Recent Advances in Optimization Software for Space Applications

Martin Schlueter

Information Initiative Center
Hokkaido University, Japan

JAXA/ISAS - Seminar
Sagamihara, Kanagwa, Japan

17^{th} Feb 2014

Outline

The Optimization Problem

MINLP

Mixed Integer Nonlinear Programming

The Optimization Problem

General MINLP problem:

$$\text{Minimize} \quad f(x,y) \qquad (x \in \mathbb{R}^{n_{con}},\ y \in \mathbb{Z}^{n_{int}},\ n_{con},\ n_{int} \in \mathbb{N})$$

$$\begin{aligned} \text{subject to:} \quad g_i(x,y) &= 0, \quad i = 1,...,m_e \in \mathbb{N} \\ g_i(x,y) &\geq 0, \quad i = m_e+1,...,m \in \mathbb{N} \\ x_l \leq\ x\ &\leq x_u \quad (x_l,\ x_u \in \mathbb{R}^{n_{con}}) \\ y_l \leq\ y\ &\leq y_u \quad (y_l,\ y_u \in \mathbb{N}^{n_{int}}) \end{aligned}$$

- No information on $f()$ or $g()$ available **[Blackbox]**
- No gradients available for $f()$ and $g()$
- Integers must be integers (no relaxation)

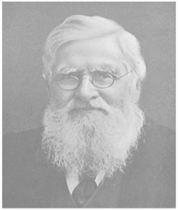
The Optimization Problem

About MINLP problems:

1. Hard to solve
2. Significanlly increased search space $\longrightarrow$ more design possibilities
3. Classic approach on MINLP: Branch and Bound (B&B)

4. **New approach** on MINLP: Evolutionary Programming

Darwin

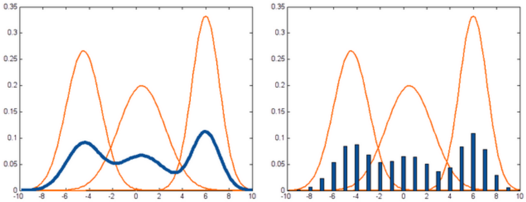


Wallace

The Optimization Software

MIDACO

Mixed Integer Distributed Ant Colony Optimization



The Optimization Software

Key features of MIDACO:

1. Written entirely from scratch (in F77)
2. Search algorithm based on evolutionary ACO heuristic
3. Improved constraint handling by *Oracle Penalty Method*
4. Successfully tested on problems with up to 1000 variables
5. Suitable for expensive problems, due to **parallelization**
6. Available for: Excel, Matlab, Python, C++ and Fortran
7. Licensed Users in over 12 countries
8. Over 7 Years of ongoing development

The Optimization Software

As shown in [1], [2] and [3], MIDACO represents the:

1. **State-of-the-art** for evolutionary programming on MINLP.

As shown **Today** (and in [4] and [5]), MIDACO also represents the:

1. **State-of-the-art** for interplanetary space mission planning.

Furthermore, due its MINLP capabilities MIDACO can:

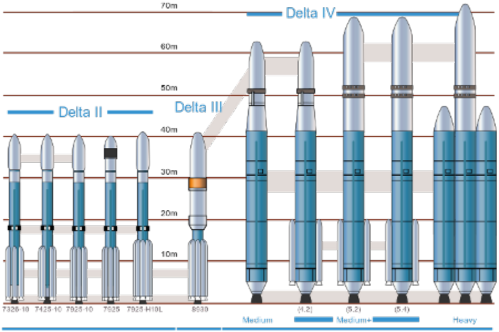
1. **Open new doors** in space application design.

Space Applications

Space Applications

Ascent of Multi-Stage Launch Vehicle (Delta III)

Ascent of Multi-Stage Launch Vehicle



Boing Delta Rocket Family

Ascent of Multi-Stage Launch Vehicle (Delta III)

MIDACO has been used to optimize the ascent of a multi-stage launch vehicle. The model of the launch vehicle was based on a Delta III Space Rocket (Boeing) and contained continuous and discrete variables simultaneously ($\rightarrow$ MINLP) The ascent of the vehicle is formulated as optimal control problem of a (discretized) constrained system of ordinary differential equations (ODE's).

