Onboard Maneuver Planning for the Autonomous Vision Approach Navigation and Target Identification (AVANTI) experiment within the DLR FireBird mission

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Workshop on Advances in Space Rendezvous Guidance
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Overall Concept of the MAneuver Planner (MAP)

The Guidance Problem

The Computation of the Maneuvers

Example of a Rendezvous

Conclusions and Current Development Status
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The FireBird Mission

- DLR Scientific Mission, based on BIRD-TET s/c bus
- Expected launch: late 2014/early 2015
- Orbit: Sun-synchronous, altitude 500-600 km
- Primary Objective: Earth observation, fire detection (infrared camera)
- Secondary Objectives: several scientific experiments

- **Autonomous Vision Approach Navigation and Target Identification (AVANTI)**
  - demonstration of autonomous rendezvous to (and departure from) non-cooperative client using vision-based navigation
  - 1 month of experiment campaign after in-orbit injection of a Picosat
AVANTI motivations

- **AVANTI is motivated by the following needs**
  - approach, identify, rendezvous with a
  - non-cooperative, passive client
  - from large distances (e.g., > 10 km)
  - in an autonomous, fuel efficient, safe manner

- **Angles-only navigation is an attractive solution**
  - low cost sensors (e.g., optical, infrared)
  - star trackers often onboard (e.g., Biros!)
  - simplicity, robustness, wide range

- but maneuvers are needed to reconstruct the relative state
AVANTI key functionalities

Key functions to be proven

- handover from ground-operations to autonomous vision-based navigation & control
- onboard processing of camera images and target identification
- real-time relative navigation based on Line-Of-Sight (LOS) info
- autonomous maneuver planning to accomplish a rendezvous (RdV)

Key performance to be proven

- LOS residuals below 40 arcsecs (half camera pixel size)
- relative orbit determination accuracy at 10% of range to client
- safe rendezvous operations between ±10 km and ±100 m
Background

- **August 2011, PRISMA - handover to OHB:** Formation Re-Acquisition
  - ground-in-the-loop, TLE + prototype of angles-only relative navigation filter

- **April 2012, PRISMA - extended mission phase:** ARGON
  Advanced Rendezvous Demonstration using GPS and Optical Navigation
  - ground-in-the-loop, image processing, angles-only relative navigation
  - man-in-the-loop, maneuver planning

- **AVANTI new challenges**
  - onboard processing of camera images and identification of Picosat
  - real-time relative navigation of Biros w.r.t. Picosat based on LOS info
  - autonomous maneuver planning
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MAP objectives

- Generation of the open-loop, impulsive maneuvers’ profile to accomplish a rendezvous (RdV)

- Operational conditions
  - delta-v budget: fuel efficiency
  - safety: safe approach during RdV
  - system requirements: time constraints to cope with
    - communication/power/thermal pointing requirements
    - thrusters’ alignment

- Autonomy
  - simplicity, preference to closed-form solutions
Overall Concept - 1

Relative Orbital Elements (ROE) as state variables

\[ \delta \alpha = \{ \delta a, \delta \lambda, \delta e_x, \delta e_y, \delta i_x, \delta i_y \}^T \]

\[ P = a \delta \alpha \quad \text{description of each possible configuration} \]

\[
\delta \alpha = \begin{pmatrix}
\delta a \\
\delta \lambda \\
\delta e_x \\
\delta e_y \\
\delta i_x \\
\delta i_y
\end{pmatrix}
= \begin{pmatrix}
\delta a \\
\delta \lambda \\
\delta e \cos \varphi \\
\delta e \sin \varphi \\
\delta i \cos \theta \\
\delta i \sin \theta
\end{pmatrix}
= \begin{pmatrix}
\frac{(a - a_d)}{a_d} \\
u - u_d + (\Omega - \Omega_d) \cos i_d \\
\frac{(a - a_d)}{a_d} e \cos \omega - e_d \cos \omega_d \\
\frac{(a - a_d)}{a_d} e \sin \omega - e_d \sin \omega_d \\
i - i_d \\
(\Omega - \Omega_d) \sin i_d
\end{pmatrix}
\]

\( a, e, i, \Omega, \) and \( M \): Keplerian elements \( u \) mean argument of latitude

“d” servicer satellite
ROE meaning and dynamics

Linearized motion + disturbances

\[
\begin{pmatrix}
\delta \dot{a} \\
\delta \alpha
\end{pmatrix}
= \Phi(t - t_0)
\begin{pmatrix}
\delta \dot{a} \\
\delta \alpha
\end{pmatrix}
\]

\[
\Phi(t - t_0)
= \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
\Delta t & 1 & 0 & 0 & 0 & 0 & 0 \\
\frac{\nu}{2} \Delta t^2 & \nu \Delta t & 1 & 0 & 0 & \mu \Delta t & 0 \\
0 & 0 & 0 & 1 & -\dot{\phi} \Delta t & 0 & 0 \\
0 & 0 & 0 & \phi \Delta t & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & \lambda \Delta t & 1
\end{bmatrix}
\]

differential drag | mean $J_2$
Overall Concept - 2

- ROE as state variables

- Layered approach
  - RdV defined as $P_0 \rightarrow P_F$ through intermediate $P_i$
  - $i$-th times: solution of the scheduling problem in compliance with time constraints
  - $P_i$ at $i$-th times computed to optimize a criterion
  - MAP operatives modes:
    - set a criterion, evaluation of the relevance of some operational conditions
    - computation of the maneuvers to establish the $P_i$
Architecture

