - V-bar transfer hops with radial impulses
  - Straight-line transfer along the V-bar

Parameter Trade Studies

- Number of V-bar transfer hops
- V-bar transfer hops to straight-line approach transition point

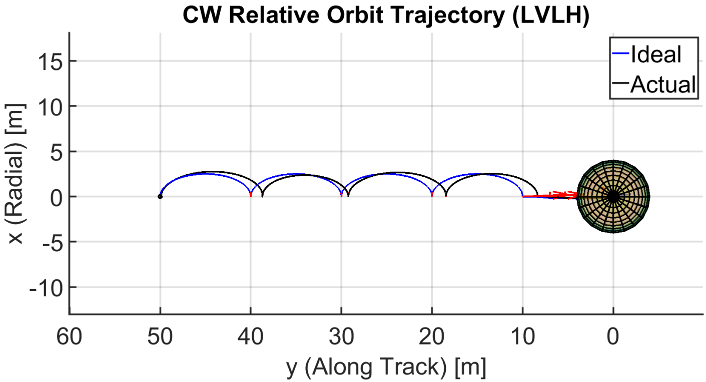
Ballistic Trajectory

The simplified model follows the High Fidelity model closely for the ballistic trajectory.



Two-phase Trajectory

The High fidelity and simplified model are consistent but additional maneuvers can result in additional error



Number of Tangential impulse Hops

Increasing the number of hops decreases the total collision probability until the penultimate last hop encounters the combined hardbody.

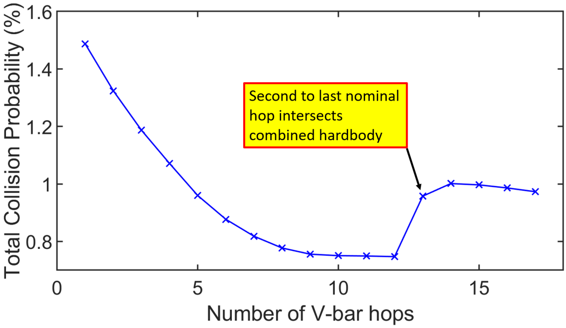


Figure 3: Total rendezvous collision probability for increasing number of V-bar hops.

V-bar / Linear Transition

There is little to no difference between an entirely straight line approach and a two-phase approach that ends further than 10 m from the origin.

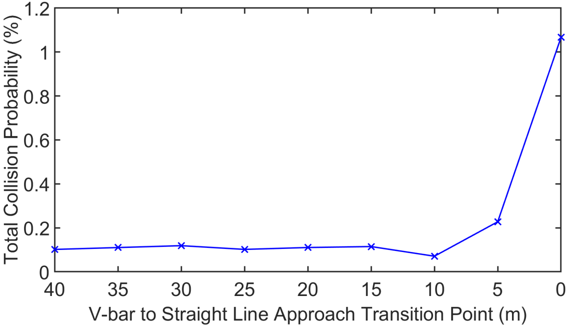


Figure 4: Total rendezvous collision probability as a function of the transition point from four V-bar hops to a straight-line approach.

Conclusion

Summary of Results

To be passively safe, a rendezvous mission should spend as little **time** in the active abort region as possible.

Trajectories that are passively safe can reduce the probability of collision if they reduce the time spent on a nominal intercept trajectory.

Contributions to the State of the Art

This research extends the state of the art through the creation of a modular **total rendezvous collision probability estimator** with elements for:

1. Rendezvous mission maneuver planning
2. Relative state estimation
3. Collision probability determination

Potential uses include:

- **Design trade study analysis**
- On-board fault protection mode transition indicator
- System requirements validation

References I

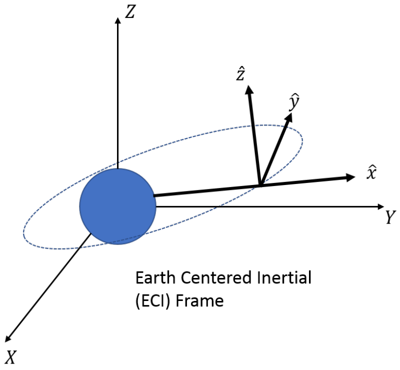
W. Fehse, "Approach safety and collision avoidance," in *Automated Rendezvous and Docking of Spacecraft*, pp. 76–111, 2003.