MINLP problem specifications:

1. 128 decision variables
2. 3 integer variables
3. 127 constraints
4. 5 equality constraints

Ascent of Multi-Stage Launch Vehicle (Delta III)

Financial constraint

5 Different types of strap-on boosters

Type	Thrust Power (N)	Mass $_{Total}$ (kg)	Mass $_{Propellant}$ (kg)	Cost
1	471375	14468	12758	0.75
2	565650	17361	15309	0.90
3	628500	19290	17010	1.00
4	691350	21219	18711	1.10
5	785625	24113	21263	1.25

Additional constraint: Maximal financial budget $= 9$

Ascent of Multi-Stage Launch Vehicle (Delta III)

Integer Extension

Formulating the type and number of strap-on boosters as variable.
5 Different Booster types. Up to 9 active booster in first stage.

Table 5: Enumeration over all (feasible) booster configurations with $B_1 \geq 6$

Booster-Config.				Booster-Config.				Booster-Config.				Booster-Config.			
B_1	T_1	T_2	Best known $f(x,y)$	B_1	T_1	T_2	Best known $f(x,y)$	B_1	T_1	T_2	Best known $f(x,y)$	B_1	T_1	T_2	Best known $f(x,y)$
6	1	1	-6685.71	8	1	1	-6848.21	7	1	1	-6789.90	9	1	-	-6855.30
6	1	2	-6808.53	8	1	2	-6900.99	7	1	2	-6883.25	9	2	-	-7324.23
6	1	3	-6884.45	8	1	3	-6935.36	7	1	3	-6942.60	9	3	-	**-7599.88**
6	1	4	-6955.92	8	1	4	-6969.11	7	1	4	-6999.74				
6	1	5	-7055.32	8	1	5	-7018.56	7	1	5	-7081.49				
6	2	1	-7075.93	8	2	1	-7297.53	7	2	1	-7213.85				
6	2	2	-7195.10	8	2	2	-7228.32	7	2	2	-7303.58				
6	2	3	-7269.14	8	2	3	-7381.77	7	2	3	-7360.66				
6	2	4	-7339.15	8	2	4	-7414.42	7	2	4	-7415.64				
6	3	1	-7315.13	8	2	5	-7321.22	7	2	5	-7494.50				
6	3	2	-7431.81	8	3	1	**-7565.08**	7	3	1	-7271.36				
6	*3*	*3*	*-7504.48*	8	3	2	**-7614.97**	7	3	2	**-7556.82**				
6	4	1	**-7539.17**	8	3	3	**-7647.50**	7	3	3	**-7612.70**				

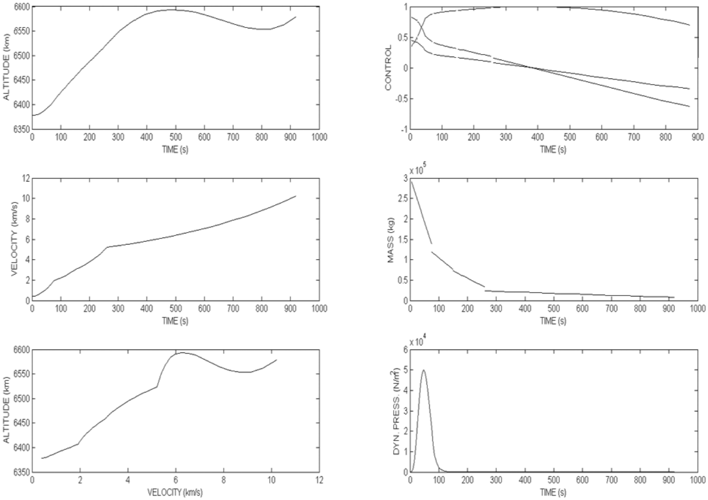
Overall best configuration: $y = \{8, 3, 3\}$, $f(x, y) = -7647.5(kg)$

