Bearings-Only Guidance and Navigation for In-Orbit Rendezvous

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Overview

- **Background & Motivation**
  - Rendezvous
  - Bearings-Only Rendezvous

- **Main Bearings-Only Challenges**
  - Bearings-Only Observability impact on GNC

- **Research Outputs**
  - Theoretical tools to design better GNC systems for Bearings-Only Rendezvous

- **Summary & Conclusions**
Background & Motivation
In-Orbit Rendezvous

- Technology to allow a chaser spacecraft reach a target
- Key technology for many space missions:
  - Mature technology (MIR, ISS, Apollo, Shuttle, ATV)
  - Generally requires complex/bulky hardware to measure the relative range
Rendezvous Sensors

- Line-of-sight angles + Range measurements to the target

- Existing Sensor Technologies:
  - Optical (Camera, LIDAR, FLASH LIDAR, etc.)
  - RF (RF interferometry, RADAR, Tracking RADAR, etc.)
  - Global Navigation Satellite Systems (GPS/Relative GPS, etc)

- Range measured by time-of-flight of repeated/reflected signal
  - Stereo vision / relative target size only works at short ranges
  - GNSS only with Earth-based cooperative satellites

- Ranging **non-cooperative** targets requires skin tracking sensors (LI/RA-DAR)
  - Prohibiting when available power is limited (Reflection power $\propto 1/\text{range}^4$)
Optical Cameras

- Optical Cameras rely on external illumination (low power consumption)
  - Close Range: Full relative position and attitude by tracking independent features.
  - Medium Range: Estimate range from known size of the target.
  - Far Range: Target is visible as a dot (no range information).

Bearings-only Navigation (no range measurement)
Range can be estimated by “triangulation” using:
- Several angular measurements (time stamped)
- Knowledge of calibrated maneuvers
- Using the relative motion dynamics

Range is only observable in the presence of known maneuvers
Motivation for Bearings-Only Rendezvous:
- Enable automatic rendezvous with non-cooperative targets
- Simplification of required (power hungry & heavy) relative navigation hardware
- Provide a back-up strategy for contingency cases (ranging not operational)

Many missions and studies have suggested its use for the far/medium range:
- Active Debris Removal (non-cooperative targets)
- Mars Sample Return (reduce sample container mass)

ARGON (PRISMA) successfully demonstrated concept
- Ground in-the-loop navigation & maneuver planning
- Identified needs for improvement in the theoretical tools to optimize navigation (due to poor navigation performance results)
Main Bearings-Only Challenges
Bearings-Only Challenges

- Several “engineering” challenges identified (refer to [6])

Example: Target **Visibility** due to illumination conditions
  - Orbital illumination periods (Eclipses).
  - Illumination incidence & phase angles.
  - Target surface properties & geometry.
  - Sensor blinding due to Sun, Moon & Planetary Albedo.

Measurements available only ~1/4 orbit (worst case, in LEO)

- More intrinsic “theoretical” challenges due to range “**observability**”
  - Great potential for improvement!
Range Unobservability

- Range (along LOS direction) is **unobservable** with angle measurements alone
  - Scaled versions of any trajectory produce **identical** angular measurement profiles

⇒ Range ambiguity can not be resolved

**Fig. 1 Type One Impulsive Unobservable Maneuver**

**Fig. 2 Type Two Impulsive Unobservable Maneuver**

**Fig. 3 Type Three Impulsive Unobservable Maneuver**
Maneuvers produce non-scaled trajectories

- Different measurement profiles (range ambiguity can be resolved)

★ There are “Unobservable” maneuvers (produce scaled trajectories)
Navigation Filters

- A Navigation Filter continuously provides a position/velocity estimate
  - Bearing-only: error along LOS direction (can not be improved)
  - Maneuver applied: range estimate can be improved

Navigation performance depends on maneuvers \(\Rightarrow\) coupling in the trajectory design!
Research Outputs
Research Outputs

- Rigorous non-linear observability analysis (Ref [2])
  - Enables the computation of the unobservable maneuver sets (impulsive & low thrust)

- Theoretically founded measure for observability (Ref [3])
  - Its simple form enables observability optimization to enhance navigation
  - Closed-form solution for optimal observability maneuvers

- RdV trajectory optimization enhancing bearings-only navigation (Ref [5])
  - Trade-off study (observability vs. fuel)
  - On-line guidance that achieves RdV while improving navigation performance

- A non-linear (Pseudo-Measurement) bearings-only navigation filter (Ref [4])
  - Advantages in estimate convergence when operating far from the true
Bearings-Only Observability

