SEARCH FOR A GRAND TOUR OF THE JUPITER GALILEAN MOONS

Humies – 2013

GECCO, Amsterdam

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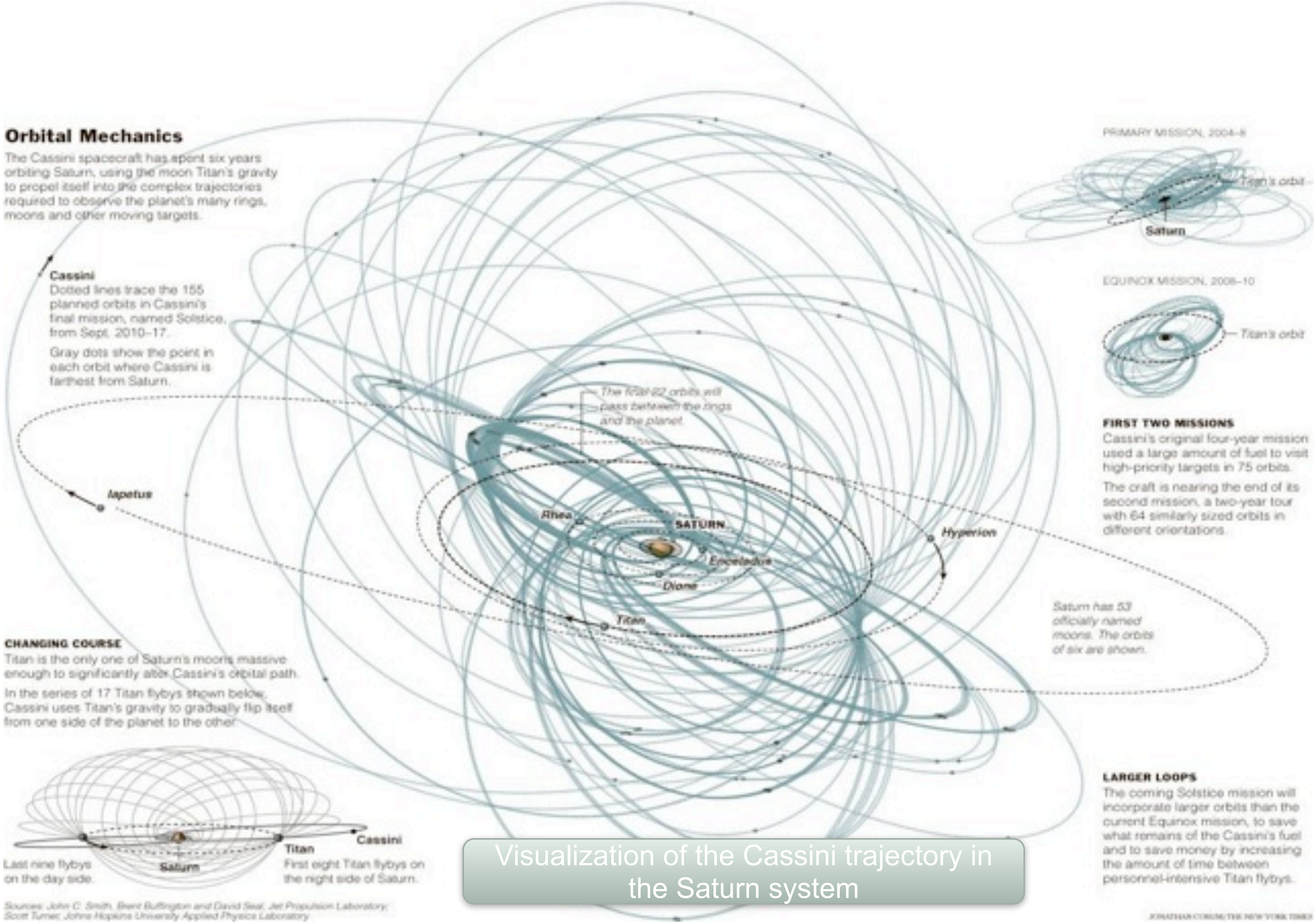
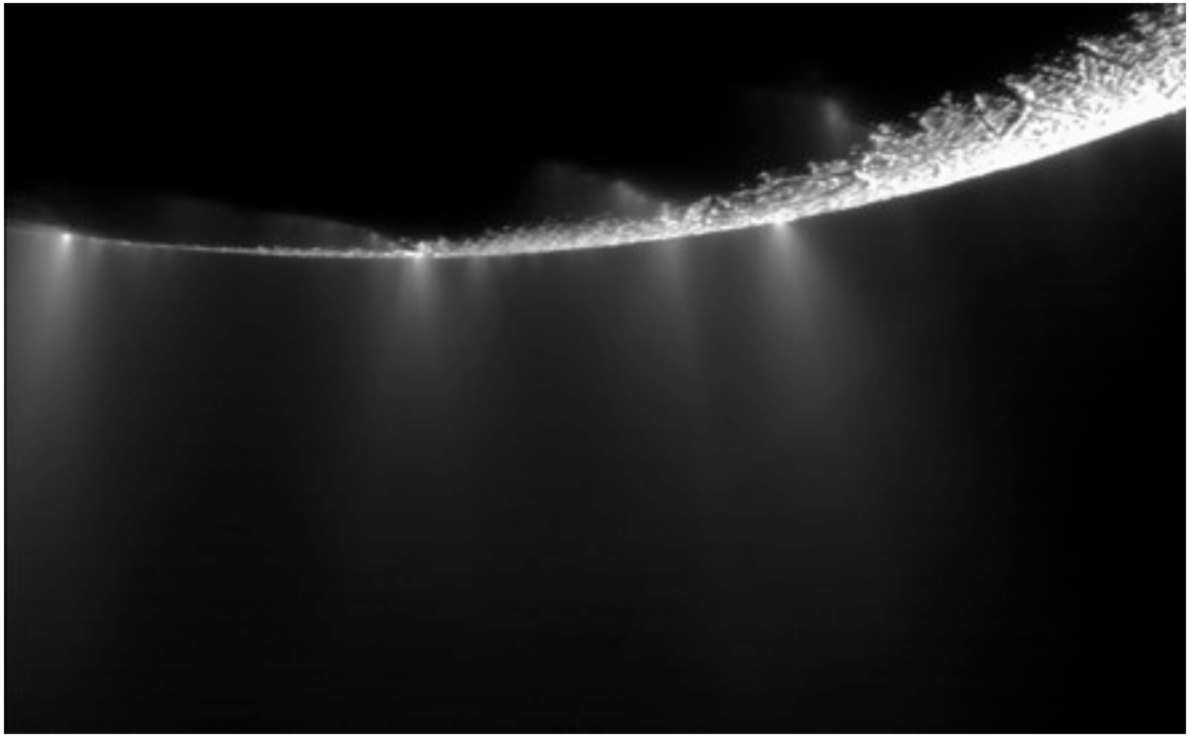
Interplanetary Trajectories are complex …