Ascent of Multi-Stage Launch Vehicle (Delta III)

Table 7: 30 runs by MIDACO (max time = 7200) + SQP (max iter=1000)

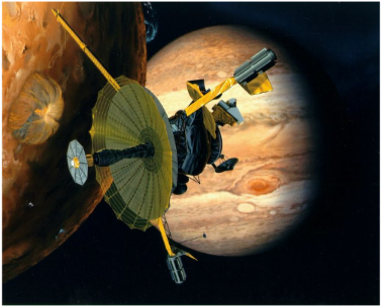
	Booster-Config.			SQP			MIDACO			
Run	B_1	T_1	T_2	$f(x,y)$	Eval	Time	$f(x,y)$	Eval	Time	
1	9	3	1	-7599.88	357908	317.7	-7419.65	3455790	7200.0	
2	9	3	1	-7599.88	353114	315.1	-7449.22	3450447	7200.0	
3	8	3	3	-7647.50	363366	321.1	-7502.77	3443609	7200.0	<- Optimal Solution reached
4	9	3	1	-7599.88	267022	236.8	-7419.91	3449060	7200.0	
5	9	3	5	-7599.88	309848	274.6	-7418.63	3460976	7200.0	
6	9	3	1	-7599.88	173384	153.8	-7436.00	3472466	7200.0	
7	9	3	1	-7599.88	346444	307.3	-7555.53	3456612	7200.0	
8	9	3	4	-7599.88	265638	234.8	-7369.10	3457577	7200.0	
9	7	3	3	-7567.75	6713	6.4	-7565.33	3445493	7200.0	
10	9	3	4	-7599.88	284148	254.1	-7524.85	3445318	7200.0	
11	8	3	3	-7524.57	7379	7.1	-7519.89	3447985	7200.0	
12	8	3	3	-7647.50	354988	313.6	-7481.90	3459946	7200.0	<- Optimal Solution reached
13	9	3	1	-7599.88	270324	240.1	-7444.49	3453002	7200.0	
14	8	3	3	-7647.50	363938	322.9	-7479.16	3451839	7200.0	<- Optimal Solution reached
15	9	3	5	-7599.88	266138	235.9	-7500.50	3464034	7200.0	
16	9	3	5	-7599.88	301198	266.8	-7519.93	3481049	7200.0	
17	9	3	3	-7599.88	344342	307.8	-7456.35	3450507	7200.0	
18	9	3	1	-7599.88	273766	242.3	-7528.82	3454741	7200.0	
19	9	3	1	-7599.88	298972	267.0	-7527.04	3458943	7200.0	
20	9	3	4	-7599.88	324916	290.1	-7431.08	3468826	7200.0	
21	9	3	5	-7599.88	355510	317.4	-7498.23	3487475	7200.0	
22	9	3	5	-7599.88	341446	322.4	-7430.29	3042720	7200.0	
23	8	3	3	-7647.43	309588	370.1	-7536.62	2879186	7200.0	<- Optimal Solution reached
24	9	3	5	-7599.88	349166	425.9	-7460.48	2435917	7200.0	
25	8	3	3	-7513.12	7360	9.2	-7505.67	2568537	7200.0	
26	6	4	1	-7539.17	361342	332.9	-7434.57	2871096	7200.0	
27	9	3	5	-7599.88	313390	313.4	-7348.84	3060132	7200.0	
28	9	3	3	-7599.88	263188	347.4	-7475.90	3150988	7200.0	
29	8	3	3	-7647.50	355292	321.1	-7470.97	2873982	7200.0	<- Optimal Solution reached
30	8	3	3	-7647.50	365252	327.5	-7491.21	3336049	7200.0	<- Optimal Solution reached

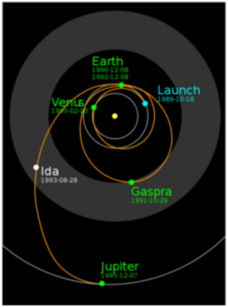
Ascent of Multi-Stage Launch Vehicle (Delta III)



