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Sven Erb

► **To cite this version:**

Sven Erb. eNLP: Application-Centric NLP-Based Optimization in the Aerospace Market. SADC0 A2CO, Mar 2011, Paris, France. inria-00585604

HAL Id: inria-00585604

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Submitted on 13 Apr 2011

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eNLP: Application-Centric NLP- Based Optimization in the Aerospace Market

Dr. Sven Erb

TEC-ECM, ESA ESTEC, The Netherlands

02/03/2011

1. Introduction
2. TEC-ECM Role & Responsibilities
3. Optimal Control Application Examples
4. Description of Optimization Architecture to Solve OCP
5. Low-Thrust GTO-GEO Transfer Optimization
6. GTO-GEO Practical Consideration
7. New European NLP Solver eNLP
8. Conclusions

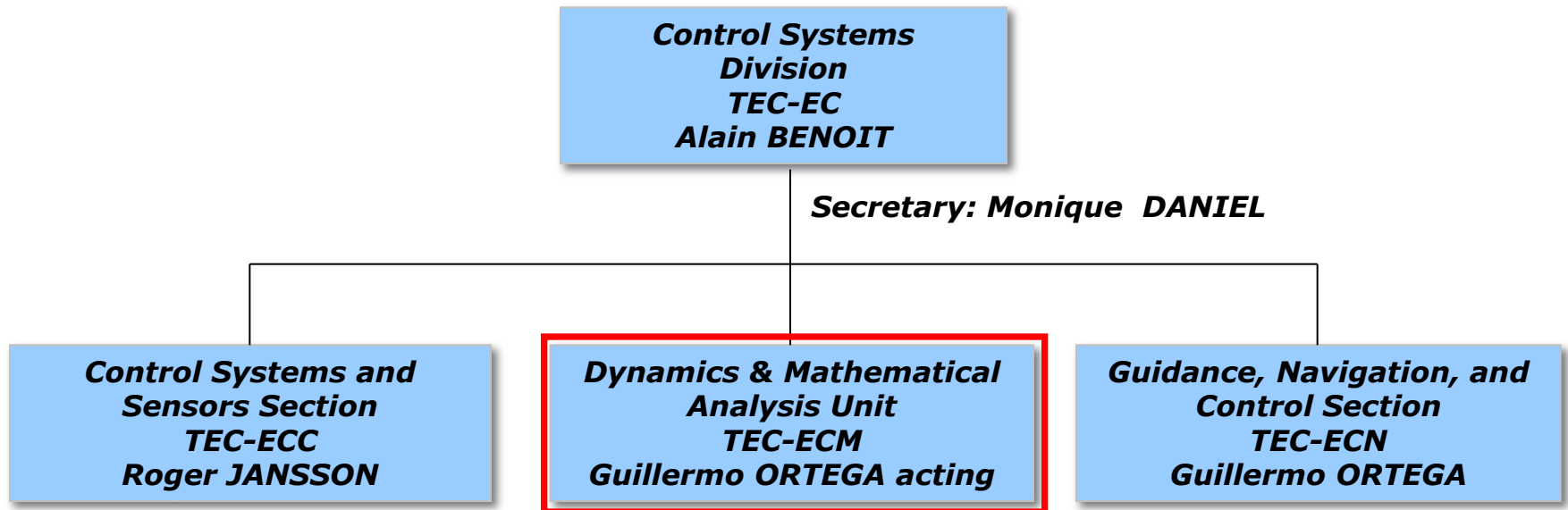
eNLP: Application-Centric NLP-Based Optimization in the Aerospace Market

Optimization is an analysis method to assess the performance of a set of parameters in a model with respect to a precisely defined objective, subject to a set of constraints (occasionally the set has dimension zero).

The work context for a trajectory and performance engineers is application-centric. we have a very **Application-Centric**. The key concern is to understand the model and best reflect all relevant aspects of the real life application.

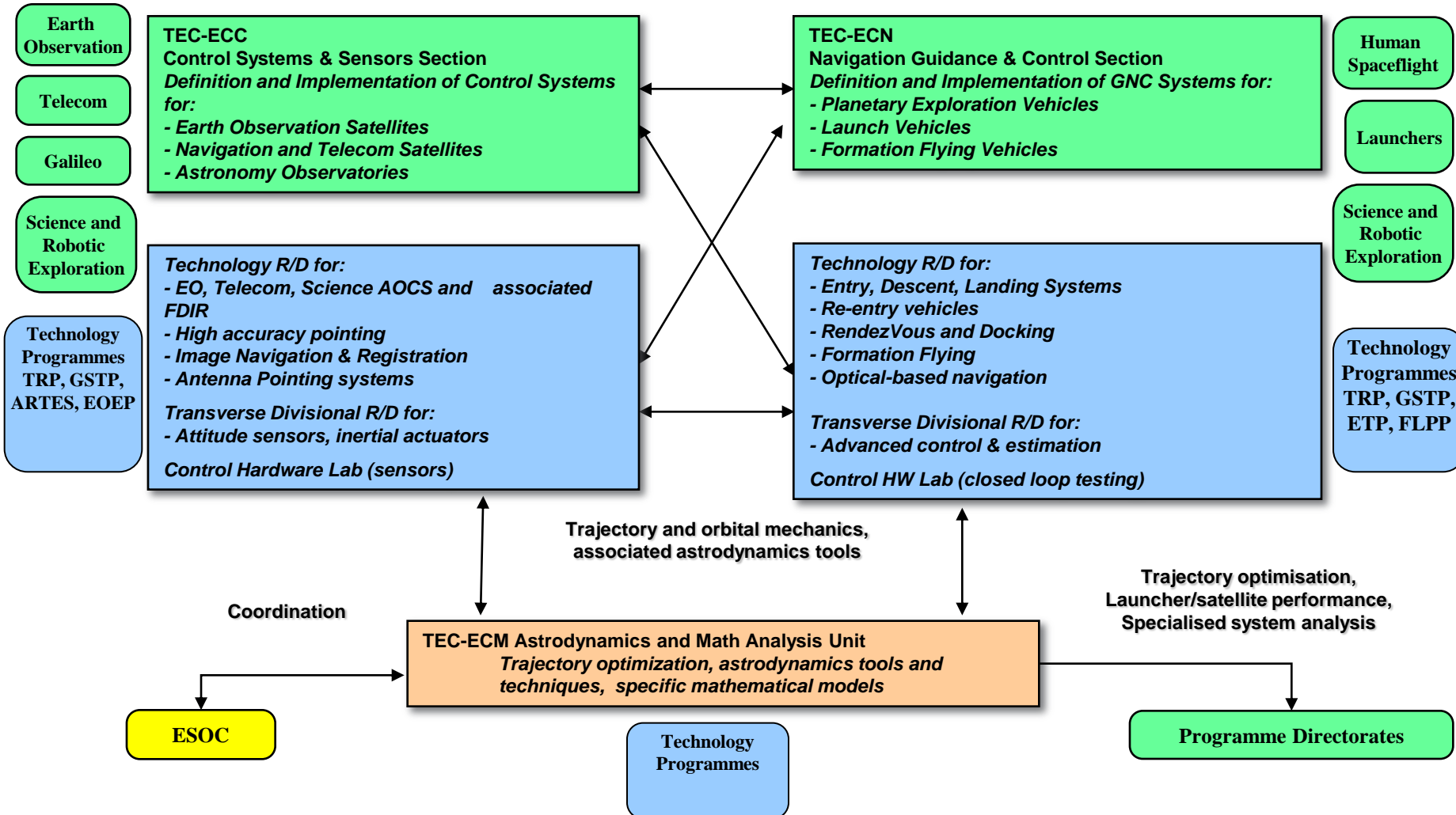
Aerospace Market: Reflects the fact that we are mostly interested in Aerospace applications and gives indication of the commercial aspects of our activities.

The primary means of optimization that is used at TEC-ECM is Nonlinear Programming, hence, **NLP-Based**.



TEC-ECM belongs to the Directorate for Technology and Quality Management D/TEC of the European Space Agency ESA and is located on the ESTEC campus in The Netherlands.

