Human-in-the-loop Performance Assessment of Optimized Descents with Time Constraints

Results from Full Motion Flight Simulation and a Flight Testing Campaign.

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Introduction

The Clean Sky Joint Technological Initiative is an EU funded research program focussed at greening aviation (www.cleansky.eu)

The Netherlands Aerospace Center (NLR), the Technical University of Delft (TUD) and the German Aerospace Center (DLR), developed a descent flight operational concept called TEMO (Time and energy managed operations) as part of the Clean Sky Systems for Green Operations (SGO) Integrated Technology Demonstrator.
Introduction

TEMO TRL achievements

Dec. 2015 – NLR-TUD’s experimental aircraft

Dec. 2014 – NLR’s GRACE full-motion flight simulator

Dec. 2012 – NLR’s APERO static simulator

2011 – Batch studies in a modelled environment

TRL: technology readiness level
TEMO: time and energy managed operations
TEM0 real-time implementation and validation supported by FASTOP and Concorde consortium partners (selected through an open call for proposals)
Introduction

- Continuous descent Operations (CDO) have shown important environmental benefits w.r.t. conventional (step-down) approaches.
- However, maintaining separation among aircraft becomes more difficult leading to important capacity reductions.
- At present, CDOs are mainly operational in low-density scenarios.
Introduction

• Continuous descent Operations (CDO) have shown important environmental benefits w.r.t. conventional (step-down) approaches.
• However, maintaining separation among aircraft becomes more difficult leading to important capacity reductions.
• At present, CDOs are mainly operational in low-density scenarios.

A possible solution to maintain capacity: Required Times of Arrival (RTA) given by ATC at one or more metering fixes.
Time and Energy Managed Operations

- **Onboard application**, aiming to achieve environmentally friendly CDO in high-density terminal maneuvering areas (TMA).
- **Optimized** descent trajectory from the Top of Descent (TOD) until the runway threshold complying with Required Times of Arrival (RTAs).
- Fixed RNAV/RNP route.
- **Energy modulation** during the descent to meet the RTAs.
- If extra energy is needed to meet the RTAs: TEMO minimizes thrust/speedbrake usage to add/remove energy.

\[ E_T = \frac{1}{2}mv^2 + mgh \]
\[ \frac{dE_T}{dt} = v(T - D) \]
An optimal control problem is solved

- Minimizing fuel and speedbrake usage, while fulfilling operational constraints (including RTAs)
- Produces a speed, N1, flap/slat, gear and speedbrake plan from current position in CRZ to the RWY THR

Strategic or tactical guidance strategies in the Time and/or Energy error channels

- Strategic: speed-on-elevator instead of conventional VNAV-path. If energy/time deviations too high → a re-plan is triggered
- Tactical: immediate action to nullify energy/time deviations actively commanding airspeed and/or thrust changes.

Planning Function

Guidance function

Trajectory Plan

Re-planning command

Air Traffic Control (ATC)

ETA
Earliest/Latest ETA

RTA (update)

CRZ: Cruise
VNAV: Vertical Navigation
RWY THR: Runway Threshold
ETA: Estimated Time of Arrival
RTA: Required time of arrival

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Human-in-the-loop Performance Assessment of Optimized Descents with Time Constraints - 8
**TEMO planning function**

Minimise

\[ J = \int_{t_0}^{t_f} FF(t) + \beta(t) \, dt \]

Subject to:

\[
\begin{align*}
\dot{v}_a &= \frac{T - D}{m} - g \sin \gamma_a - \dot{W}_v \\
\dot{s} &= \sqrt{v_a^2 \cos^2 \gamma_a - W_x^2 + W_s} \\
\dot{h} &= v_a \sin \gamma_a \\
\dot{m} &= -FF
\end{align*}
\]

States: \( v_a, s, h, m \)

Controls: \( N1, \beta, \xi \)

