Bearings-Only Guidance and Navigation for In-Orbit Rendezvous

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by

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Acronyms and Abbreviations

2D	Two-Dimensions
3D	Three-Dimensions
ADR	Active Debris Removal
ARE	Algebraic Riccati Equation
ARGON	Advanced Rendezvous Demonstration using GPS and Optical Navigation
ATV	Automated Transfer Vehicle
BCs	Boundary Conditions
CPU	Central Processing Unit
CW	Clohessy-Wiltshire
DEOS	DEutsche Orbitale Servicing
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
EKF	Extended Kalman Filter
ESA	European Space Agency
FIM	Fisher Information Matrix
GAs	Genetic Algorithms
GEO	Geo-Stationary Orbit
GNC	Guidance, Navigation and Control
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HARVD	High Integrity Autonomous Rendezvous & Docking Control System
ICs	Initial Conditions
ISS	International Space Station

J2	Second Tesseral Harmonic
KKT	Karush-Kuhn-Tucker
LEO	Low Earth Orbit
LHS	Left Hand Side
LIDAR	Laser RADAR
LOS	Line-of-Sight
LP	Linear Programming
MPC	Model Predictive Control
MSR	Mars Sample Return
NPI	Networking/Partnering Initiative
OTV	Orbital Transfer Vehicle
PBH	Popov-Belevitch-Hautus
PDF	Probability Density Function
PMF	Pseudo-Measurement Filter
PRISMA	Prototype Research Instruments and Space Mission Technology Advancement (Swedish technology demonstrator)
QP	Quadratic Programming
RADAR	Radio Detection And Ranging
RF	Radio Frequency
RHS	Right Hand Side
RK4	Fourth Order Runge-Kutta
SLAM	Simultaneous Localization and Mapping
SQP	Sequential Quadratic Programming
TAS	Thales Alenia Space
UAV	Unmanned Aerial Vehicle
UKF	Unscented Kalman Filter
VBS	Vision-Based Sensor

Mathematical Nomenclature

α, w	Arbitrary constant
A	Linear constraint matrix
B	System input selector matrix
$\mathbf{b}$	Linear constraint values
$\boldsymbol{\epsilon}$	Measurement noise vector
$\mathbf{F}$	Linear objective Gradient
G	Particular solution for the system inputs
G_r	Position-related portion of G
G_i	Particular solution for impulsive maneuvers
G_c	Particular solution for constant thrust maneuvers
$\mathbf{h}(\mathbf{x})$	Measurement equation
I	Identity matrix
J	Optimization objective function
J_f	Fuel objective function
J_o	Observability objective function
$\mathcal{H}$	Quadratic objective Hessian
$H(\mathbf{y})$	Linear measurement matrix with respect to the states
H_r	Position related portion of the linear measurement matrix
Φ	State transition matrix
Φ_s	Position-related portion of Φ
$\mathbf{s}_i$	Slack variable at time step i
T	Orbital period
ΔT	Discretization time step
t	Time after a maneuver
θ, ϕ	Azimuth and elevation measurement angles
$\delta\theta, \delta\phi$	Azimuth and elevation measurement noise
$\mathbf{U}$	Vector of maneuvers along the discretized trajectory
$\mathbf{u}(\mathbf{t})$	Maneuver input
$\mathbf{u}_i$	Vector of maneuver magnitudes/directions at time step i

ω	Orbital rate of the target
$\mathbf{X}$	Vector of states along the discretized trajectory
$\mathbf{x}_i$	State vector at time step i
$\mathbf{x}_m$	State vector at the time of a maneuver
$\mathbf{Y}$	Optimization decision vector
$\mathbf{y}_i$	Measurement vector at time step i
$\bar{\mathbf{y}}_i$	Measurement vector at time i without maneuvers
x, y, z	Cartesian components of the relative position

Notes:

Vector quantities are written in **bold**.

Matrices are defined with square brackets $[\cdot]$

Parentheses $(\cdot)$ divide mathematical expressions

Abstract

In-orbit rendezvous is a key enabling technology for many space missions that already enjoys significant heritage. Nevertheless, skin tracking sensors are required to measure the relative range when the target is non-cooperative. These sensors, such as RADAR or LIDAR, require high power to operate at long distances. Since bearing (angular) measurements can be acquired using simple sensors such as a single optical camera, bearings-only rendezvous would significantly reduce the mass and power requirements for these missions. Nevertheless, several challenges arise from the lack of a direct range measurement, which renders the navigation problem instantaneously unobservable. This was first identified in the Naval and Military literature, where it was established that the execution of known maneuvers is necessary to introduce observability to the estimation problem. This results in an intrinsic coupling between the guidance and navigation design, as the guidance inputs determine the achievable navigation performance. In the context of space rendezvous, these issues surrounding bearings-only observability have only been treated from a navigation perspective. However, little research has been performed treating the impact of observability on the rendezvous trajectory design and overall Guidance, Navigation and Control (GNC) architecture.