TEC-EC Organisation & Interfaces



Atmospheric Flight

Ascent



Entry



Descent and Landing



Aerocapture, Aerobraking

Aerogravity assist

Flight under Parachute, parafoil



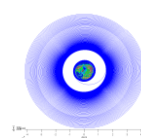
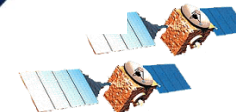
Non-Atmospheric Flight

Rendezvous and Docking

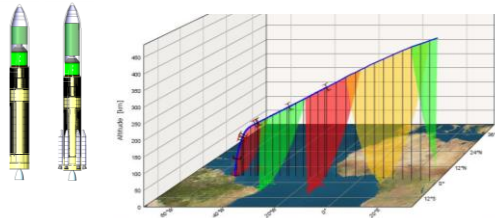
Station-Keeping / Collocation

Formation Flying

Low Thrust Transfers



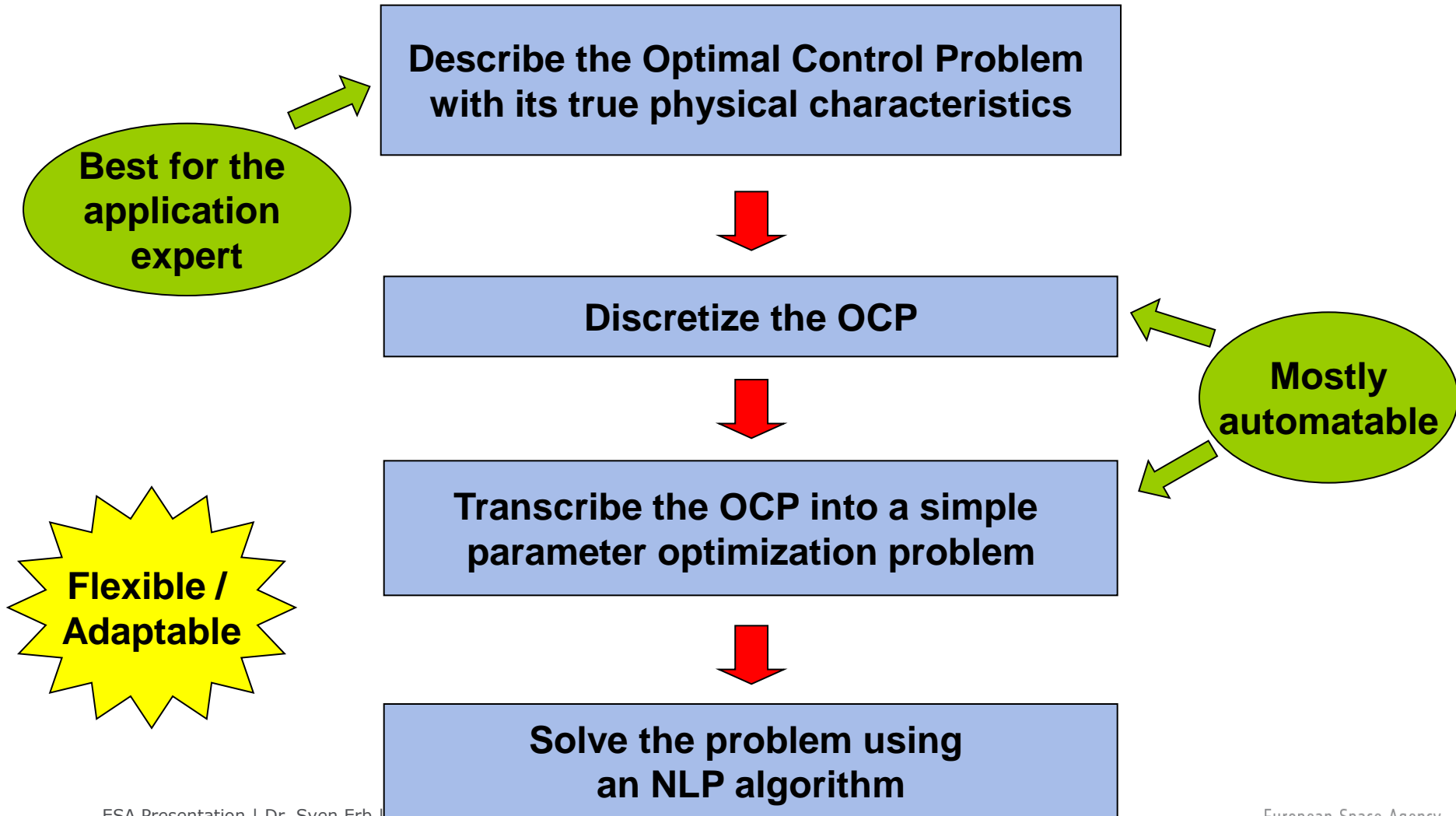
Launch Vehicle



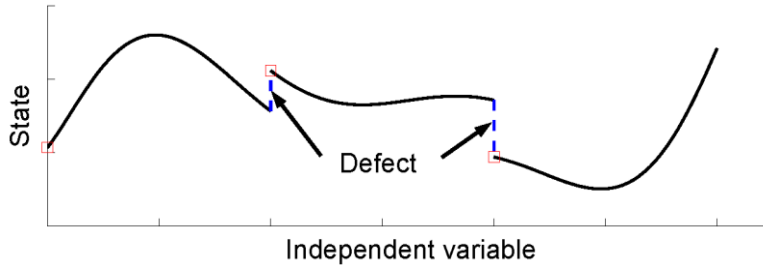
- Maximum P/L performance,
- Optimal control under constraints: lift-off conditions, pad clearance, azimuth, heat flux, dynamic pressure, axial acceleration, ground station visibility, separation conditions, stage drop zones,
- Minimum GLOW, design optimization, engine sizing,
- Look-up tables with aero data, etc.

1. Trajectory optimization problems with **Optimal Control** properties!
2. Context **somewhat similar**,
3. Particular applications **differ** quite substantially with respect to:
 - a. type of suitable equations of motion,
 - b. applicable set of constraints,
 - c. type of objective.
4. Problem formulations are **generally nonlinear**,
5. Apart from the optimizable control, there is a **set of design parameters** that is also optimizable.

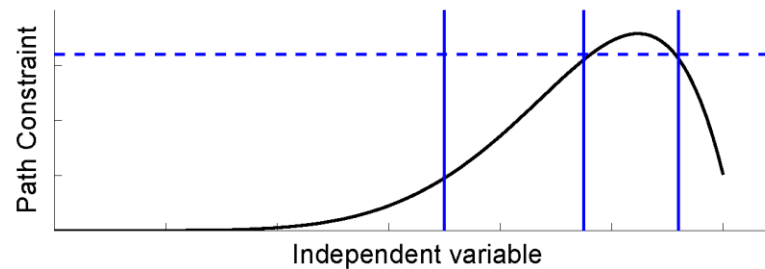
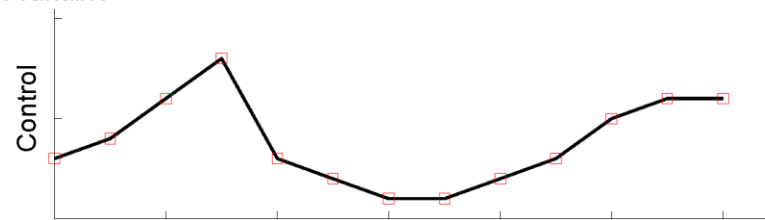
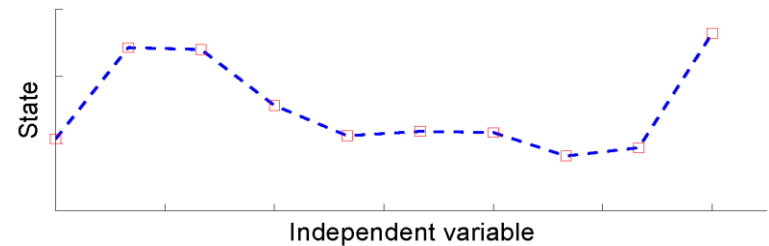
Discretize then Optimize



Shooting Method



Collocation Method



- Monitor the ODE tolerance,
- Refine the grid,
- GIGO: Garbage In – Garbage Out.