Visualization of the Cassini trajectory in the Saturn system

... and deliver amazing science



Water rich plume discovered during a fly-by in the south pole region of Enceladus - Courtesy: NASA

Global Trajectory Optimization Competition (GTOC)

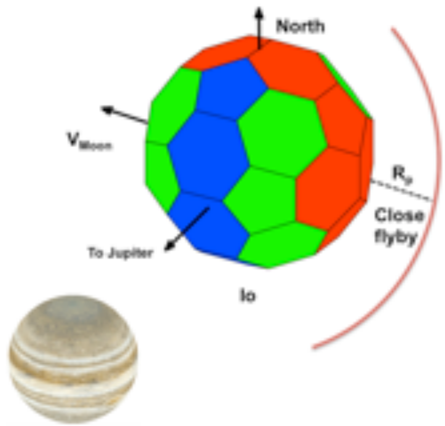
- Gathers the top worldwide experts on interplanetary trajectory design
- Forum for cross-fertilization of ideas in this complex domain
- ~100 different institutions over the years: academia, industry and space agencies
- ~1 month to solve an exceptionally hard problem
- Winner organizes the next edition
- Yearly workshops
- All results/methods "peer-reviewed", Journal special issues follow
- Evolutionary Algorithms used by some of the teams over the years (Neuro Controllers, PSO, GA, GP, ...)
- but never competitive ... until now
- [Dedicated web portal]