Interplanetary Space Trajectory (MGA-DSM-MINLP)

Interplanetary Space Trajectory (MGA-DSM-MINLP)

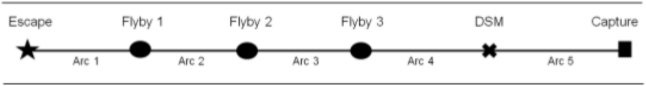




NASA’s Galileo Mission (launched 1989)

Interplanetary Space Trajectory (MGA-DSM-MINLP)

Mission Layout (MGA-DSM)



Possible integer choices for Fly-By Planets:

Number	Planet
1	Mercury
2	Venus
3	Earth
4	Mars
5	Jupiter
6	Saturn
7	Uranus
8	Neptune
9	Pluto

MINLP: 21 Variables (3 Integer) & 12 Constraints

Interplanetary Space Trajectory (MGA-DSM-MINLP)

Table 9: Optimization variables x (continuous) and y (integer) with bounds

Variable	Description	Lower Bound	Upper Bound
continuous			
x_1	Launch Date	0 (01 Jan. 1989)	730 (31 Dec. 1990)
x_2	Duration of Arc 1	0 (days)	200 (days)
x_3	Duration of Arc 2	0 (days)	400 (days)
x_4	Duration of Arc 3	0 (days)	800 (days)
x_5	Duration of Arc 4	0 (days)	100 (days)
x_6	Duration of Arc 5	0 (days)	1200 (days)
x_7	Thrust Escape (X direction)	-6000.0 (m/sec)	6000.0 (m/sec)
x_8	Thrust Escape (Y direction)	-6000.0 (m/sec)	6000.0 (m/sec)
x_9	Thrust Escape (Z direction)	-3000.0 (m/sec)	3000.0 (m/sec)
x_{10}	Thrust Capture (X direction)	-6000.0 (m/sec)	6000.0 (m/sec)
x_{11}	Thrust Capture (Y direction)	-6000.0 (m/sec)	6000.0 (m/sec)
x_{12}	Thrust Capture (Z direction)	-3000.0 (m/sec)	3000.0 (m/sec)
x_{13}	Thrust DSM (X direction)	-1000.0 (m/sec)	1000.0 (m/sec)
x_{14}	Thrust DSM (Y direction)	-1000.0 (m/sec)	1000.0 (m/sec)
x_{15}	Thrust DSM (Z direction)	-500.0 (m/sec)	500.0 (m/sec)
x_{16}	Altitude Flyby 1	0.00 ($\sim Alt_{min}$)	1.00 ($\sim Alt_{max}$)
x_{17}	Altitude Flyby 2	0.00 ($\sim Alt_{min}$)	1.00 ($\sim Alt_{max}$)
x_{18}	Altitude Flyby 3	0.00 ($\sim Alt_{min}$)	1.00 ($\sim Alt_{max}$)
integer			
y_1	Planet Flyby 1	1 (Mercury)	9 (Pluto)
y_2	Planet Flyby 2	1 (Mercury)	9 (Pluto)
y_3	Planet Flyby 3	1 (Mercury)	9 (Pluto)

Interplanetary Space Trajectory (MGA-DSM-MINLP)