Nonlinear Program:

Minimize the cost function

$$f(x), \quad x \in \mathfrak{R}^n$$

subject to equality constraints

$$h(x) = 0, \quad h \in \mathfrak{R}^{m_e}$$

and inequality constraints.

$$g(x) \geq 0, \quad g \in \mathfrak{R}^{(m-m_e)}$$

Lagrange-Function:

$$L(x, \lambda, \mu) = f(x) - \lambda^T g(x) + \mu^T h(x)$$

Optimal solution:

$$(y^*)^T = \left[(x^*)^T \quad (\lambda^*)^T \quad (\mu^*)^T \right]$$

which satisfies the Karush-Kuhn-Tucker conditions

$$g(x^*) \geq 0$$

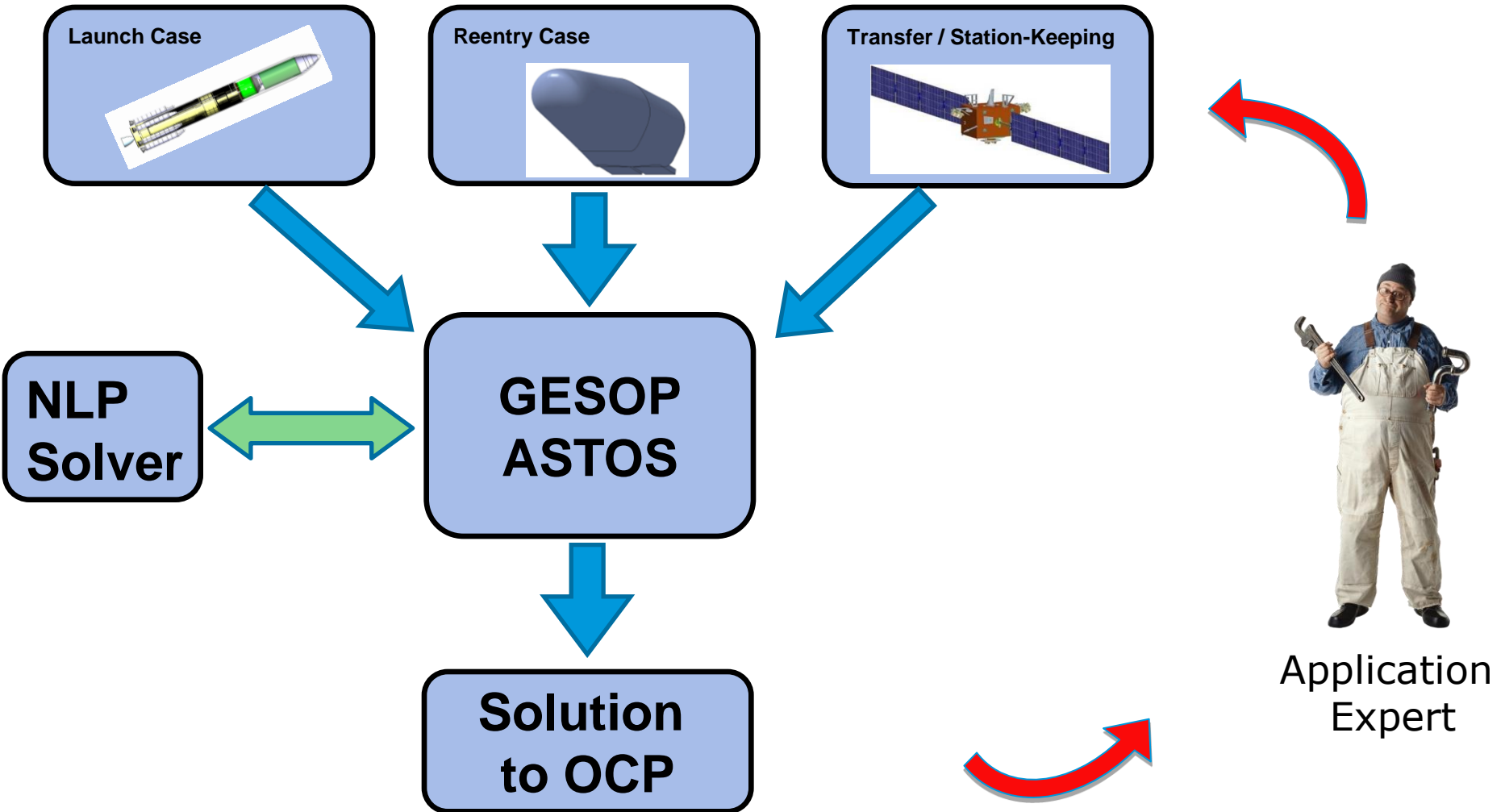
$$h(x^*) = 0$$

$$\lambda^* g(x^*) = 0$$

$$\lambda^* \geq 0$$

$$L_x(x^*, \lambda^*, \mu^*) = f_x(x^*) - g_x^T(x^*) \cdot \lambda + h_x^T(x^*) \cdot \mu = 0$$

General Architecture



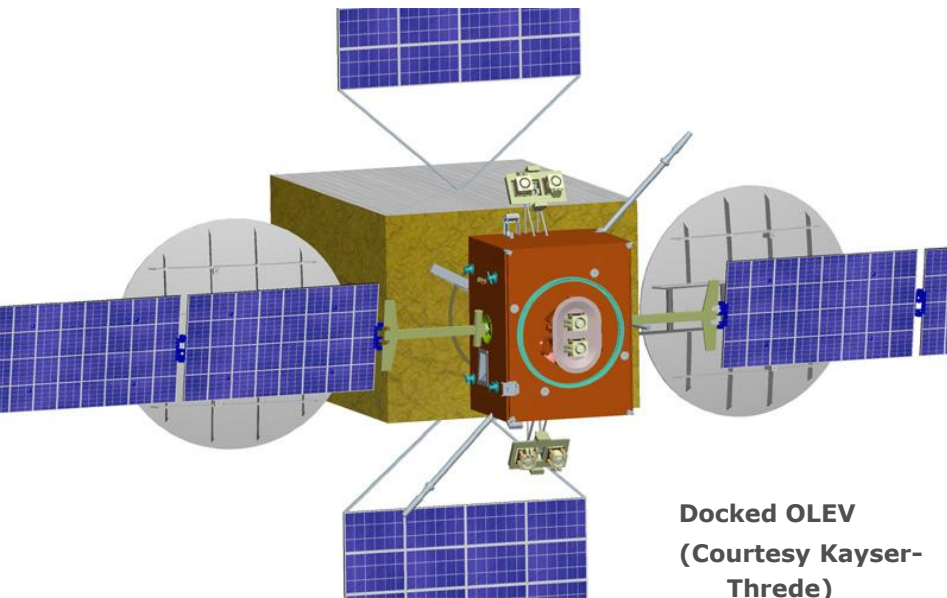
EP Transfer as Part of the Business Case

OLEV – Orbital Life Extension Vehicle:

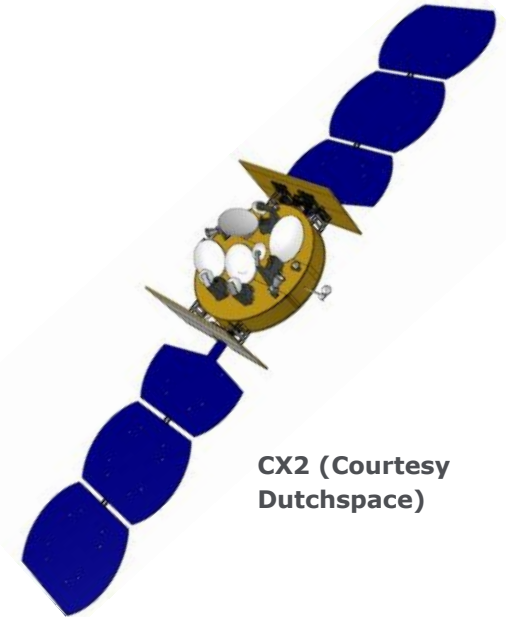
1. Target is to provide commercially viable life extension services for fuel depleted, operational GEO telecom satellites,
2. OLEV docks with client satellite and takes over station-keeping tasks from the client.

