Some Things That GTOC Taught Us in Eighteen Years (and Counting)

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POLITECNICO DI TORINO

Outline

GTOC

- the Global Trajectory Optimisation Competition was inaugurated in 2005 originating from an idea by Dario Izzo of the Advanced Concepts Team, European Space Agency
- participating teams are invited to solve a high-complexity space trajectory global optimization problem
- purposes
    - test existing optimization methods
    - stimulate new ideas
    - involve people from different fields (e.g., mathematicians) with their specific knowledge

Competition

- 4 weeks to solve the proposed problem
- clear rules to classify the solutions and ensure a competition winner
- the winning team organizes the next competition (schedule, problem definition, rules, etc.)

Problems

- the design space is large and a large number of local optima exist;
- the problem is complex but not overwhelming, and should be solved within the prescribed 4-week time frame;
- the mathematical formulation is sufficiently simple so that it should also be solved by researchers not experienced in astrodynamics;
- even though registered teams may have developed tools for the analysis of the proposed kind of mission, the problem peculiarities should make it new to all the teams

Features

- combinatorial problem:
  - define sequence of gravity assists
  - select targets among a large set
  - select sequence of specified targets
- trajectory problem:
  - low-thrust (or continuous-thrust)
  - impulsive-thrust

GTOC1: Save the Earth

- maximize the energy change of a potentially hazardous asteroid with a kinetic impactor equipped with low thrust propulsion
- winner: Jet Propulsion Laboratory (JPL)
- key: gravity assists to achieve a retrograde orbit

GTOC2: Multiple Asteroid Rendezvous

- low-thrust spacecraft must rendezvous with one asteroid from each of four defined groups of asteroids while maximizing the ratio of final spacecraft mass to flight time
- winner: Politecnico di Torino
- key: exploit orbit geometry for transfers

GTOC3: Multiple Sample Return

- low-thrust spacecraft launches from Earth, must rendezvous with three asteroids from a specified group of NEAs and finally rendezvous with the Earth, while maximizing a function of final mass and stay-time on the asteroids
- winner: Centre National d'Etudes Spatiales (CNES)
- key: simplified global search + separate local optimization of each leg

GTOC4: Asteroid Billiard

- maximize the number of asteroids visited by a low-thrust spacecraft en route to rendezvous with another asteroid
- winner: Moscow State University
- key: build long chains of connected asteroids

GTOC5: Penetrators

- maximize number of visited asteroid by a low-thrust spacecraft, which must first rendezvous and the perform a flyby of each asteroid propulsion
- winner: define (restricted) set of feasible transfers between asteroids for global search

GTOC6: Mapping of Galilean Moons

- maximize the number of regions mapped by a low-thrust spacecraft, where mapping requires to perform a flyby with periapsis above the region
- winner: Politecnico di Torino - Università di Roma Sapienza
- key: exploit tools to design resonant/non resonant trasfers + adjust timing with propulsion

GTOC7: Multi-Spacecraft Exploration the Asteroid Belt

- maximize the number of Main Belt asteroid visited by three exploration probes; probes are released by and must return to a mothership
- winner: Jet Propulsion Laboratory (JPL)
- key: global search techniques

GTOC8: Very Large Baseline Interferometry

- maximize an index related to the number of radio sources observed by three low-thrust spacecraft in formation, quality of observation, source location; lunar gravity assists are allowed
- winner: ESA's Advanced Concepts Team - JAXA
- key: Moon gravity assists and resonances to achieve high orbits

GTOC9: Kessler Run

- remove 123 space debris objects with multiple launches while minimizing an index related to masses at launch; each launch sends a spacecraft to an object, and the spacecraft moves with impulsive thrust to reach additional objects
- winner: Jet Propulsion Laboratory (JPL)
- key: global search capabilities + transfer cost estimation

GTOC10: Settlers of the Galaxy

- maximize an index related to the number of colonized galaxies and their spatial distribution (futuristic propulsion technology)
- winner: National University of Defense Technology / Xi'an Satellite Control Center
- key: galactic Lambert problem + tree development + global coverage

GTOC11: Dyson Sphere

- maximize an index related to the total mass of asteroids moved to the vicinity of the sun with a futuristic propulsion technology
- winner: Tsinghua University - Shanghai Institute of Satellite Engineering
- key: Lambert solver and global search + mass distribution among stations + increasing the number of asteroids may decrease the index

GTOC12: Asteroid Mining

- maximize the mass collected on multiple asteroids by low-thrust ships and returned to the Earth (the mass from each asteroid is weighted with a bonus factor)
- winner: Jet Propulsion Laboratory (JPL)
- key: *??? I had no time to study the problem (academic responsibilities conflict with research work) !!!*

Direct Versus Indirect Methods

- direct and indirect methods are the techniques traditionally employed in space trajectory optimization
- direct methods: more robust but more computationally expensive
- indirect methods: usually faster but need tailored tentative solutions
- GTOC results seem to show that both method are mostly equally effective

Local Versus (?) Global

- global and local optimization techniques are often seen a juxtaposed methods
  - global search for the combinatorial problem
  - local search for the trajectory optimization problem
- however
  - global exploration is only feasible on reasonable-size sets: pruning and cost estimations are required (i.e., some sort of local optimization is needed)
  - local search can only be applied to subsets that can only be defined with global search methods
- is there any difference ?

What Has Changed in 18 Years

- complexity of the problems has increased exponentially: from a few objects and gravity assists to thousands of objects and hundreds of gravity assists
- computational power has also grown and allows for more exhaustive global search
- are we going to stress G (global) versus T (trajectory) in GTOC?

Knowledge and Tools

- non-exhaustive list of GTOC fruits
  - strategies to define tentative solutions for legs and leg-joining
  - orbital parameters are a useful pruning tool but false-negative may affect the solutions
  - Edelbaum approximation can be adapted to non-circular orbits
  - Lambert problem can be used for low-thrust arc approximation (but only for short burn arcs)
  - design of Moon tours: try to use 1:1 resonance when time constraints are present
  - optimal noncoplanar geocentric transfers exploiting J2
  - better having global search capabilities ready (or start developing them!)

Personal Notes

- people can work 20 hours a day when sufficiently motivated !!!
- only join GTOC if people around you (either parents, spouse, or children, whatever is your family situation) are very patient
- my daughter was born on December 5$^{\text{th}}$ 2005, the day solutions for GTOC1 were due: I was tempted to give her the name "GTOC" but then went with Sara (and she is very grateful for this)

Contacts and Aknowledgments

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