Acta Astronautica

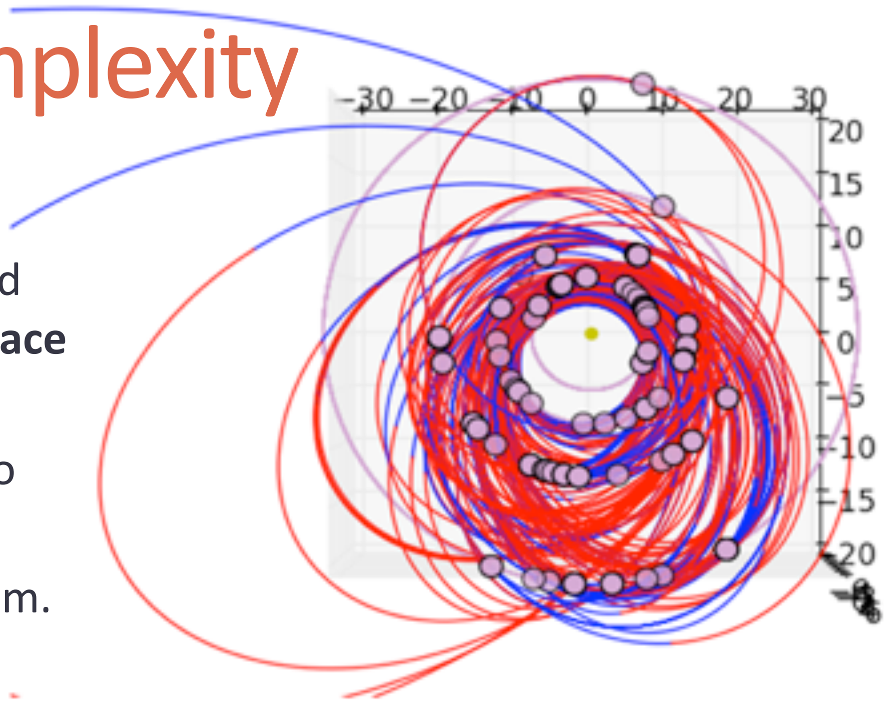
GTOC Trophy

GTOC 6th edition

- Problem formulated by NASA (JPL), winners of the previous edition
- Relevant to the "JUpiter ICy moon Explorer" (JUICE) mission and Jupiter Europa Orbiter (JEO) under evaluation at the European Space Agency and NASA
- Exploration of the Jupiter inner system with a next generation Ion propulsion engine
- Moons represented by a “soccer ball” with high, medium and low score faces.
- Goal: design a trajectory that maps as much as possible of the 4 Galilean moons (Io, Europa, Ganymede and Callisto)
- Minimal reality gap: accurate representation of spacecraft dynamics is demanded
- Billions of dollars per mission (>3 for Cassini): each additional mapped area matters (a lot!)



GTOC 6: problem complexity



Roughly …

… a 500 dimensional continuous box-bounded global optimization problem, if the **moon/face sequence** was given …

… but 10^{269} possible **moon/face sequences** to choose from, if launch date was fixed …

… but a 10 year launch window to choose from.