Table 13: 10 test runs by MIDACO on mission model with 3% sphere of action

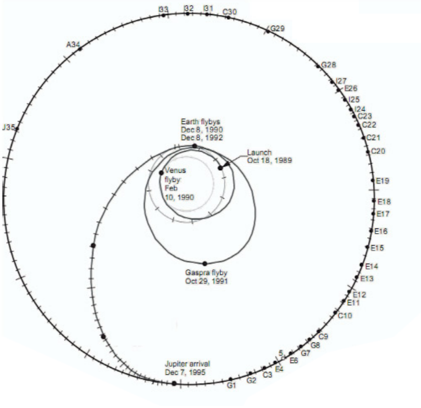
Run	Launch	ΔV	Duration	FlyBy 1	FlyBy 2	FlyBy 3
1	6 Nov. 1989	2553	5.88	Venus	Earth	Earth
2	30 Nov. 1989	3310	4.83	Venus	Earth	Earth
3	30 Nov. 1989	3218	4.88	Venus	Earth	Earth
4	10 Jul. 1989	3390	3.97	Venus	Earth	Mars
5	20 Nov. 1989	2890	4.77	Venus	Earth	Earth
6	23 May 1989	2759	5.35	Earth	Venus	Earth
7	21 Mar 1989	*infeasible*	4.85	Earth	Earth	Mars
8	13 Apr. 1989	3290	4.54	Earth	Venus	Earth
9	30 Nov. 1989	3289	4.79	Venus	Earth	Earth
10	16 Sep. 1989	2684	6.10	Venus	Earth	Earth

Table 14: Comparison between original Galileo and MIDACO Missions

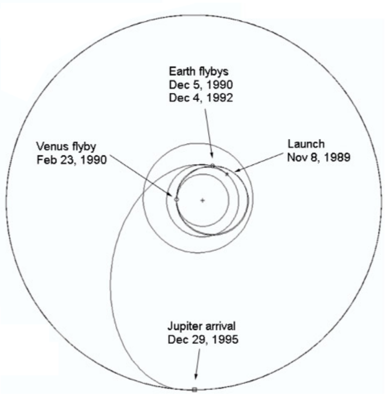
	Galileo Mission	Mission1 refine 0.5 %	Mission4 refine 0.5 %
Launch	18 Oct. 1989	8 Nov. 1989	6 Jul. 1989
Duration	6.14 Years	6.14 Years	4.15 Years
ΔV	*unknown*	3,350 m/sec	5,177 m/sec
1st Flyby			
Planet	Venus	Venus	Venus
Date	10 Feb. 1990	23 Feb. 1990	21 Jan. 1990
Altitude	16,000km	28,901km	3,013km
2nd Flyby			
Planet	Earth	Earth	Earth
Date	8 Dec. 1990	5 Dec. 1990	4 Sep. 1990
Altitude	960km	473,191km	1,754km
3rd Flyby			
Planet	Earth	Earth	Mars
Date	8 Dec. 1992	4 Dec. 1992	31 Dec. 1990
Altitude	303km	300km	39km

Interplanetary Space Trajectory (MGA-DSM-MINLP)

Comparison of original Galileo Trajectory and MIDACO Mission1



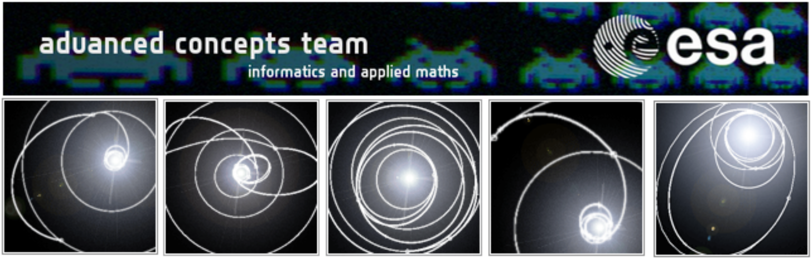
Galileo



MIDACO

ESA Space Benchmarks (ACT-GTOP)

GLOBAL TRAJECTORY OPTIMISATION PROBLEMS DATABASE



Please visit:

http://www.esa.int/gsp/ACT/inf/projects/gtop/gtop.html

ESA Space Benchmarks (ACT-GTOP)

GTOP database benchmark problems

Benchmark Name	Variables	Constraints	Number of submissions	Time between first and last submission
Cassini1	6	4	3	6 Month
GTOC1*	8	6	2	13 Month
Messenger (reduced)	18	0	3	11 Month
Messenger (full)*	26	0	8	55 Month
Cassini2*	22	0	7	14 Month
Rosetta	22	0	7	6 Month
Sagas	12	2	1	-

*Best solution found by MIDACO and published on ESA Website (2013).

