ACT Global Optimization Competition Workshop
Evolutionary Neurocontrol

Team 1

Bernd Dachwald
German Aerospace Center (DLR)
Mission Operations Section
Oberpfaffenhofen

bernd.dachwald@dlr.de

Andreas Ohndorf
German Aerospace Center (DLR)
Institute of Space Simulation
Cologne
Drawbacks of Local Trajectory Optimization Methods

• require an adequate initial guess prior to optimization
  – convergence behavior is very sensitive to the initial guess
  – similar initial guesses yield often very dissimilar optimization results
    ➔ initial guess can not be improved iteratively
    ➔ trajectory optimization becomes “more of an art than science”
• can only be applied by an expert in astrodynamics and optimal control theory
• require frequent interactions with the expert
• are often time-consuming (and thus expensive)
• run typically into the local optimum which is closest to the initial guess (rarely close to the global optimum)
• initial conditions are typically not optimized, although they are crucial for mission performance
Smart Global Trajectory Optimization

- Choose target body
- Choose initial conditions

Evolutionary Neurocontroller (ENC)

Artificial Neural Network

Evolutionary Algorithm

- Interval for launch time
- Interval for hyperbolic excess velocity
- Interval for initial propellant mass

Near-globally optimal trajectory found
The Flight Control System of the Housefly:
a natural evolutionary neurocontroller (ENC)
Spacecraft Trajectory Optimization Using Evolutionary Neurocontrol

- Evolutionary neurocontroller
  - Evolutionary algorithm
    - Optimizes
  - Neurocontroller
    - Artificial neural network
      - ≈ 50 neurons
      - Performs
    - Spacecraft steering
Artificial Neural Networks
simulating information processing in nervous systems

- information processing and intelligence is based on the propagation of stimuli in neurons
- neurons are built relatively simple and uniform
- complexity is created by the synaptic topology of the nervous system
- learning is performed by changing the synaptic topology and the synaptic efficiency
Artificial Neural Networks

- computability paradigm alternative to conventional serial digital computers
  - massively parallel
  - analog
  - fault tolerant
  - adaptive
- comprise information processing elements that model the most essential features of biological neurons
- show some characteristics of the brain
  - learning from experience
  - generalizing from previous examples to new ones
  - extracting essential characteristics from inputs that contain noisy and/or irrelevant data
Artificial Neural Networks

as associative mapping functions

Network function $N_\pi$, defined by its (constant) internal parameters $\pi \in \mathbb{R}^{28}$

$$N_\pi: X \subseteq \mathbb{R}^4 \rightarrow Y \subseteq (0,1)^2$$

This neural network maps a 4D input space onto a 2D output space.
Evolutionary Algorithms

simulating the optimization principles of genetics and evolution

• as a rule, all life forms are most advantageously adapted to their environment, i.e. they are possible solutions to the difficult optimization problem „survive under the current environmental conditions to create offspring”

• evolutionary algorithms are optimization methods based on the principles of genetics and natural evolution
  – inheritance
  – mutation and recombination of genetic material
  – natural selection
  – survival of the fittest
Combining Artificial Neural Networks and Evolutionary Algorithms

- an artificial neural network can be mapped onto a “chromosome“
- the artificial neural network that performs best on a given task can be „bred“ with an evolutionary algorithm
Trajectory Optimization Using Evolutionary Neurocontrol

outer NC optimization loop

holds a population of NCs $\pi_1, \ldots, \pi_q$

evaluates NC from population

inner trajectory integration loop

$\pi \in \{1, \ldots, q\}$

some transformations

$u(\hat{t}_i)$

neurocontroller

$N_\pi : \mathcal{X} \rightarrow \mathcal{U}$

$X_T(\hat{t}_i)$

$X_{SC}(\hat{t}_i)$

no

termination condition is met?

yes

$x_{SC}(\hat{t}_{i+1})$

equations of motion

$\dot{x}_{SC} = G(x_{SC}, u)$

trajectory $x_{SC}[\ell]$

Fitness function

evaluates the trajectory
Trajectory Optimization Using Evolutionary Neurocontrol

outer NC optimization loop

holds a population of NCs $\pi_1, \ldots, \pi_q$

evaluates NC from population

evolutionary algorithm

NC fitness $J(\pi_j)$

Fitness function

evaluates the trajectory

1 life of a fly

inner trajectory integration loop

$x_T(t_i)$
x_SC(t_i)

perceived environment

no

termination condition is met?

yes

equations of motion

$\dot{x}_{SC} = G(x_{SC}, u)$

trajectory $x_{SC}[t]$
Transformation Chromosome → Trajectory

chromosome/individual/string $\xi$

=  
NC parameter set $\pi$

NC network function $N$

=  
spacecraft steering strategy $S$

spacecraft control function $u[t]$

=  
spacecraft trajectory $x_{sc}[t]$
InTrance uses a non-standard evolutionary algorithm
• tailored to optimal control problems
• based on approaches that have been proposed to avoid the problems associated with standard genetic algorithms