(~10^{80} atoms in the universe)

May be thought of as a complex Travelling Salesman Problem, where re-visits are allowed, and cities are "moving":

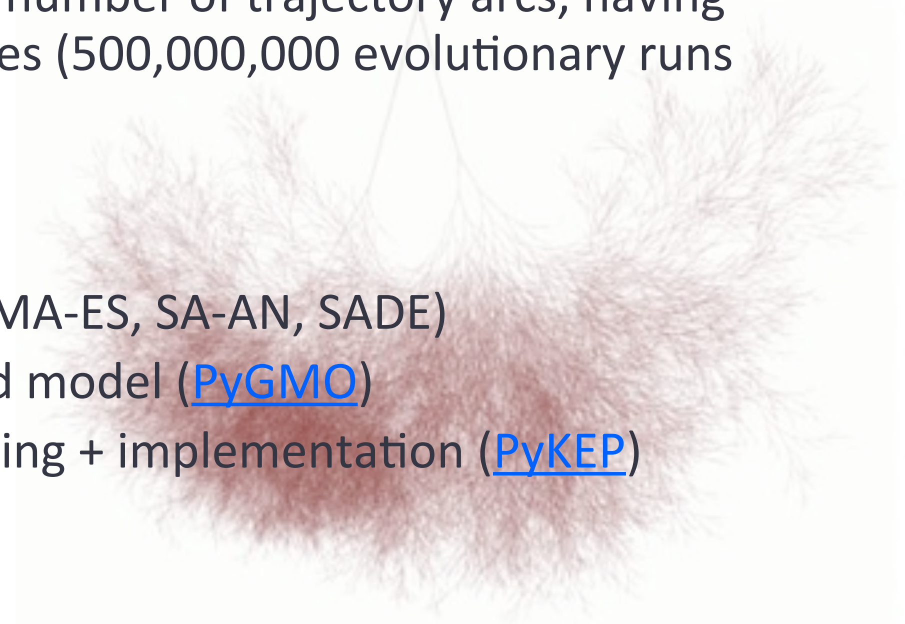
- 128 cities (4 moons * 32 faces)
- **Connectivity graph** (**topology** and **cost**) is dynamic and determined through evolution
- Tour quality is the value of cities visited within the available budget

Our strategy

- Higher level optimization of moon/face sequences (by a novel multi-criteria tree search method) auto-tunes and launches evolutionary optimizations of trajectory arcs, that it then evaluates & assembles into full trajectories.
    - ... can be seen as a Meta Genetic Algorithm (MGA!)

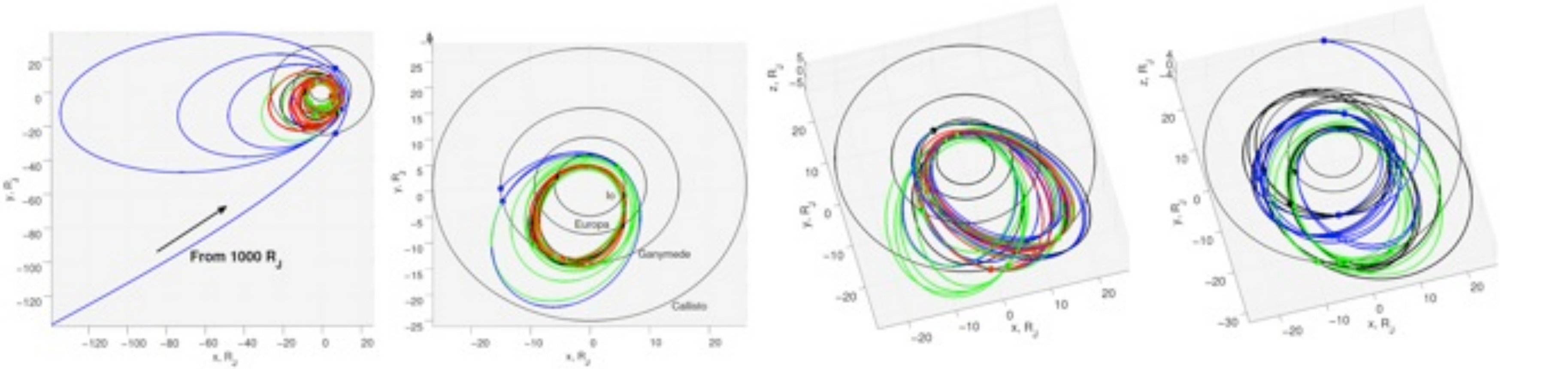
- Challenge: need to evolve a very high number of trajectory arcs, having **dramatically varying fitness** landscapes (500,000,000 evolutionary runs needed to obtain our solution!)