This thesis addresses the main issues surrounding bearings-only observability from first principles, building a framework that yields a complete GNC solution for bearings-only rendezvous. Specifically, it develops new theoretical observability analysis and optimization tools in a simple, yet mathematically rigorous manner. Arising all from a common framework, these tools allow to find the sets of unobservable maneuvers that should be avoided during a rendezvous, and yield closed form solutions for optimal observability maneuvers on any given trajectory. In addition, the simplicity of the resulting expressions enables the integration of observability optimization within the complete rendezvous trajectory design. This yields an optimal rendezvous guidance scheme that guarantees observable trajectories, enhancing bearings-only navigation performance and targeting dispersions. In addition, a dedicated non-linear navigation filter is derived from the same theoretical framework, mitigating some of the estimate divergence issues that can arise in traditional filters due to instantaneous range

unobservability. All these contributions address the main GNC issues arising from the inherent unobservability of the bearings-only navigation problem, bringing the state of the art one step closer to a fully autonomous in-orbit bearings-only rendezvous mission.

Kurzfassung

Rendezvous im Orbit ist eine Schlüsseltechnologie für viele Raumfahrtmissionen, deren Machbarkeit bereits mehrfach demonstriert wurde. Allerdings werden bisher Sensoren benötigt die die Entfernung messen, falls das Ziel nicht kooperativ ist. Solche Sensoren wie z.B. RADAR oder LIDAR haben einen hohen Energieverbrauch wenn sie in großer Distanz betrieben werden. Da reine Richtungsmessungen auch von einfachen Sensoren wie optischen Monokameras geliefert werden können, würde deren Verwendung signifikant die Anforderungen dieser Missionen in Hinsicht auf Masse und Leistung verringern. Leider entstehen durch die fehlende Entfernungsmessung einige Probleme, welche dazu führen, dass die Navigationslösung nicht mehr direkt beobachtbar wird. Dies wurde erstmalig in der Marine- und Militärliteratur erwähnt, wo gezeigt wurde, dass bekannte Manöver nötig sind um Beobachtbarkeit zu erhalten. Daraus resultiert jedoch eine direkte Kopplung zwischen Bahnplanungs- und Navigationsentwurf, da die Bahnplanung die erreichbare Navigationsgüte beeinflussen kann. Bei Raumfahrtmissionen wurden diese Probleme jedoch bisher nur aus der Sicht der Navigation behandelt. Bisher wurde wenig Forschungsaufwand getrieben, um den Einfluss der Beobachtbarkeit auf den Entwurf der Anflugtrajektorie und allgemein auf die Architektur des Lenk- und Regelungssystems zu untersuchen.

Diese Arbeit behandelt die Hauptprobleme der Beobachtbarkeit bei Verwendung von Richtungsmessungen. Beginnend bei den grundlegenden Prinzipien wird ein Verfahren für die Lenkung und Navigation für Rendezvous mit Richtungsmessungen entwickelt. Hierzu wird die theoretische Grundlage für eine nichtlineare Beobachtbarkeitsanalyse und Optimierung gelegt, die in den Entwurf der Anflugtrajektorie integriert werden kann. Dies liefert eine optimale Bahnplanung, die beobachtbare Trajektorien liefert, die Navigationsgüte verbessert und Abweichungen während des Rendezvous reduziert. Zusätzlich wird ein nichtlinearer Navigationsfilter auf der gleichen theoretischen Basis hergeleitet, der die Einflüsse auf den Schätzfehler gegenüber traditionellen Filtern verbessert. Alle diese Beiträge dienen dazu, die Probleme im GNC zu behandeln, die durch die fehlende Beobachtbarkeit bei reinen Richtungsmessungen entstehen können. Dadurch wird der aktuelle Stand der Wissenschaft weitergebracht in Richtung einer

vollautonomen Rendezvousmission im Orbit mit Richtungsmessungen.