ConeXpress2:

1. ConeXpress will be a smaller-than-small platform for GEO applications



Docked OLEV
(Courtesy Kayser-Threde)



CX2 (Courtesy Dutchspace)

- Launch costs are lowered by flying as additional payload to GTO,
- Transfer from GTO to GEO, repositioning and station-keeping is performed with low-thrust electric propulsion.

1. Combinations of simple control laws,
2. Superposed or consecutive,
3. With coast arcs/thrust arcs,

Strategy suggested by J.E. Pollard for GTO-GEO:

1. Phase: Primarily increase semi major axis a to final value

$$u_r = 0$$

$$u_{th} = \cos|\beta|$$

$$u_h = \sin|\beta|$$

2. Phase: Decrease eccentricity and inclination to zero; $a = \text{const.}$

$$u_r = \frac{\cos|\beta|\sqrt{1-e^2}\sin(E)}{1-e\cos(E)}$$

$$u_{th} = \frac{\cos|\beta|(\cos(E)-e)}{1-e\cos(E)}$$

$$u_h = \sin|\beta|$$

$$\tan|\beta| = \left| \frac{(i_2 - i_1)(3\alpha + \cos\alpha \sin\alpha)}{2\cos\varpi \sin\alpha \left[\ln\left(\frac{e_2+1}{e_2-1} \frac{e_1-1}{e_1+1}\right) - e_2 + e_1 \right]} \right|$$

α : Ecc. anom. arc switch. cond.

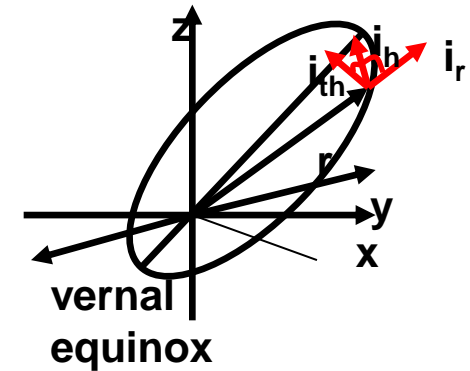
β : Out - of - plane angle

E : Eccentric anomaly

e : Eccentricity

i : Inclination

ϖ : Argument of perigee



Spacecraft and Mission Model Description for GTO-GEO Transfer



Wet mass BOL: 1335.7 kg

Thrust data:

Constant thrust 2 * 0.0891 N = 0.1782 N
Fuel flow rate 2 * 5.4733 E-6 = 10.9466 E-6 kg/s

Launch Orbit:

Inclination 6 deg
Perigee height 250 km
Apogee height 35,943 km
Argument of perigee 178 deg

Disturbances:

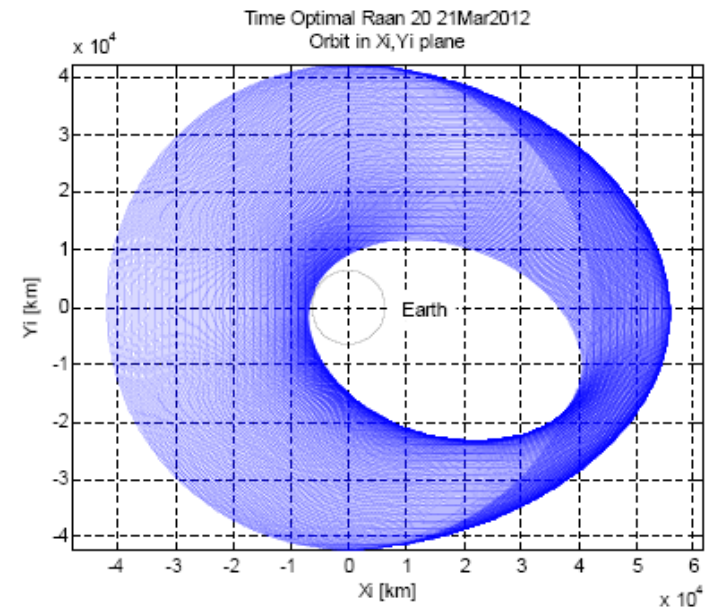
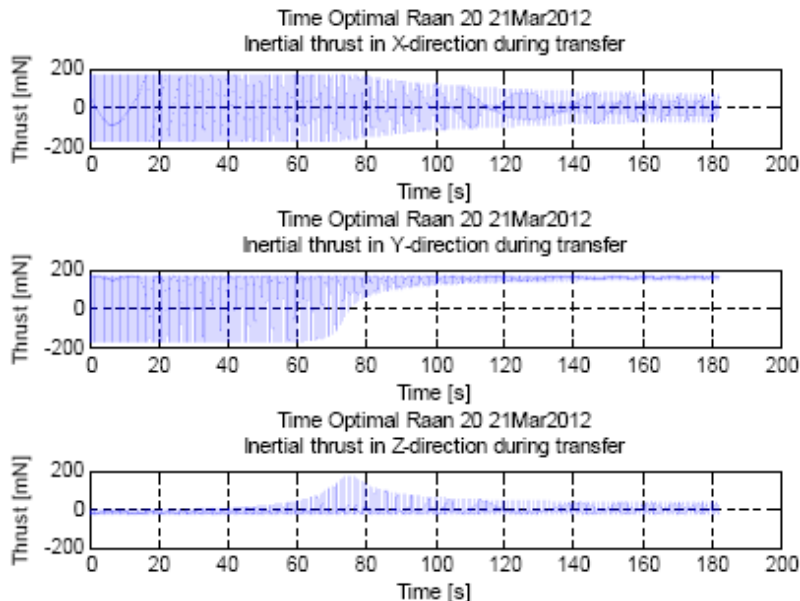
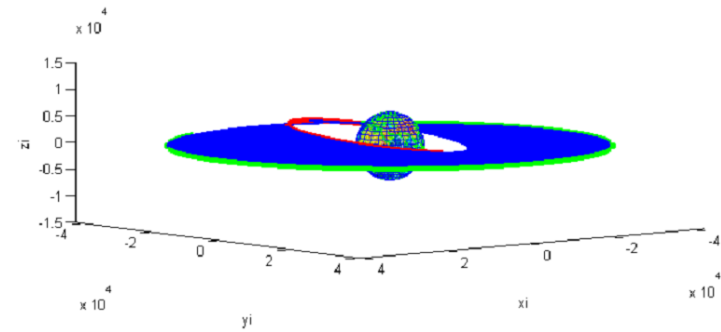
Earth gravity field including J2 yes
Gravitation of Sun and Moon yes
Solar radiation fixed Sun radiation, 1388 W/m²
Drag no
Gravity gradient no
Magnetic no

Target Orbit:

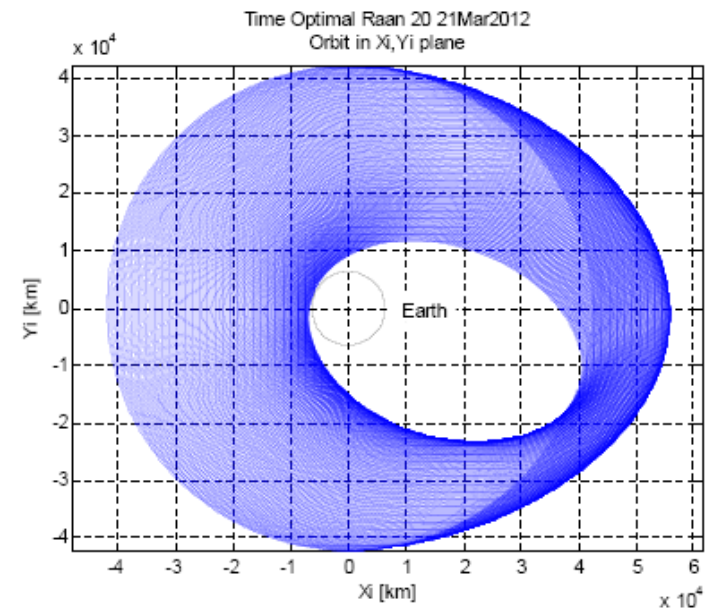
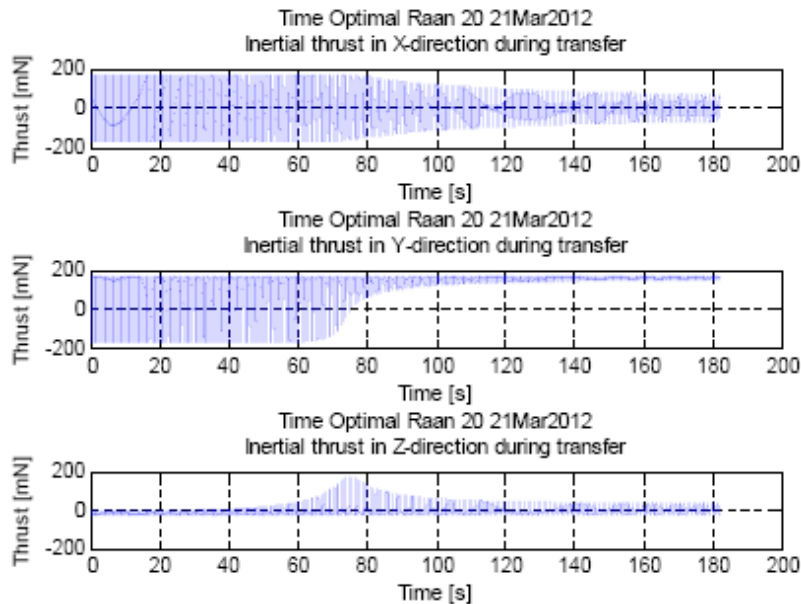
Eccentricity 0.0
Semi major axis 41,810 km (GEO radius – 1 day of spiral thrust increase: 354.2 km)
Inclination 0.0 deg

Nonlinear Programming Based Optimization

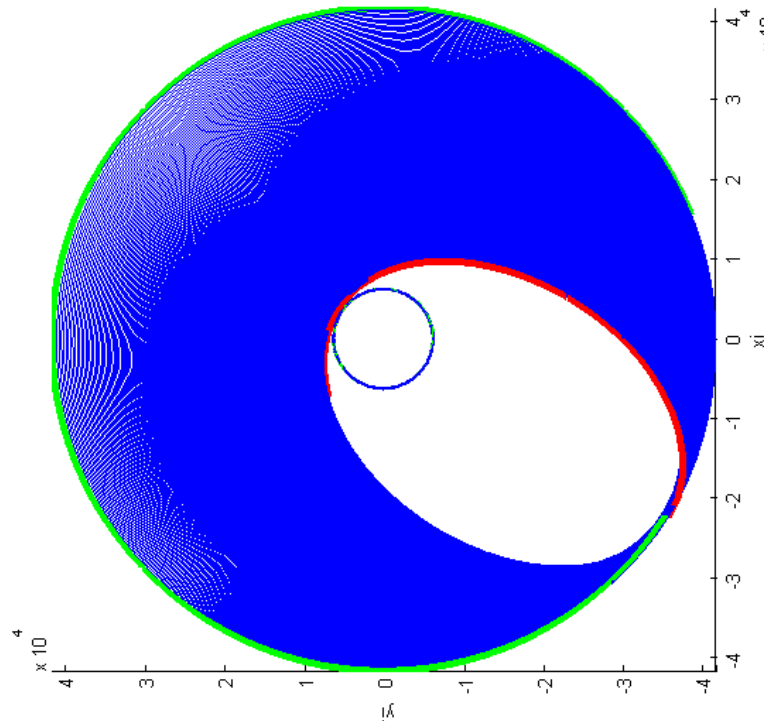
1. NLP can solve long EP transfer trajectory optimization problems,
 2. Order of 100,000 parameters and constraints,
 3. First discretize, then optimize,
 4. Complex model with EP patterns, perturbing accelerations, eclipses can be considered,
- Result is an optimal thrust vector history with huge degree of parameterization.



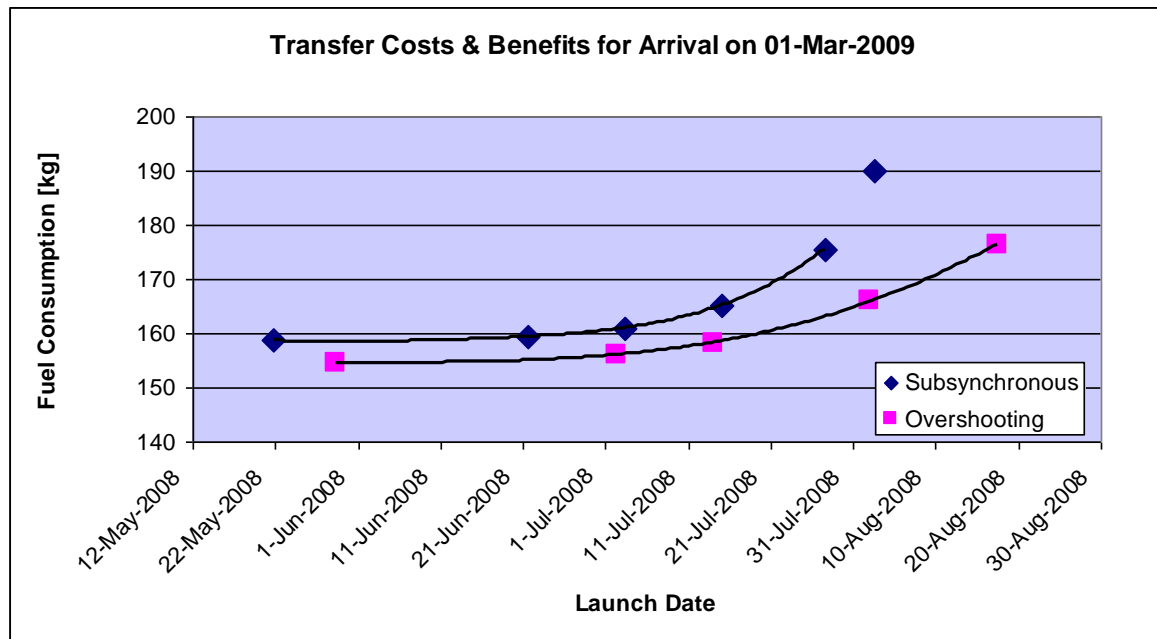
1. Optimize control in order to minimize transfer time (= fuel, in case of permanent thrust),



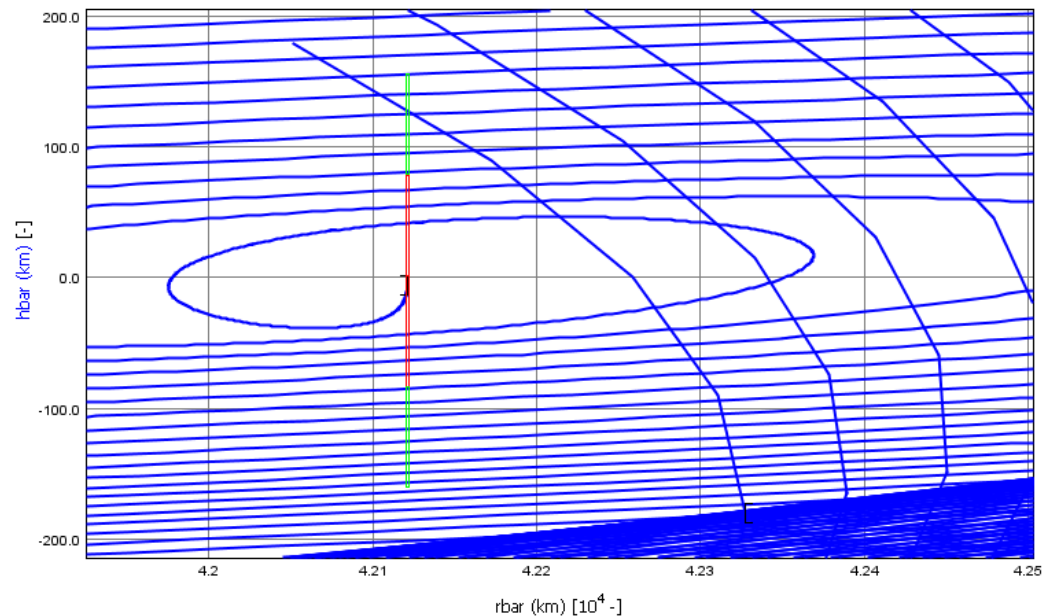
- 2. Optimize control in order to perform a time optimal sub-synchronous transfer,



3. Optimize control in order to minimize radiation exposure in Van Allen belt,
4. Optimize control, taking account of eclipses and power cycling,
5. Optimal control for a fuel optimal transfer with time limit (thrust on-off),



6. Optimize control in order to avoid intermediate crossing through the GEO belt.



Graph shows a time optimal transfer trajectory in a rotating frame; the red box marks GEO ± 75 km, green + red mark GEO ± 150 km; every crossing of the blue trajectory through the boxes marks a GEO crossing.