- Solution:
    - self-adaptation (jDE chosen over CMA-ES, SA-AN, SADE)
    - parallelisation: asynchronous island model (PyGMO)
    - speed is critical: MGA-1DSM encoding + implementation (PyKEP)



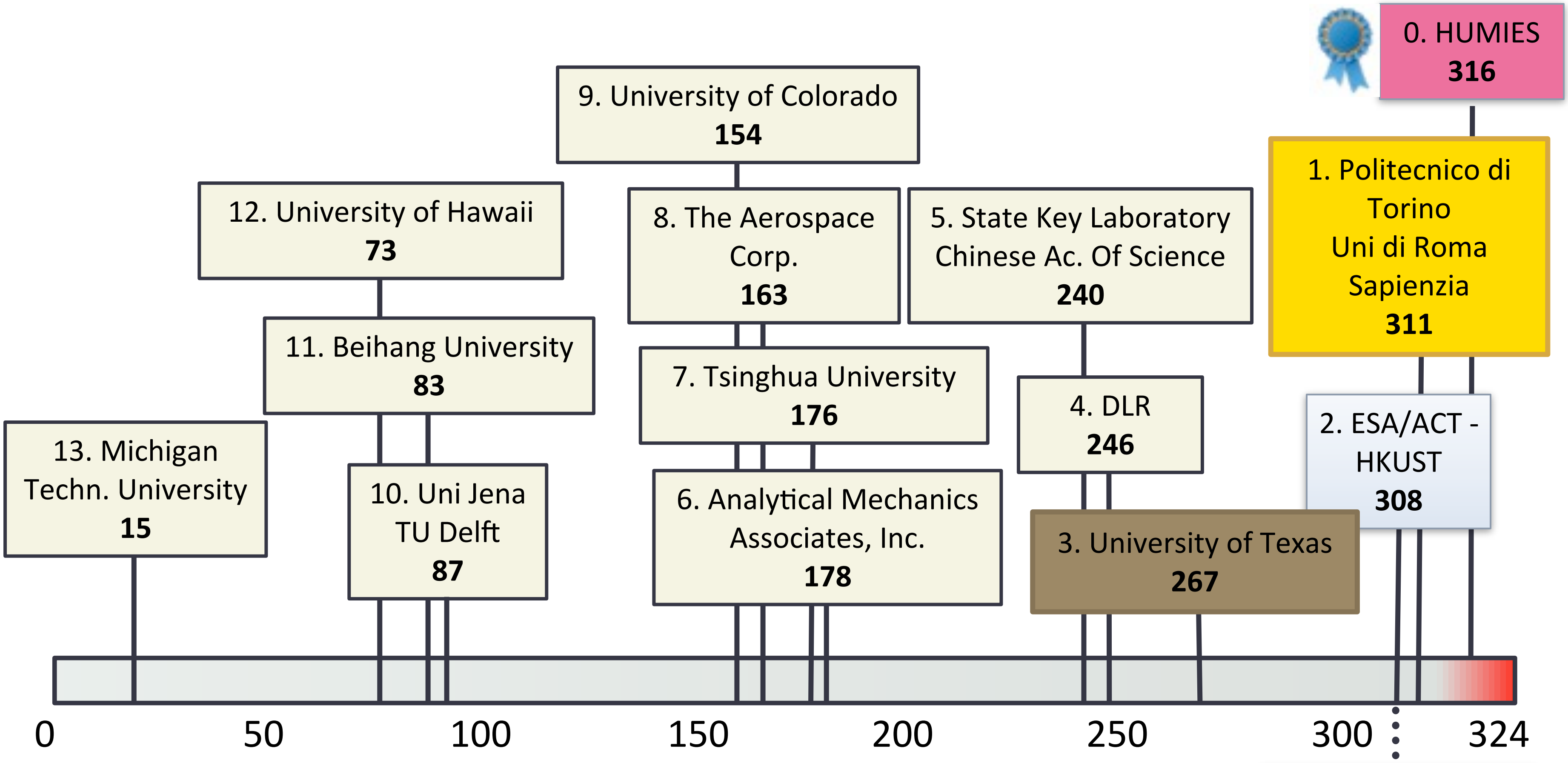
Our best trajectory

- 141 flybys, 120 faces mapped (out of 128), 316 points (out of 324)
- Flyable trajectory (**verified** by NASA/JPL)
- Algorithm finds and exploits:
  - moon resonances
  - moon backflips
  - moon hops (quick transfers between nearby moons)