Input:
\[ y_0, (P,t)_0, (P,t)_F, \text{ Mode} \]

Guidance
(Scheduling, Planning, Safety)

Control
(Maneuvers placement)

Maneuvers’ profile

Time constraints

Forbidden time intervals
Minimum time to first maneuver
Minimum time spacing between maneuvers
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ROE sets planning: problem statement - 1

- Evolution of the motion through $\Phi(\Delta t)$, effect of the maneuvers at $t_i$: discontinuities in ROE

$\begin{align*}
P_1 &= \Phi_{1,0} P_0 + a(\Delta \delta \alpha)_1 \\
P_2 &= \Phi_{2,1} P_1 + a(\Delta \delta \alpha)_2 \\
&\quad \cdots
\end{align*}$

- End-conditions: achievement of $P_F$ at $t_F$

$\begin{bmatrix}
\Phi_{F,1}^{\delta^*} & \cdots & \Phi_{F,m-1}^{\delta^*} & \Phi_{F,m}^{\delta^*} \\
\end{bmatrix}_{\text{first column}}
\begin{bmatrix}
\Phi_{F,1}^{\delta^*} & \cdots & \Phi_{F,m-1}^{\delta^*} & \Phi_{F,m}^{\delta^*} \\
\end{bmatrix}_{\text{last column}}
\begin{pmatrix}
x_{1,1} \\
\vdots \\
x_{1,m} \\
\vdots \\
x_{p,1} \\
\vdots \\
x_{p,m}
\end{pmatrix} = b_0$

$b_0 = P_F - \Phi_{F,0} P_0$

$(x_1, \cdots, x_p) \rightarrow (\Delta \delta \dot{a}, a\Delta \delta a, a\Delta \delta \lambda, a\Delta \delta \dot{i}_x, a\Delta \delta \dot{i}_y)$ or $(a\Delta \delta e_x, a\Delta \delta e_y)$
ROE sets planning: problem statement - 2

- **Functional cost**, convex form of the ROE jumps over \( m \) steps:
  \[
  J_{\text{plan}} = \sum_{i=1}^{m} (\Delta \delta \alpha)_i^T (\Delta \delta \alpha)_i
  \]

- ROE variations not due to the natural dynamics
- describes delta-v cost (Gauss’ variational equations in ROE)

- **Optimality conditions** to minimize \( J_{\text{plan}} \) reduce to a **linear system**
  in \( \Delta \text{ROE} \) due to:
  - structure of \( \Phi(\Delta t) \rightarrow \text{property:} \ \Phi(t_j, t_i) \cdot \Phi(t_i, t_k) = \Phi(t_j, t_k) \)
  - approximation in the relative eccentricity sub-problem
    (neglected terms of \( \dot{\phi}^2 \Delta t^2 \) and \( \dot{\phi}^3 \Delta t^3 \) after the 3rd jump)
ROE sets planning: problem solution

- **Optimal solution:**
  \[ m - 1 \text{ opt. jumps } (\Delta \delta \alpha)^{\text{opt}} = M^{-1} b \]
  \[ M \text{ and } b \text{ function of } (t_i, \nu, \mu, \lambda) \text{ and } (t_i, \dot{\varphi}) \]
  \[ m \text{ end-cond. } P_F = \Phi_{F,0} P_0 + \Phi_{F,1} a(\Delta \delta \alpha)^{\text{opt}}_1 + \cdots + \Phi_{F,m} a(\Delta \delta \alpha)^{\text{opt}}_m \]

- **Generalization of a geometrical approach stepwise reconfiguration, disturbances compensation**

- **Suitable for automatic implementation**
## Supported Operative Modes

<table>
<thead>
<tr>
<th>Modes</th>
<th>Motivations</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>minimum delta-v</td>
<td>absolute min cost</td>
<td>small reconfigurations</td>
</tr>
<tr>
<td>direct $P_0 \rightarrow P_F$</td>
<td></td>
<td>accurate $P_0$</td>
</tr>
<tr>
<td>4 maneuvers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>maximum observability</td>
<td>intensify maneuvers’ activity</td>
<td>large reconfigurations</td>
</tr>
<tr>
<td>user defined $t_i \Rightarrow P_i$</td>
<td>spread burns over horizon</td>
<td>uncertainty on $P_0$</td>
</tr>
<tr>
<td>($4 \times i$ maneuvers)</td>
<td>maneuver execution errors</td>
<td></td>
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### Synergies

- criterion: minimum delta-v
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Local control: problem statement - 1

- Establishment of a (intermediate) reconfiguration $P_{0,i} \rightarrow P_i$ over a finite control window $[u_{0,i}, u_{F,i}]$
  - fixed time, fixed end-conditions problem