7. Optimize control so that it complies with attitude constraints and can be uplinked to the spacecraft.

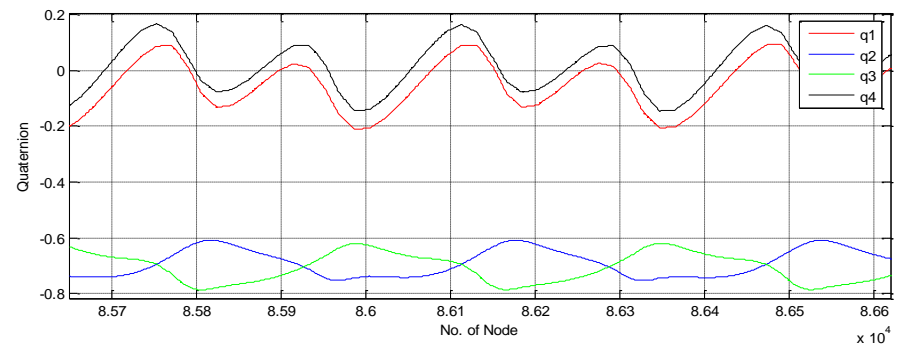
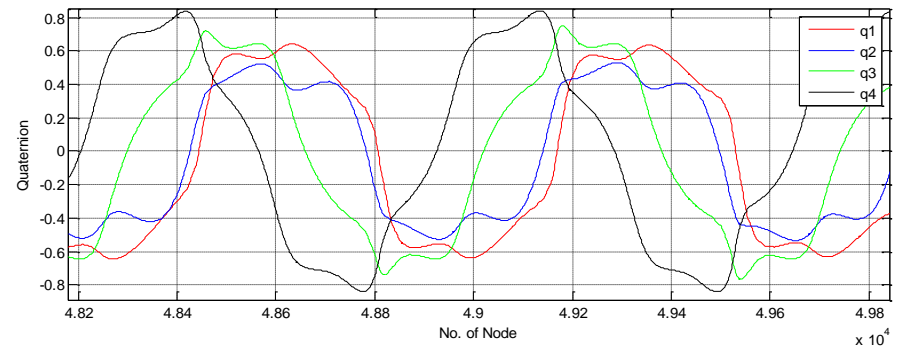
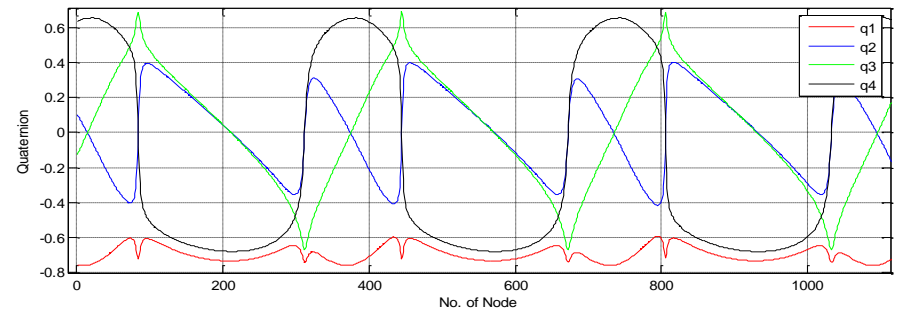
- Ensure sun-pointing of solar array for power generation,
- Limit slew rates of spacecraft to comply with GNC specs.,
- Optimized manoeuvre plan / attitude history needs to be parameterized and uplinked to spacecraft,
- Amount of parameters needs to comply with data rate of communication system and duration of ground contacts.

Quaternion History

1. Source data contains 250 revolutions for transfer with 360 nodes each,
2. The NLP solution needs to be treated further to generate attitude profiles for satellite control,
3. 3-element thrust vector history is converted into 4-element quaternion profile,
4. Requirement on solar array pointing is superimposed in order to secure sufficient power budget,

Graphs show the quaternion history over three revolutions during:

- a. Early transfer,
- b. Close to mid-point of transfer,
- c. Towards end of transfer,



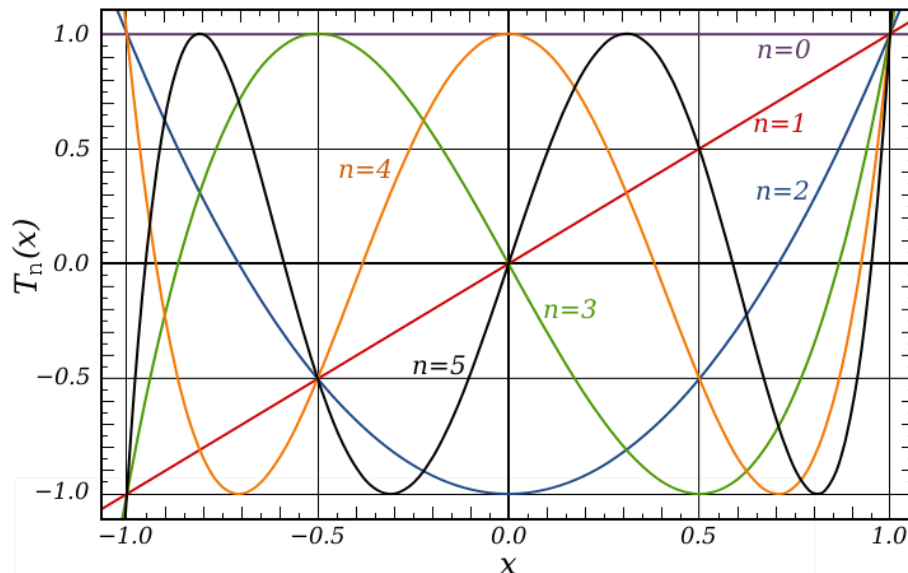
1. Apply least squares method to optimally fit the Chebyshev polynomial to the entire attitude history of the quaternions,
2. Segment the entire history suitably and choose degree of Chebyshev polynomials in order to minimize the required number of coefficients while achieving a maximum error that is below the performance requirement,
3. Empirical study shows that CP of degree 8 is an efficient compromise between increased number of coefficients and increased number of segments to improve the approximation.

Note:

Naturally, the true anomaly is the better independent variable.