- Highly efficient in propellant usage: (nearly) ballistic trajectory



1: capture + Europa & Io | 2: Ganymede & Io | 3: Callisto & Io | 4: Europa + Ganymede + Callisto

(H) - The result holds its own or wins a regulated competition involving human contestants (in the form of either live human players or human-written computer programs).

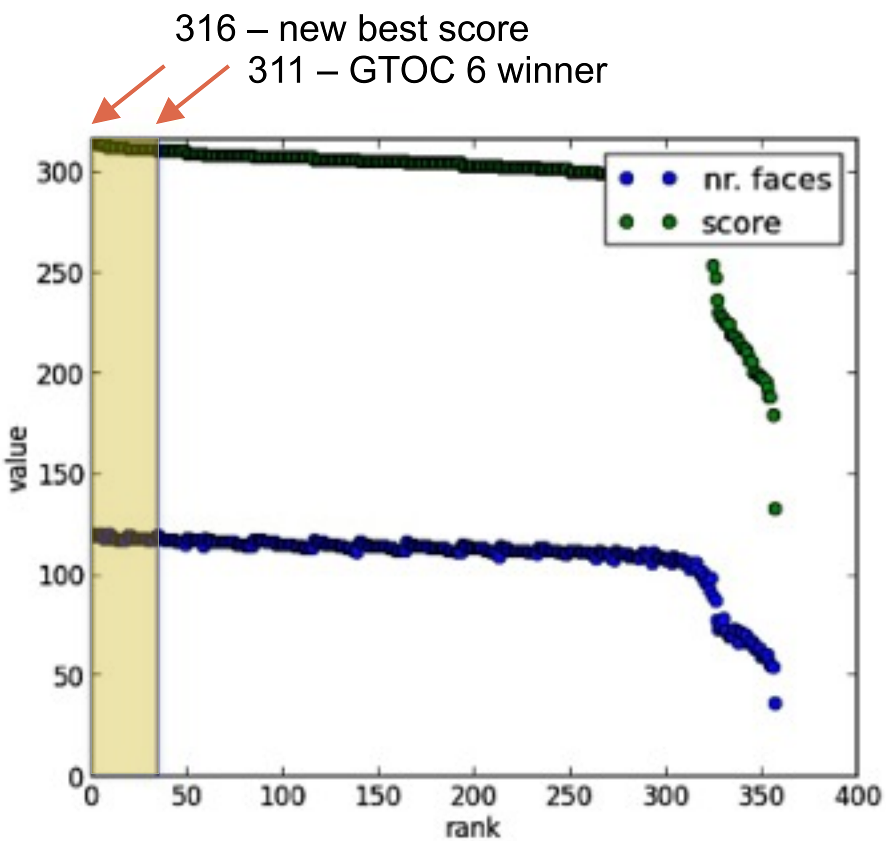


early version of our algorithm

Final GTOC 6 rankings
(only 13, out of 33 teams, were able to return a solution)