Input data

\[
\begin{align*}
FF(v_a, h, N1) \\
T(v_a, h, N1) \\
D(v_a, h, \gamma_a, \beta, \xi) \\
W_s(x_g, W_n, W_e) \\
W_x(x_g, W_n, W_e) \\
\dot{W}_v(v_a, \gamma_a, x_g, W_n, W_e)
\end{align*}
\]

and...
### TEMO planning function

<table>
<thead>
<tr>
<th>Phase</th>
<th>Name</th>
<th>Initial/final conditions</th>
<th>Configuration</th>
<th>Optimization Constraints</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cruise</td>
<td>( h_p(t_0) = 30,000 \text{ft} )&lt;br&gt;( s(t_0) = s_0 )&lt;br&gt;( t_f \geq t_0 + \Delta t_{ATC} )</td>
<td>Clean Gear UP</td>
<td>( \beta(t) = 0 )&lt;br&gt;( M(t) = 0 )&lt;br&gt;( M_{\text{min}} \leq M(t) \leq \text{MMO} )&lt;br&gt;( h_p(t) = 30,000 \text{ft} )</td>
</tr>
<tr>
<td>2</td>
<td>Mach descent</td>
<td></td>
<td>Clean Gear UP</td>
<td>( M(t) = 0 )&lt;br&gt;( M_{\text{min}} \leq M(t) \leq \text{MMO} )</td>
</tr>
<tr>
<td>3</td>
<td>CAS descent</td>
<td></td>
<td>Clean Gear UP</td>
<td>( \psi_{\text{CAS}}(t) = 0 )&lt;br&gt;( \psi_{\text{CAS}}(t) \leq VMO )</td>
</tr>
<tr>
<td>4</td>
<td>Fast Deceleration</td>
<td>( h(t_f) \geq 8,000 \text{ft} )&lt;br&gt;( 215 \text{kt} \leq \psi_{\text{CAS}}(t_f) \leq 250 \text{kt} )</td>
<td>Clean Gear UP</td>
<td>( \psi_{\text{CAS}}(t) = 0 )&lt;br&gt;( -1.6 \text{kt/s} \leq \dot{\psi}_{\text{CAS}}(t) \leq +0.5 \text{kt/s} )</td>
</tr>
<tr>
<td>5</td>
<td>CAS approach</td>
<td>( s(t_0) = s_{\text{TOLKO}} )&lt;br&gt;( t_0 = RTA_{\text{TOLKO}} )</td>
<td>Clean Gear UP</td>
<td>( \psi_{\text{CAS}}(t) = 0 )&lt;br&gt;( 215 \text{kt} \leq \psi_{\text{CAS}}(t) \leq 250 \text{kt} )</td>
</tr>
<tr>
<td>6</td>
<td>Approach Deceleration 1</td>
<td>( h_p(t_f) \geq 3,500\text{ft} )&lt;br&gt;( v_{\text{CAS}}<em>{\text{min}} \leq \psi</em>{\text{CAS}}(t_f) \leq 220 \text{kt} )</td>
<td>Clean Gear UP</td>
<td>( \psi_{\text{CAS}}(t) = 0 )&lt;br&gt;( -1.0 \text{kt/s} \leq \dot{\psi}_{\text{CAS}}(t) \leq -0.3 \text{kt/s} )</td>
</tr>
<tr>
<td>7</td>
<td>Approach Deceleration 2</td>
<td>( s(t_0) = s_{\text{EH740}} )&lt;br&gt;( v_{\text{CAS}}<em>{\text{min}} \leq \psi</em>{\text{CAS}}(t_f) \leq \psi_{\text{CAS}}<em>{1</em>{\text{max}}} )</td>
<td>Clean Gear UP</td>
<td>( \psi_{\text{CAS}}(t) = 0 )&lt;br&gt;( -0.9 \text{kt/s} \leq \dot{\psi}_{\text{CAS}}(t) \leq 0.2 \text{kt/s} )</td>
</tr>
<tr>
<td>8</td>
<td>Approach Deceleration 3</td>
<td>( h_p(t_f) = 2,000 \text{ft} )</td>
<td>Flaps Flap</td>
<td>( \psi_{\text{CAS}}(t) = 0 )</td>
</tr>
<tr>
<td>9</td>
<td>CAS on GS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Deceleration on GS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>GS stabilized</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Original Optimal control problem discretised by **collocation** methods and solved with Non Linear Programming (NLP)
TEMO planning function