G. W. Hill, "Researches in Lunar Theory," *American Journal of Mathematics1*, vol. 1, no. 1, pp. 5–26, 1878.

The lvlh Frame

The reference frame of interest in relative dynamics is known as the local vertical, local horizontal (lvlh) reference frame*.

- Orbital radial vector[$\hat{x}$]
- Orbital angular momentum vector [$\hat{z}$]
- Vector completing the right handed triad [$\hat{y}$]



**Also known as Hill's frame [2], RIC, and RSW frames*

High fidelity & simplified models

Two models were created to evaluate passive safety.

- A simplified model takes advantage of simplifying assumptions to create the desired trajectory and to introduce repeatability.
- A high-fidelity model is used to validate the simplified model and provide more accurate insight into a specific rendezvous scenario.

	Simplified Model	**High-Fidelity Model**
Propagation	CW	Nonlinear + J2 Perturbation
Filter	Linear Kalman Filter	Unscented Kalman Filter
Maneuvers	From True state	From state estimate

State Observation Sensors

Program/ project	Narrow Angle Vis	Wide Angle Vis	IR	LIDAR	Video Guidance Sensor	Laser Range Finder
CPOD	X	X	X			
Orbital Express	X	X	X		X	X
PRISMA	X	X				
ATV			X	X	X	X
Cygnus			X	X		
Dragon			X	X		
HTV					X	X

Assumptions

1. Chief is in near circular orbit - CW motion dominates between state observations
2. Chief is observable
3. Process noise is small
4. Maneuvers occur at designated time
5. Maneuvers are impulsive
6. State observation frequency is higher than maneuver frequency
7. Instantaneous collision probability at time of predicted closest approach* is representative of trajectory collision probability.

*Closest approach defined by ratio of line of sight distance to probability distribution along the line of sight.

Chief Orbit

	Central Body	Mars
a	semi-major axis	50 m
e	eccentricity	0 m
i	inclination	$0\,\mathrm{deg}$
$J2$	J2 spherical harmonic	1960.45e-6

Instantaneous Probability Location

The Method of Approximate Distributions (MAD) and the line of sight projection distance (D_p) are the best indicators of maximum collision probability.

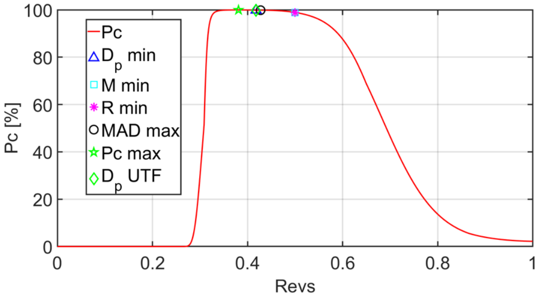


Figure 5: Instantaneous collision probability and collision probability indicators corresponding to the trajectory and covariance ellipsoids in figure 1.

Ballistic Trajectory parameters

y_0	Initial hold position	50 m
a_r	V-bar relative semi-major axis	5 m
x_r	V-bar center of motion	0 m
$y*$	phase transition range	10m
σ_m	Maneuver magnitude error	1.5%
σ_p	Maneuver pointing error	1.5%
P_A	Probability of anomaly	1/30 revs
P_T	Total Collision Probability	1.48%
ΔV_T	Total Delta V	10.68 mm/s
$\#\Delta V$	Number of impulses	1
Δt	Elapsed time	55 min

Two-phase Trajectory parameters

y_0	Initial hold position	50 m
a_r	V-bar relative semi-major axis	5 m
x_r	V-bar center of motion	0 m
$y*$	phase transition range	10m
σ_m	Maneuver magnitude error	1.5%
σ_p	Maneuver pointing error	1.5%
P_A	Probability of anomaly	1/30 revs
P_T	Total Collision Probability	0.07%
ΔV_T	Total Delta V	78.36 mm/s
$\#\Delta V$	Number of impulses	7
Δt	Elapsed time	249 min