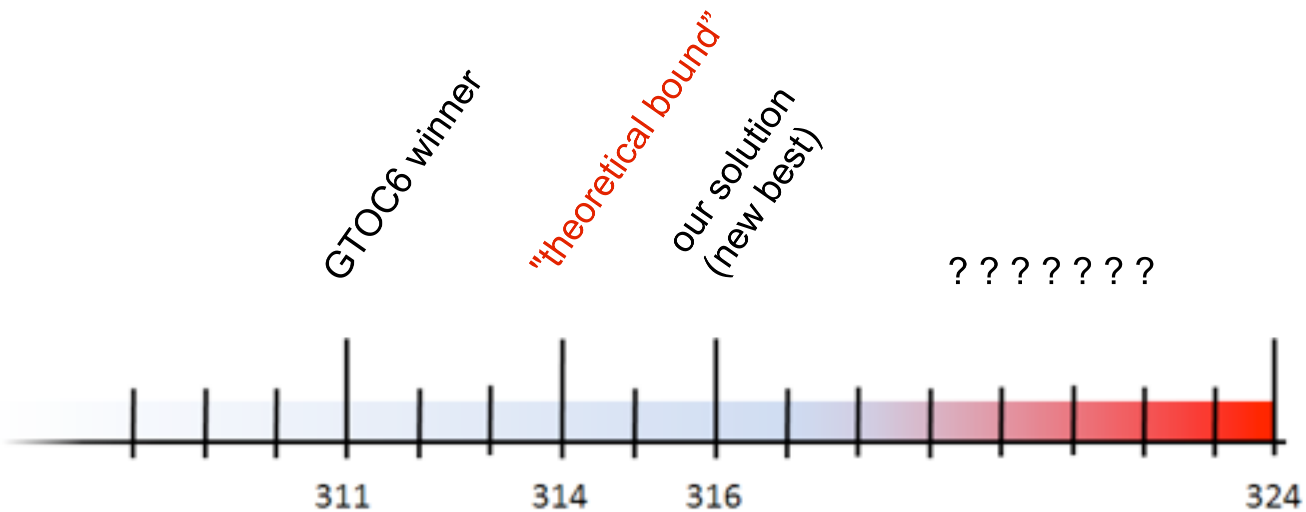
(F) - The result is equal to or better than a result that was considered an achievement in its field at the time it was first discovered.

(C) - The result is equal to or better than a result that was placed into a database or archive of results maintained by an internationally recognized panel of scientific experts



- The GTOC Portal acknowledges our best result as a valid trajectory and superior to the one returned by the competition winner.
- GTOC6 winner: 311/324
- Our algorithm:
  - running time 9 days on 32 CPUs
  - many solutions exceeding 311, all using moon hopping.

(G) - The result solves a problem of indisputable difficulty in its field.



(D) - The result is publishable in its own right as a new scientific result-independent of the fact that the result was mechanically created.

- An innovative strategy emerged from our algorithm: "moon hopping"
  - Rapid transfers between moons (in contrast to fully mapping one moon after another),
  - Exploitation of momentaneous phasings between moons, that enable short-time transfers

- Design of large hopping sequences (100+ flybys) was not considered as a feasible approach by human experts prior to our finding

Conclusions

- Our algorithm (a Meta Genetic Algorithm)
  - outperforms all other algorithms and human designed contributions to the GTOC6 problem
  - is completely automated and does not need expert knowledge
  - is the first human-competitive algorithm for designing multiple fly-by trajectories of this complexity (>100 fly-bys)

- Our evolved solution
  - is recognized as the current best known flyable trajectory for the problem issued by NASA/JPL
  - solves a problem highly relevant to a real mission (JUICE - JEO)
  - proves the value of a mission design strategy that was not considered as competitive before: moon hopping (a strategy that cannot be designed by "hand" for such complex trajectories)

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