- Inclusion of realistic wind fields and non-standard atmosphere
  - Air pressure, temperature and horizontal wind dependency on altitude and geographic location
  - Data fitted to B-spline functions

\[
\begin{align*}
W_n(h, s) & \quad W_e(h, s) \\
\tau(h, s) & \quad p(h, s)
\end{align*}
\]

- Data sources
  - Standard weather GRIB files*
  - In-flight recorded weather data from previous run (only in flight trials)

(*) provided by the KNMI (Royal Netherlands meteorological Institute)
TEMO guidance function

- **Time channel variants**
  - Follow CAS speed plan [strategic]
  - Follow CAS speed plan *with deltas* nullifying time deviations [tactical]

- **Energy channel variants**
  - Follow N1 and speedbracke plan [strategic]
  - Monitor deviations in altitude/energy, compensate using thrust or speedbrakes [tactical]

*If time or energy deviations exceed predefined limits, a replan is triggered.*

*CAS: Calibrated Airspeed*
Setup of the experiments

3 full days in July 2014 at NLR’s GRACE full flight simulator
Setup of the experiments

October 2015
20 approaches

NLR – TUD
Cessna Citation II
research aircraft
Setup of the experiments
Setup of the experiments

Specific Human Machine Interface features

Cues for flap/slats and gear changes

Cues for throttle/speedbrake segments
Setup of the experiments

Rekken1G arrival
TOLKO1G approach
RNAV-ILS RWY 23
Groningen-Eelde airport (EHGG)

Clear DES
RTA@IAF
TEMO ON

Clear APPR + RTA@RWY

TEMO OFF
GRACE: Experiment setup

- 2 qualified pilots
- Auto speed-brake and auto-throttle
- Weather data from Jan 13th 2008 (GRIB file)
- Simulation starting in cruise (FL300/M.60)
- Data-link clearances and RTAs
**GRACE: Experiment setup**

<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAF metering</td>
<td>Runway metering</td>
<td>Guidance</td>
</tr>
<tr>
<td>RTA</td>
<td>RTA</td>
<td>RTA</td>
</tr>
<tr>
<td>IM-Achieve</td>
<td>IM-Achieve</td>
<td>Hybrid</td>
</tr>
</tbody>
</table>

**Hybrid: Energy strategic and Time tactical (speed on elevator)**

**IM:** Interval Management  
**ASAS:** Airborne Separation Assurance System

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Seattle, Washington  
June 26 - 30, 2017
## GRACE: Experiment setup

<table>
<thead>
<tr>
<th>ID</th>
<th>Run configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>xx1</td>
<td>no wind forecast errors</td>
</tr>
<tr>
<td>xx2</td>
<td>3 kt/2° constant wind error</td>
</tr>
<tr>
<td>xx3</td>
<td>6 kt/4° constant wind error</td>
</tr>
<tr>
<td>xx4</td>
<td>9 kt/6° constant wind error</td>
</tr>
<tr>
<td>xx5</td>
<td>3 kt/2° constant wind error + replanning malfunction</td>
</tr>
<tr>
<td>xx6</td>
<td>3 kt/2° constant wind error + manual flight with flight director</td>
</tr>
</tbody>
</table>