Optimal Observability

Rendezvous Trajectory Optimization

Non-Linear Navigation Filter
Unobservable Maneuvers

- Find maneuver sets creating scaled trajectories

Three Dimensional Trajectory

- Only under tight conditions (but some may occur during an approach)
  - Guidance must avoid these maneuvers
Bearings-Only Observability

Optimal Observability

Rendezvous Trajectory Optimization

Non-Linear Navigation Filter
Optimal Observability

- Maximizing “trajectory difference” $\Rightarrow$ different measurement profiles
  $\Rightarrow$ Maximum observability (Ref [3])

- Simple, theoretically-based “measure” of observability
  - Trend predictor of navigation performance
  $\Rightarrow$ Objective function enabling observability optimization

- Bearings-only observability is a function of:
  - Maneuver size and direction ($u$)
  - Position in the relative trajectory where the maneuver is performed (ICs)
  - Future time when observability is to be evaluated (time dependent!)
  $\diamond$ Maneuver type and target orbit define equations (non-optimizable)
Bearings-Only Observability

Optimal Observability

Rendezvous Trajectory Optimization

Non-Linear Navigation Filter
Off-Line Trajectory Optimization

- A complete trajectory optimization using optimal observability function
  - Multi-objective optimization: fuel + observability
  - Discrete transcription demanding observability all along the trajectory

- Mission example: RdV from ~100 km to 1km in front of target (LEO, T~90 min)
  - Fuel vs. Observability trade-off study

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Bearings-Only Guidance and Navigation for In-Orbit Rendezvous
Navigation Performance (OL)

“Open-loop” Monte-Carlo simulations for navigation performance verification:

- Higher Observability ➞ faster convergence (Improved navigation)

![Diagram showing the process of navigation performance](image)

Sample 1–σ Navigation Errors

- 0.00 Obs Weight
- 0.40 Obs Weight
- 0.85 Obs Weight

Fuel vs. Norm of 1–σ Navigation Errors

- \(\Delta V \text{ [m/s]}\)
- Navigation Errors [m]
Closed Loop Guidance

- On-Line optimization inside the simulation loop:
  - Re-optimizes on-line demanding observability only when navigation errors are large
Navigation Performance (CL)

- **Mean Monte Carlo navigation performance**

  ![Absolute Navigation Uncertainty](image1)

  ![Fuel vs. Navigation (trade-off)](image2)

  - **Increased Observability ➔ Faster Filter Convergence:**
    - Decrease in overall navigation errors
    - Decrease in navigation errors at arrival
Bearings-Only Observability

Optimal Observability

Rendezvous Trajectory Optimization

Non-Linear Navigation Filter
Navigation Filter Issues

- Navigation estimate diverges when no maneuvers are executed

\[\text{Range Dispersions (1\sigma)}\]

- Particular problem for rendezvous (long periods without maneuvers)

- Traditional filters (EKF) not effective when far from their linearization point!

- A Non-linear filter:
  - More robust to initialization errors
  - Successfully re-converge when a maneuver is applied after estimate divergence

- Non-Linear Bearings-Only Navigation Filter (Optimal):
  - Pseudo-Measurements: equation re-arranged to be linear w.r.t. states.
  - Dedicated filter structure assuming a Gaussian estimate (more details in [5])
Non-Linear Filter Performance

- Filter comparison simulation

- Initial navigation errors ~3%, ~5%, ~60%, maneuver after 0.5 orbits:

Bearings-Only Guidance and Navigation for In-Orbit Rendezvous
Summary & Conclusions
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- Observability of Bearings-Only navigation poses several theoretical challenges
  - Maneuvers are needed for range observability (not all provide observability)
  - Navigation performance (range) depends on maneuvers performed
  - Navigation estimate divergence (filter reliability issues)
  - Intrinsic coupling of Bearings-Only Navigation and Guidance

- Several contributions to improve the observability-related issues
  - Comprehensive Observability analysis (unobservable maneuvers)
  - Simple measure of observability (enabling observability optimization)
  - Closed form optimal observability maneuvers (to improve navigation)
  - Complete Rendezvous trajectory optimization enhancing navigation (full trajectory)
  - Non-Linear Bearings-Only navigation filter (immune to estimate divergence issues)
Thank you for your attention!

Further details? Email: jonathan.grzymisch@ifr.uni-stuttgart.de

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Additional Information on RdV Sensors
**Not Suitable for Un-Cooperative Targets**

- AGPS and RGPS limited by multipath and shadowing effects
- Absolute GPS w. S/A
- Absolute GPS w/o S/A
- Relative GPS
- Radar
- Camera Type Sensor
- Laser Range Finder

**Only remaining option for non-cooperative targets**

- => Not suitable if available power is limited!