$\longrightarrow$ Best known solutions required several **Month and even Years**

ESA Space Benchmarks (ACT-GTOP)

Many researchers worked on GTOP benchmarks

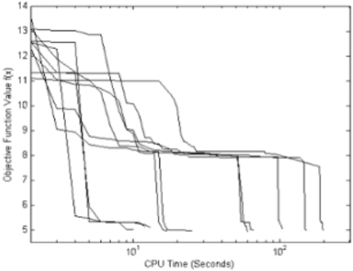
Author(s)	Problems	Solved
Gruber (2009)	1	1
Lancinskas, Zilinskas & Ortigosa (2010)	1	0
Danoy, Pinto & Dorronsoro (2012)	1	1
Islam, Roy & Suganthan (2012)	2	0
Gad (2011)	2	0
Ampatzis and Izzo (2009)	2	1
Biazzini, Banhelyi, Montresor et al. (2009)	2	1
Musegaas (2012)	2	2
Henderson (2013)	2	1
Biscani, Izzo & Yam (2010)	3	2
Izzo (2010)	4	1
Addis, Cassioli, Locatelli et al. (2011)	4	3
Vinko & Izzo (2008)	5	1
Stracquadanio, La Ferla, De Felice et al. (2011)	7	6

$\longrightarrow$ GTOP benchmarks are **Hard to solve**

ESA Space Benchmarks (ACT-GTOP)

10 Test Runs of MIDACO (with default parameters) on Cassini1 (0.1%)

Run	$f(X)$	*Blocks*	*Eval*	*Time (Sec)*
1	4.933760	226,556	1,812,448	12
2	4.935615	1,290,295	10,322,360	66
3	4.935378	189,257	1,514,056	10
4	4.935624	328,743	2,629,944	17
5	4.935491	1,050,408	8,403,264	60
6	4.935602	2,019,317	16,154,536	103
7	4.934514	2,926,304	23,410,432	152
8	4.935575	240,084	1,920,672	13
9	4.935630	471,085	3,768,680	25
10	4.934698	865,179	6,921,432	198



Best known solution $f(x) = 4.9307$ (DeltaV)

Cassini1 is the *easiest* GTOP problem

ESA Space Benchmarks (ACT-GTOP)

MIDACO holds 1st and 2nd Record Solution on Messenger (Full) **[Hardest GTOP Problem]**

OBJECTIVE FUNCTION (KM/S)	SOLUTION VECTOR	CREDITS:	DATE:
6.943	N/A	M. Schlueter, J. Fiala, M. Gerdts, University of Birmingham (found by MIDACO solver)	19/06/2009
6.404	N/A	G. Stracquadanio, A. La Ferla, G. Nicosia, University of Catania (Found by SAGES Self-Adaptive- Gaussian Evolutionary Strategy)	17/11/2009
6.047	N/A	M. Schlueter, University of Birmingham, M. Gerdts, University of Wuerzburg, M. Munetomo and K. Akama, Hokkaido University, S. Erb and G. Ortega, ESTEC/TEC-ECM (found by MIDACO solver)	30/11/2009
4.254	N/A	F. Biscani and D. Izzo, ESTEC Advanced Concepts Team. Found using PaGMO	01/12/2009
2.970	CLICK HERE	G. Stracquadanio, Dept of Biomedical Engineering, Johns Hopkins University, A. La Ferla, G. Nicosia, University of Catania (Found by SAGES Self-Adaptive-Gaussian Evolutionary Strategy)	28/02/2011
2.113	CLICK HERE	G. Stracquadanio, Dept of Biomedical Engineering, Johns Hopkins University, A. La Ferla, G. Nicosia, University of Catania (Found by SAGES Self-Adaptive-Gaussian Evolutionary Strategy)	10/04/2012
2.104	CLICK HERE	M. Schlueter, M. Munetomo (found by MIDACO solver)	17/10/2013