### Time offsets used to define the RTAs (RTA = ETA + ΔT)

<table>
<thead>
<tr>
<th>Metering fix</th>
<th>ETA</th>
<th>Late</th>
<th>Early</th>
<th>Very Late</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAF</td>
<td>ΔT=0</td>
<td>ΔT=20s</td>
<td>ΔT=-20s</td>
<td>ΔT=+30s</td>
</tr>
<tr>
<td>THR</td>
<td>ΔT=0</td>
<td>ΔT=10s</td>
<td>ΔT=-10s</td>
<td>ΔT=+15s</td>
</tr>
</tbody>
</table>
Flight trials: experiment setup

- 1 test pilot + 1 safety pilot
- **NO** Auto speed-brake and **NO** auto-throttle
- Weather models from KNMI OR recorded weather from previous run
- Simulation starting in cruise (FL240/M.60)
- For benchmarking FMS step-down procedure (FL70 level-off)
- Simulated data-link clearances and RTAs coming from experiment leader
Flight trials: experiment setup
## Flight trials: experiment setup

<table>
<thead>
<tr>
<th>ID</th>
<th>Planning &amp; guidance</th>
<th>RTA update</th>
<th>Date and time</th>
<th>Weather data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>909</td>
<td>TEMO $E_s/T_s$</td>
<td>ETA</td>
<td>19-10-2015 17:09</td>
<td>Recorded</td>
</tr>
<tr>
<td>901</td>
<td>FMS step down</td>
<td>ETA</td>
<td>19-10-2015 17:43</td>
<td>Recorded</td>
</tr>
<tr>
<td>901.1</td>
<td>FMS step down</td>
<td>ETA</td>
<td>22-10-2015 16:18</td>
<td>GRIB</td>
</tr>
<tr>
<td>905</td>
<td>TEMO $E_t/T_t$</td>
<td>ETA</td>
<td>22-10-2015 16:40</td>
<td>Recorded</td>
</tr>
<tr>
<td>909.1</td>
<td>TEMO $E_s/T_s$</td>
<td>ETA</td>
<td>22-10-2015 17:22</td>
<td>Recorded</td>
</tr>
<tr>
<td>913</td>
<td>TEMO $E_s/T_s$</td>
<td>ETA</td>
<td>22-10-2015 20:10</td>
<td>GRIB</td>
</tr>
<tr>
<td>902</td>
<td>FMS step down</td>
<td>Very late</td>
<td>22-10-2015 20:43</td>
<td>Recorded</td>
</tr>
<tr>
<td>906</td>
<td>TEMO $E_t/T_t$</td>
<td>Very late</td>
<td>22-10-2015 21:07</td>
<td>Recorded</td>
</tr>
<tr>
<td>910</td>
<td>TEMO $E_s/T_s$</td>
<td>Very late</td>
<td>22-10-2015 21:43</td>
<td>Recorded</td>
</tr>
<tr>
<td>914</td>
<td>TEMO $E_s/T_t$</td>
<td>Very late</td>
<td>23-10-2015 15:45</td>
<td>GRIB</td>
</tr>
<tr>
<td>903</td>
<td>FMS step down</td>
<td>Early</td>
<td>23-10-2015 16:08</td>
<td>Recorded</td>
</tr>
<tr>
<td>911</td>
<td>TEMO $E_s/T_s$</td>
<td>Early</td>
<td>23-10-2015 16:44</td>
<td>Recorded</td>
</tr>
<tr>
<td>907</td>
<td>TEMO $E_t/T_t$</td>
<td>Early</td>
<td>23-10-2015 17:24</td>
<td>Recorded</td>
</tr>
<tr>
<td>915</td>
<td>TEMO $E_s/T_t$</td>
<td>Early</td>
<td>26-10-2015 15:37</td>
<td>GRIB</td>
</tr>
<tr>
<td>904</td>
<td>FMS step down</td>
<td>Late</td>
<td>26-10-2015 16:13</td>
<td>Recorded</td>
</tr>
<tr>
<td>908</td>
<td>TEMO $E_t/T_t$</td>
<td>Late</td>
<td>26-10-2015 16:35</td>
<td>Recorded</td>
</tr>
<tr>
<td>912</td>
<td>TEMO $E_s/T_s$</td>
<td>Late</td>
<td>26-10-2015 17:23</td>
<td>Recorded</td>
</tr>
<tr>
<td>916</td>
<td>TEMO $E_s/T_t$</td>
<td>Late</td>
<td>26-10-2015 19:47</td>
<td>GRIB</td>
</tr>
<tr>
<td>917</td>
<td>TEMO $E_t/T_s$</td>
<td>Late</td>
<td>26-10-2015 20:21</td>
<td>Recorded</td>
</tr>
<tr>
<td>919</td>
<td>TEMO $E_s/T_s$</td>
<td>ETA</td>
<td>26-10-2015 21:15</td>
<td>Recorded</td>
</tr>
</tbody>
</table>
Results of the experiments
Results of the experiments
Results of the experiments