- Total ROE jump pre-corrected by disturbances effects over the window
  - locally maneuvers computed with $\tilde{\Phi}$ of Kepler motion

- General framework for the p-pulses formulation:

\[
\begin{pmatrix}
\tilde{\Phi}_{F,1}B_1 & \cdots & \tilde{\Phi}_{F,p}B_p
\end{pmatrix}
\begin{pmatrix}
\delta v_1 \\
\vdots \\
\delta v_p
\end{pmatrix}
= n(\Phi_{F,0}^i P_{0,i})
= n\Delta \delta \tilde{\alpha}_i
\]
Local control: problem solution - 1

- Choice of $\delta \lambda$ instead of $\delta u$ and structure of control input matrix $B$: where $\Delta \delta \alpha = B(u_M) \delta v$
  - out-of-plane and in-plane motions are decoupled

- Out-of-plane solution, deterministic:
  
  $u_{oop} = \arctan \left( \frac{\Delta \delta \tilde{i}_y}{\Delta \delta \tilde{i}_x} \right)$
  
  $|\delta v_n| = na \left\| \Delta \delta \tilde{i} \right\|$
  
  two options per orbit

- In-plane solution, underdetermined:
  
  minimum 2 impulses required $\Rightarrow$ 6 unknowns in 4 equations
In-plane reconfiguration: possible maneuvers’ schemes

Reconfiguration: $\delta a_0 \rightarrow \delta a_f$, $u_0$, $u_f$

- in-plane
- out-of-plane

Enforcement of all End-conditions

$u_{oop}$, $\delta v_{oop}$
$u_{ip}$, $\delta v_{ip}$

Planning drivers:
- Thrusters’ duty cycle (# pulses)
- Attitude constraints (type of pulses)
- Safety & Visibility (ROE predictability)
- Determinism (computation of $u_i$)
- Delta-v cost

Generalty:
- $\Delta \delta$*
- $\Delta \delta a \neq 0 \land \Delta \delta^*$
- $\Delta \delta a = 0 \land \Delta \delta^*$
- $\Delta \delta a = 0 \land \Delta \delta \lambda \neq 0 \land \Delta \delta^*$
- $\Delta \delta a = 0 \land \Delta \delta \lambda = 0 \land \Delta \delta^*$

No-Type analytical
No-Type numerical

2-RT, 3-T, 3-T
2-RT, 3-T, 3-T
2-RT, 3-T, 3-T
2-RT, 3-T, 3-T
2-RT, 3-T, 3-T
2-RT, 2-T
Local control: problem solution - 2

AVANTI design drivers for the choice of the in-plane scheme:
- autonomy, predictability
- maneuvers’ spacing constraints
- communication pointing constraints
- minimum delta-v

Maneuvers are located in:
\[ \bar{u} = \text{mod} \left( \arctan \left( \frac{\Delta \delta \tilde{e}_y}{\Delta \delta \tilde{e}_x} \right), \pi \right) \]
\[ u_{ipj} = \bar{u} + k_j \pi, \quad j = 1 \ldots 3 \]
\[ k_1 < k_2 < k_3 \]

Multiple (finite number) feasible solutions: one selected according to
1. preference to minor delta-v cost
2. preference to wider spacing between burns
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Safety concept: ROE movement due to local control

Out-of-plane control

In-plane control

optimal / sub-optimal
Safety concept: ROE movement due guidance

- **Passive safety** related to $\phi = \varphi - \theta$
- Keep (anti) parallel $\delta e / \delta i$ during RdV
- Guidance to minimize the total $\Delta$ROE
- $P_i$ distribute along the direction of ROE total variation
Example of a Rendezvous - 1

- **Scenario**
  - 500 km high, inclination 98 deg
  - $B_{\text{target}}$: 0.01 m$^2$/kg
  - $\Delta B/B$: 2%

- **Input to MAP**
  - $P_0 = [5, 10000, -50, -250, -30, 200]$ m
  - $P_F = [0, 3000, 0, -100, 0, 100]$ m
  - $t_F$: 18 orbits after $t_0$
  - time constraints
  - mode: max-observability

---

**Normalized $\delta e/\delta i$ plane**

Total delta-v: 0.2168 [m/s]

**Graphical representation**
Example of a Rendezvous - 2

Relative eccentricity and inclination vectors

Drift and mean relative longitude over time
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Conclusions and current development status

- **Impulsive MAaneuvers Planner** for formation reconfigurations and rendezvous for the AVANTI experiment (DLR/FireBird mission)
  - experiment operational conditions (onboard functioning, space segment requirements, ...)
  - design concept (simplicity and determinism)
  - provided an example of the MAP output

- **Current work**
  - flight software implementation
  - performance assessment in realistic simulation environment

- **Future work**
  - design of the AVANTI experiment campaign
ROE parameterization and safety concept


ARGON development and flight results


MAP development

Onboard Maneuver Planning for the AVANTI experiment within the DLR FireBird mission

- AVANTI experiment
- MAP Concept
- Guidance Solution
- Control Solution
- Example
- Conclusions