Record Nr. 1 (Feb 2014)	Record Nr. 2 (Nov 2013)
1.986 km/sec	2.104 km/sec
x[0] = 2037.793650139994270;	x[0] = 2060.627272281109072;
x[1] = 4.035829738138824;	x[1] = 4.042601735668291;
x[2] = 0.555436051620218;	x[2] = 0.440387114371649;
x[3] = 0.636393238132614;	x[3] = 0.653458177621111;
x[4] = 451.447750355605706;	x[4] = 428.903525341671866;
x[5] = 224.694208867341700;	x[5] = 224.687235869007964;
x[6] = 221.880177091452026;	x[6] = 221.385427446748679;
x[7] = 265.151670648704567;	x[7] = 266.124367319569956;
x[8] = 358.288400601717910;	x[8] = 358.048599982140672;
x[9] = 534.212841688461253;	x[9] = 444.429427422362778;
x[10] = 0.538362042300023;	x[10] = 0.581561467686441;
x[11] = 0.753339114855577;	x[11] = 0.821640755039470;
x[12] = 0.719294670714628;	x[12] = 0.698772357707937;
x[13] = 0.750352217362636;	x[13] = 0.720609016544215;
x[14] = 0.830544140272688;	x[14] = 0.829340143768712;
x[15] = 0.902346174479331;	x[15] = 0.875166415983967;
x[16] = 1.424520437366302;	x[16] = 1.576183861868870;
x[17] = 1.100327418086428;	x[17] = 1.100003220464050;
x[18] = 1.050586612441532;	x[18] = 1.052869945803204;
x[19] = 1.164323431714812;	x[19] = 1.050000430115585;
x[20] = 1.072024806423244;	x[20] = 1.477180737136582;
x[21] = 2.820081320974608;	x[21] = 2.786201469971995;
x[22] = 1.515793529485625;	x[22] = 1.603649010967501;
x[23] = 2.588292685117210;	x[23] = 2.622074959673106;
x[24] = 1.756804428126312;	x[24] = 1.571933956929996;
x[25] = 1.530086523658156;	x[25] = 1.606318012513329;

8 Solution submission over a period of 4.5 Years $\longrightarrow$ **Very Hard**

ESA Space Benchmarks (ACT-GTOP)

Out-of-the-box performance of MIDACO on GTOP Benchmarks

Benchmark	Best Time	Average Time	Successrate
Cassini1	10 Seconds	1 Minute	100%
GTOC1	-	-	0%
Messenger (reduced)	1 Hour	9 Hours	60%
Messenger (full)	-	-	0%
Cassini2	15 Hours	15 Hours	20%
Rosetta	10 Minutes	9 Hours	90%
Sagas	1 Minute	12 Minutes	100%

⟶ MIDACO solves 5 out of 7 within **Minutes to Hours**

⟶ MIDACO can solve **7 out of 7** with some tuning

The Impact of Parallelization

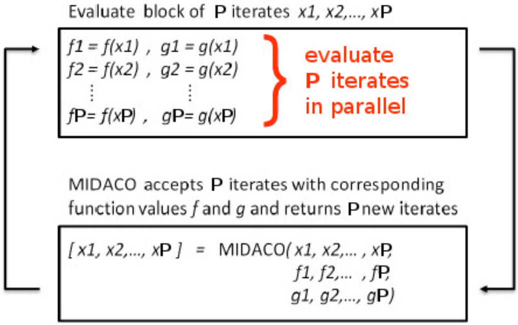
The Impact of Parallelization

on

Space Trajectory Optimization

The Impact of Parallelization

MIDACO distributes the problem evaluation calls:



$\longrightarrow$ Useful for **cpu-time expensive** applications!