GRACE simulations

- IAF time accuracy
  - target +/- 10s

- RWY time accuracy
  - target +/- 5s

![Time error chart]

The chart shows the time error for different runs with three different systems: TOLKO, EH512, and THR. The error is measured in seconds with targets of +/- 10s for IAF and +/- 5s for RWY.
Results of the experiments

Flight trials

IAF time accuracy
target +/- 10s

RWY time accuracy
target +/- 5s
Results of the experiments

- Time accuracy at the IAF well below target objective of +/-10s
- Time accuracy at the RWY THR well above target objective +/-5s
- Time accuracy at the FAP around +/-5s

  - TEMO logic disabled shortly before overflying the FAP (no actions performed to meet the RTA).
  - Heavily constrained optimization on final approach segment.
  - Engine dynamics not modelled and not negligible for rapid and short inputs of thrust
  - Wind prediction errors are relatively larger at low aircraft speeds
Results of the experiments

Higher cruise altitude in GRACE simulations (lower fuel consumption)
More dispersion in flight trials due to: Weather diversity and variants tested
Results of the experiments

For some runs KNMI predictions were as good as recorded data

Wind prediction errors
Along track wind component (Ws)
(Only Flight Trials)
Conclusions

• Time and Energy managed operations (TEMO) as a solution for environmentally friendly procedures in high-density TMAs (allowing CDOs while maintaining capacity)

• Importance of wind and real atmosphere accurate modeling to achieve very demanding time accuracies, specially at lower altitudes and speeds.

• Pilots rated TEMO procedures safe and acceptable.

• Some improvements still needed: avoiding to intercept ILS glideslope from above, improve estimation of initial position, model engine dynamics in final approach, anticipation for anti-ice usage, ... 

• No statistical evidences to assess the best guidance strategy.
References


Thank you!
Any Questions?

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Cockpit HMI variants

FMS step-down

Es-Ts

Et-Tt

Es-Tt
New SOP

New Procedures (2 pilot Crew):
- Descent preparation
- RTA
- IM select target
- IM spacing
- Unable plan
- Auto speed-brake
- Auto-QNH
- Configuration change
- Approach and landing

<table>
<thead>
<tr>
<th>RTA PROCEDURE</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PF</td>
<td>PM</td>
</tr>
<tr>
<td>Datalink received</td>
<td>&quot;ATC MESSAGE&quot; call out</td>
</tr>
<tr>
<td>Confirms “CHECK”</td>
<td></td>
</tr>
<tr>
<td>Selects ‘LOAD’ to enter data from datalink to FMS</td>
<td></td>
</tr>
<tr>
<td>Confirms “CHECK”</td>
<td></td>
</tr>
<tr>
<td>Reads out datalink</td>
<td></td>
</tr>
<tr>
<td>Opens RTA page of RTA waypoint</td>
<td></td>
</tr>
<tr>
<td>Activates RTA</td>
<td></td>
</tr>
<tr>
<td>When plan return, reads out ETA at the same check with RTA-RTA</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>APPROACH AND LANDING</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PF</td>
<td></td>
</tr>
<tr>
<td>At GEAR selection (~2000ft) presses APP mode</td>
<td></td>
</tr>
<tr>
<td>De-selects Auto Speed brake by selecting speed brake lever down</td>
<td></td>
</tr>
<tr>
<td>Arms the Speed Brake for landing</td>
<td></td>
</tr>
<tr>
<td>Expect landing clearance from ATC</td>
<td></td>
</tr>
<tr>
<td>Configures to Flap Lands when instructed</td>
<td></td>
</tr>
<tr>
<td>Selects Missed Approach altitude</td>
<td></td>
</tr>
<tr>
<td>Performs landing checklist (including ECAM Memo)</td>
<td></td>
</tr>
</tbody>
</table>
New SOP