Chebyshev Polynomials

1. Sequence of orthogonal polynomials,
2. Chebyshev Polynomials (CP) of first kind:
 - a. Degree 0: $T_0(x)=1$
 - b. Degree 1: $T_1(x)=x$
 - c. Degree n: $T_{n+1}(x)=2x T_n(x)- T_{n-1}(x)$
 - d. x is the normalized independent variable, $x \in [-1, 1]$,



$$T_0(x) = 1$$

$$T_1(x) = x$$

$$T_2(x) = 2x^2 - 1$$

$$T_3(x) = 4x^3 - 3x$$

$$T_4(x) = 8x^4 - 8x^2 + 1$$

$$T_5(x) = 16x^5 - 20x^3 + 5x$$

$$T_6(x) = 32x^6 - 48x^4 + 18x^2 - 1$$

$$T_7(x) = 64x^7 - 112x^5 + 56x^3 - 7x$$

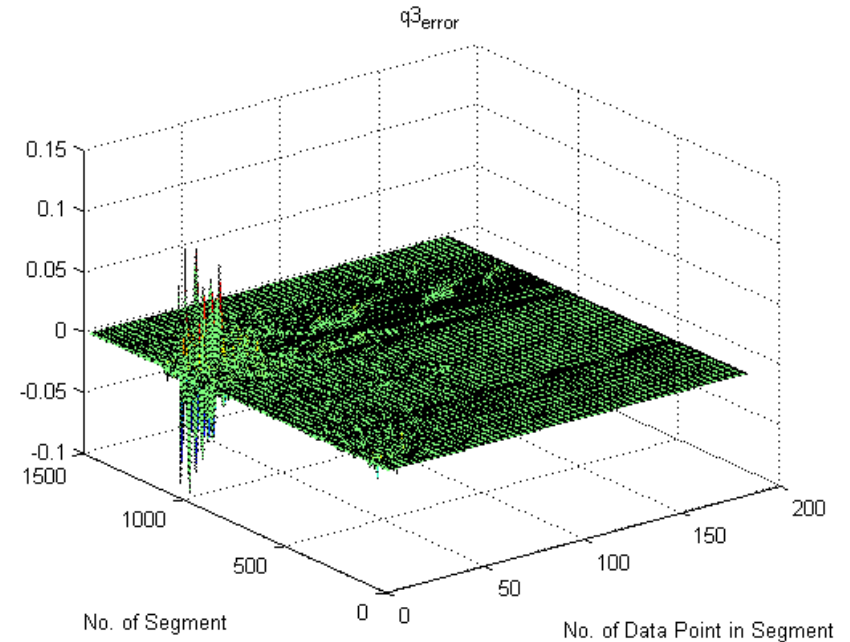
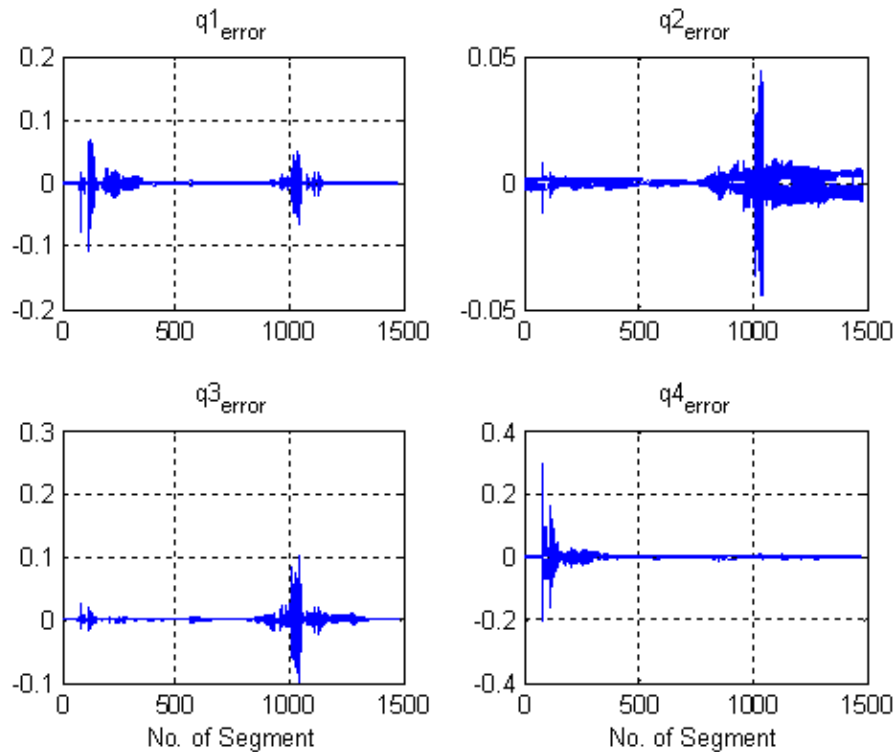
$$T_8(x) = 128x^8 - 256x^6 + 160x^4 - 32x^2 + 1$$

$$T_9(x) = 256x^9 - 576x^7 + 432x^5 - 120x^3 + 9x$$

- Optimum polynomial fit by use of straight forward least squares method,
- Ensure continuity and smoothness across segment bounds.

Example: Results for 1483 Segments: q3 error

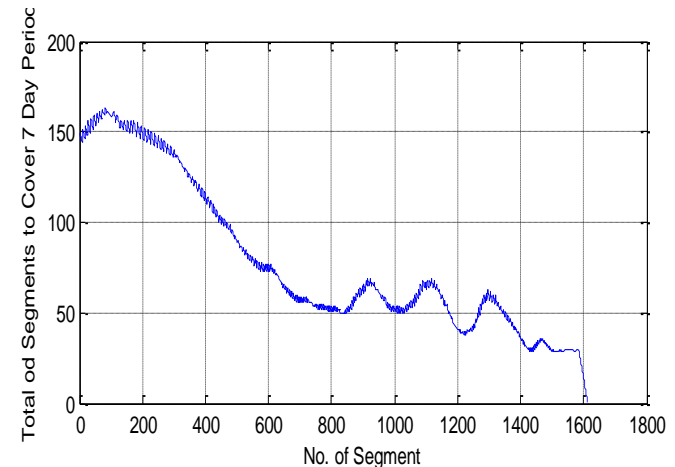
1. Error quaternion (residual rotation) as measure for the quality of the polynomial fit:
$$Q_{\text{error}}(t) = Q_{\text{cp}}(t)' * Q_{\text{input}}(t),$$



Refinement of Segmentation

1613 segments	$X = q1_{\text{error}}$	$X = q2_{\text{error}}$	$X = q3_{\text{error}}$	$X = q4_{\text{error}}$
Mean(abs(x))	0.573e-4	1.89e-4	1.336e-4	0.965e-4
$\sigma(x)$	0.00041	0.00033	0.00042	0.00064
$\text{abs}(x) > 0.05$	0.0033 %	null %	0.0078 %	0.0089 %
$\text{abs}(x) > 0.01$	0.13 %	0.04 %	0.17 %	0.04 %
$\text{abs}(x) > 0.001$	3.7 %	17.7 %	9.9 %	6.45 %

- Spacecraft autonomy period, communication link and on-board memory size need to be dimensioned to be able to handle transfer precision requirements,
- Figure depicts how many subsequent segments are required to approximate the quaternion profiles for any upcoming 7 day period, when using the Chebyshev set with 1613 segmentations ,
- Maximum of 166 segments,
- CP degree 8 => 9 parameters,
- 6308 4-bit parameters needed (memory requirements),
- Better to treat/smoothen input data, than to improve methodology for polynomial fit.



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Motivation for the Development of a New NLP Solver

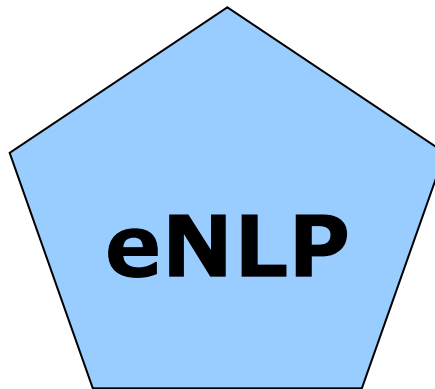


- Most existing solvers are sandboxes for **academic research**,
 - **Maintenance, bug-fixes, enhancement, licensing** depend primarily on academic interests and/or passions,
 - Industrial grade software products are very scarce (coding standards, **documentation, support, verification status**),
 - NLP solver performance characteristics are **driven by particular interests** and not to provide a complete, flexible, state-of-the-art optimization environment,
 - Most NLP solvers have **ONE** state-of-the-art solution **strategy** implemented (with variations),
 - Development competition is driven by **Math** Problem Library performance, **rather than “real life” engineering problems**,
 - Many solvers do not achieve sufficient optimality performance when it comes to **large, sparse problems**.
- ESA proposed the development of a new NLP solver that meets industrial grade requirements.