The Impact of Parallelization

Impact of parallelization for **P** = 1,2,4,8 on GTOP-Cassini1 Benchmark

P	$f(x)$	$Blocks$	$Eval$	$Time$
1	4.977279	3150654	3150654	99
2	4.977542	1683175	3366349	57
4	4.977675	991475	3965898	38
8	4.977332	458177	3665418	23

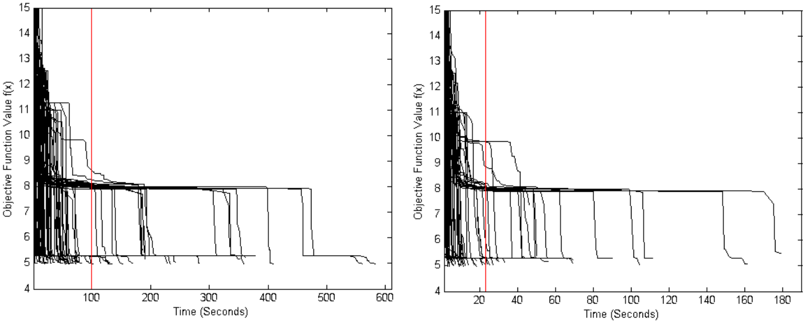
Comparison of *potential* and *actual* speed up

P	Potential Speed Up	Actual Speed Up
2	1.87	1.74
4	3.18	2.61
8	6.88	4.31

$\longrightarrow$ Cassini1 is *too light* to fully benefit from parallelization

The Impact of Parallelization

Convergence curves for **P**=1 and **P**=8 (based on 100 runs)



$\longrightarrow$ Nearly identical convergence behaviour

The Impact of Parallelization

So far, only small parallelization facors for **P** has been considered.

What happens, if larger factors are applied?

How far does this concept scale up?

$\longrightarrow$ Some preliminary results

The Impact of Parallelization

Table : Average *Blocks* needed for **P**=1 and **P**=500 (based on 100 runs)

Benchmark	Blocks (**P** = 1)	Blocks (**P** = 500)
Cassini1 (6 Variables)	3,150,654	37,276
Sagas (18 Variables)	230,641,118	1,315,877

Table : Potential Speed-Up

Benchmark	Speed Up
Cassini1	85 times
Sagas	175 times

Massive Parallelization = Massive Speed-Up

Conjecture: More Variables = More Speed Up

The Impact of Parallelization

Hypothetical case study based on previous experience

Table : Hypothetical Mission Details

Number of Variables	9
Evaluation Time	6 Seconds (expensive)
Required *Blocks* for **P**=1	5,000,000
Potential speed up for **P**=500	100 times

Table : Estimation of Time required to solve mission with MIDACO

Time to solve with **P**=1	30,000,000 Seconds	$\approx$ **1 Year**
Time to solve with **P**=500	300,000 Seconds	$\approx$ **3.5 Days**

References

References

Literature References (selected)

[1] Schlueter M., Gerdts M., Rueckmann J.J.:
A Numerical Study of MIDACO on 100 MINLP Benchmarks.
Optimization (Taylor & Francis), Vol 61, Issue 7, Pages 873-900 (2012)

[2] Schlueter M., Munetomo M.:
Parallelization Strategies for Evolutionary Algorithms for MINLP.
Proc. Congress on Evolutionary Computation (IEEE-CEC), Pages 635-641 (2013)

[3] Schlueter M., Erb S., Gerdts M., Kemble S., Rueckmann J.J.:
MIDACO on MINLP Space Applications.
Advances in Space Research (Elsevier), Vol 51, Issue 7, Pages 1116-1131 (2013)

[4] Schlueter M.:
MIDACO Software Performance on Interplanetary Trajectory Benchmarks.
Advances in Space Research (Elsevier), *submitted* (2014)

[5] Schlueter M., Munetomo M.:
Parallelization for Space Trajectory Optimization.
Proc. Congress on Evolutionary Computation (IEEE-CEC), *submitted* (2014)

Conclusions

1. MINLP can **open new possibilities** in space application design.
2. MIDACO is **powerful** enough to solve MINLP space applications.
3. MIDACO holds **1st** (and 2nd) record on **hardest ESA benchmark**.
4. MIDACO is the **state-of-the-art** for trajectory optimization.
5. **Parallel** MIDACO can significantly speed up expensive applications.

Thank you for your attention!

m(_ _)m