**APPROACH CHECKLIST**

<table>
<thead>
<tr>
<th>Item</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECAM STATUS</td>
<td>CHECK</td>
</tr>
<tr>
<td>SEAT BELTS</td>
<td>CHECK ON</td>
</tr>
<tr>
<td>MDA/DH</td>
<td>X-CHECK</td>
</tr>
</tbody>
</table>

**DESCENT CHECKLIST**

<table>
<thead>
<tr>
<th>Item</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUTO SPEED BRAKES</td>
<td>ARMED</td>
</tr>
<tr>
<td>MCP ALTITUDE</td>
<td>SET</td>
</tr>
</tbody>
</table>

**LANDING CHECKLIST**

<table>
<thead>
<tr>
<th>Item</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROUND SPOILERS</td>
<td>SET</td>
</tr>
<tr>
<td>GO AROUND ALT</td>
<td>SET</td>
</tr>
<tr>
<td>GEAR</td>
<td>DOWN</td>
</tr>
<tr>
<td>FLAPS</td>
<td>SET</td>
</tr>
</tbody>
</table>
## Cockpit HMI variants

<table>
<thead>
<tr>
<th>Phase</th>
<th>FMS step down</th>
<th>TEMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise</td>
<td>Follow speed yoyo with throttle AP - ALT hold</td>
<td>Follow speed yoyo with throttle FBW - ALT hold</td>
</tr>
<tr>
<td>Descent</td>
<td><strong>Non-level segments</strong>&lt;br&gt;Follow speed yoyo using AP SoE mode and idle thrust&lt;br&gt;<strong>Level segments</strong>&lt;br&gt;Follow speed yoyo with throttle</td>
<td>FBW follows speed yoyo (SoE)&lt;br&gt;<strong>In case N1/sb cues visible</strong> follow N1/sb cues with throttle/sb,&lt;br&gt;<strong>otherwise</strong> use N1/sb on own discretion to follow alt yoyo</td>
</tr>
<tr>
<td>G/S</td>
<td>Cessna Citation II Standard Operating Procedures</td>
<td>Follow speed yoyo with throttle/sb&lt;br&gt;Follow ILS indication using AP</td>
</tr>
</tbody>
</table>
GRACE: Experiment results

Trajectories for Run 1-1

- RTA at RWY received
- RTA at IAF received

Speed [kt] - Altitude [FL]

Pressure Altitude
Route Waypoint
RTA update

N1 Setting [%] - Speed Brake Setting [%]

Flight Path Angle [deg]

RTA at RWY received
RTA at IAF received

Prats et al. - 12th USA/Europe Air Traffic Management Research and Development Seminar
Human-in-the-loop Performance Assessment of Optimized Descents with Time Constraints - 39
Seattle, Washington
June 26 - 30, 2017
GRACE: Experiment results

Controls for Runs 1-1 and 1-4

![Graph showing controls for runs 1-1 and 1-4 with annotations for RTA at RWY and IAF received.]

- **Run 1-4**
  - RTA at RWY received
  - RTA at IAF received

- **Strategic re-plans**
  - RTA at RWY received
  - RTA at IAF received
GRACE: Experiment results

CAS profiles for Runs 1-1 and 1-4

![CAS profiles graph](image_url)