The eNLP Team



Dept. Mathematics
Univ. of Bremen



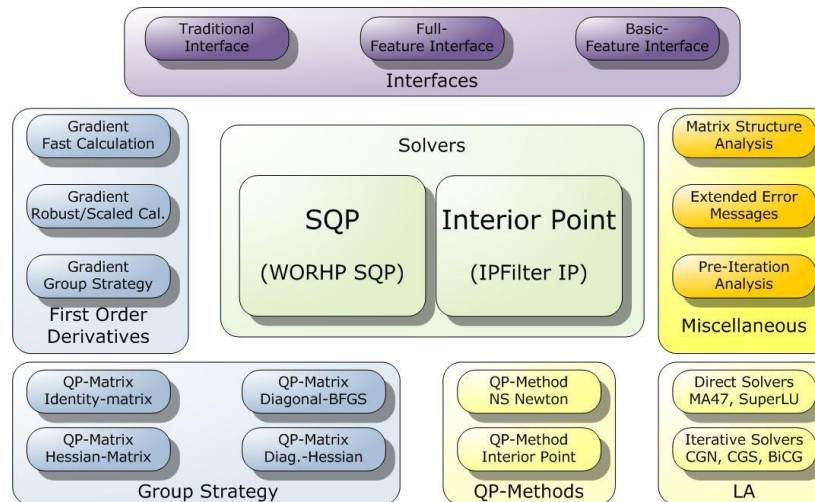
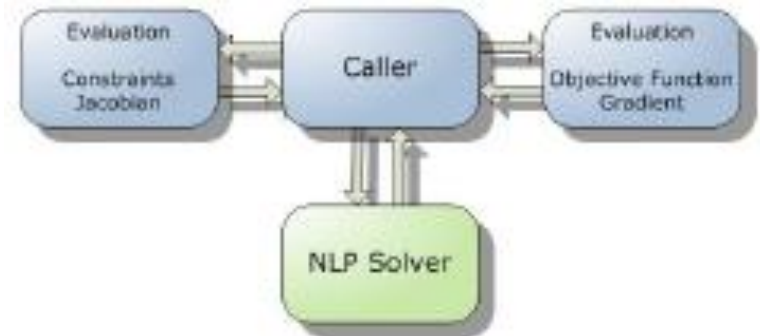
Dept. Mathematics
Univ. Coimbra

Dept. Mathematics
Univ. Birmingham



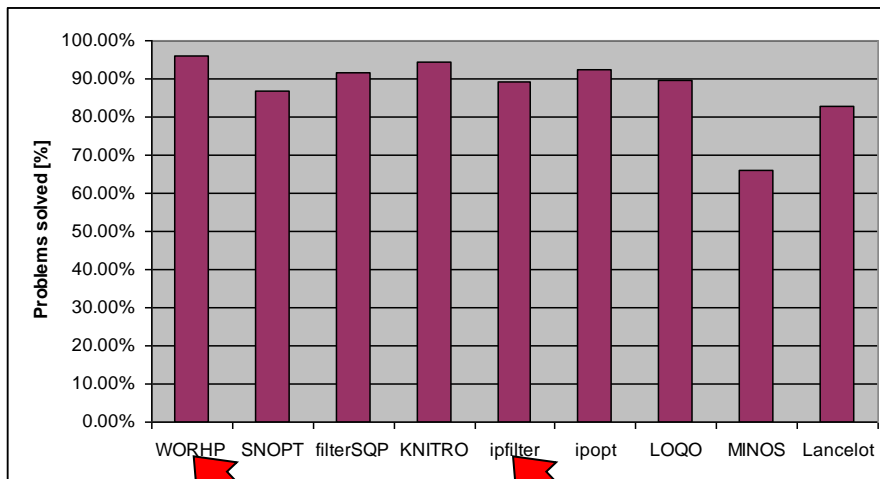
Some Key Features

1. Modular architecture,
2. Reverse communication,
3. Hessian update schemes,
4. Globalization schemes,
5. Failure output.



As of Spring 2010 (old):

1. CUTEr tests for eNLP project are run via AMPL (918 test cases available, <http://www.princeton.edu/~rvdb>),
2. Fully automated process; problems solved with various high-performance benchmark solvers:
3. With 96.1% WORHP-eNLP is the top performer (versatility),
4. Not leading in computation speed yet, but similar to KNITRO, IPOPT,
5. WORHP-eNLP shows superior capabilities for large problems,
6. Further, WORHP-eNLP has been tested and applied to aerospace application cases including interplanetary trajectories.



Some very recent numbers:

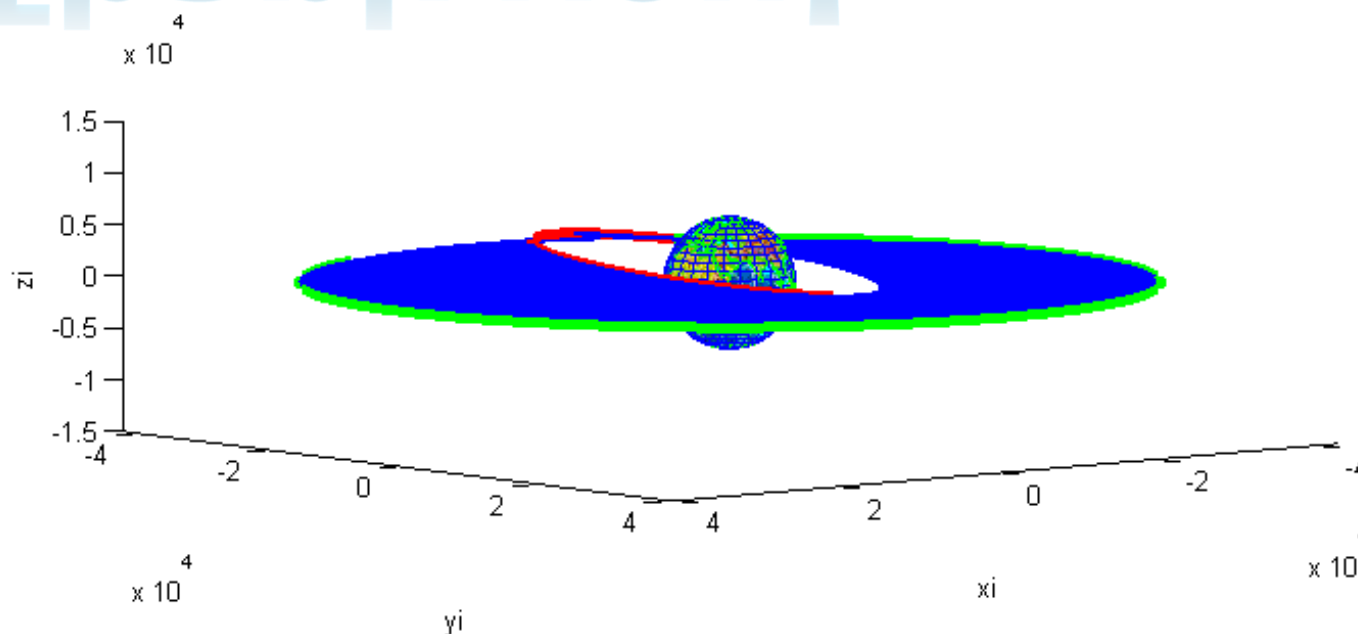
	WORHP LS	WORHP Filter
Problems solved	670	665
Optimal level	664	652
Not solved	2	7
Percentage	99.70%	98.96%
Time	72.51s	111.72s

Latest **confirmed** record (mccormck, 256 GB memory):
> 400,000,000 variables with
> 800,000,000 constraints
➤ Solved!

Conclusions

1. TEC-ECM is making excellent experience with the Direct Transcription approach for solving Optimal Control Problems in a versatile and application driven environment,
2. TEC-ECM keeps expanding the application range in its domain,
3. Development of new NLP solver in Europe provides performance boost, extension of capabilities and added-value for users.
4. WORHP-eNLP is available as Stand-Alone solver and as NLP solver for ASTOS.
5. The eNLP team setup is geared towards commercial/industrial as well as academic use,
6. WORHP-eNLP has taken the lead when it comes to optimality performance,
7. Current efforts are geared towards pushing WORHP-eNLP higher up in the top tier when it come to computation speed and efficiency (Hessian update, Filter, linear algebra, memory management, etc.).
8. www.worhp.de - "We Optimize Really Huge Problems"

Thank you!



Questions?