• real-valued parameter encoding
• multi-objective tournament selection
• real delta coding
• non-standard evolutionary operators
• tailored fitness function
Multi-Objective Tournament Selection

Population at time step $t$

Tournament 1
- Winner 1
- Loser 1

Tournament 2
- Winner 2
- Loser 2

Reproduction
- Parent 1
- Offspring 1
- Parent 2
- Offspring 2

Population at time step $t+1$
Real Delta Coding (RDC)

- Partial solution
- Individual
- Best individual

$$e_0 \rightarrow e_1$$

- Time $$t_0$$ in epoch $$e_0$$
- Time $$t_c > t_0$$ in epoch $$e_0$$
- Time $$t_c$$ in epoch $$e_1$$
Evolutionary Operators

One-point crossover

Uniform crossover

Crossover nodes

Parents

Offspring
(Sub)fitness Function Definition

\[ J = J(J_r, J_v, J_{\text{ACT}}) = \begin{cases} 
-10 & : J_r \leq -10 \\
J_r - J_v & : J_r > -10 \\
J_{\text{ACT}} & : J_r > 0 
\end{cases} \]

\[ J_r = \log_0 \left( \frac{\Delta v_{\text{max}}}{\Delta v_f} \right) \]

\[ J_v = \frac{|\vec{v}_f|}{v_{\text{max}}} \]

\[ J_{\text{ACT}} = m_r \cdot \left| \frac{(\vec{v}_{\text{ast}} - \vec{v}_f) \cdot \vec{v}_{\text{ast}}}{\vec{U}_{\text{rel}}} \right| \]

maximum final distance
achieved final distance
„guidance“ velocity (6..8 km/s)
InTrance: Retrograde Asteroid Impact with a Solar Sail

2004WR impact with 81.4 km/s

Sail Temp. [K]
- 520
- 500
- 450
- 400
- 350
- 300

2004WR orbit
Earth orbit
Determination of Optimal Launch and Impact Date

• asteroid has highest orbital velocity at perihelion

• s/c must impact asteroid at its perihelion with low transversal velocity (or even negative transversal velocity ⇒ retrograde impact)

• without gravity assists, we considered a retrograde impact to be infeasible

• what would be the optimal impact orbit?

• our first guess (before the first optimization runs):
  • perihelion must be as close as possible near the sun (0.2 AU constraint)
  • aphelion must be at asteroids perihelion
Optimal Launch Constellation

Option 1:
launch at Earth with injection in direction of Earth’s orbital velocity
⇒ raises aphelion

Option 2:
launch at Earth with injection against direction of Earth’s orbital velocity
⇒ lowers perihelion

By trial & error, option 1 was found to be superior.
Optimal Launch Constellation

Option 1:

- launch at Earth with injection in direction of Earth’s orbital velocity
  - raises aphelion

- asteroid impact at its aphelion passage

By trial & error, option 1 was found to be superior

The longest interval between the Earth being at launch position and the asteroid being at the impact position is 10880.2 days
Best Solution with Variable Control

Launch time:
19 Apr 2014 (MJD2000 5222.181)

Hyperbolic excess velocity:
2.5 km/s

Arrival time:
09 Apr 2035 (MJD2000 12882.181)

Impact velocity:
16.28552 km/s

Flight time:
7,660 days (20.972 years)

Final mass:
768.0744 kg

Objective function value:
292071.194

Final distance to target:
99,952 km
Best Solution with Variable Control - Surprises

- no coast phases
- aphelion of s/c orbit is larger than asteroid’s perihelion
  - ⇒ the line of apsides of the impact orbit is slightly rotated
  - ⇒ transveral velocity component is lower ...
  - ... but it costs propellant
  - ⇒ optimizer must perform a trade-off between aphelion of impact orbit and consumed propellant
**Best Solution with Bang-Bang Control**

- **Launch time:** 15 Apr 2026 (MJD 2000 9601.415)
- **Hyperbolic excess velocity:** 2.5 km/s
- **Arrival time:** 11 Feb 2056 (MJD 2000 20495.415)
- **Impact velocity:** 18.58612 km/s
- **Flight time:** 10,894 days (29.826 years)
- **Final mass:** 838.3076 kg
- **Objective function value:** 337,015.018
- **Final distance to target:** 9,991,860 km (0.0679 AU)
Best Solution with Bang-Bang Control

- Coast phases occur
- Aphelion of s/c orbit is again larger than asteroid’s perihelion
- The line of apsides of the impact orbit is again slightly rotated
- The distribution of thrust and coast phases is clearly sub-optimal
- The trajectory looks ugly
Why has InTrance not found the global optimum (without gravity assist)?

- InTrance has problems with finetuning the solution locally because it is not an analytic method.
- InTrance is not good for finding solutions for problems with very tight final constraints.
- The tighter the requested accuracy of the final constraint, the easier it gets stuck to a local optimum because:
  - it first optimizes the accuracy of the final constraint and then
  - it optimizes the objective function
  - (thereby it is not allowed to "loose the final constraint" again)
- The basin of attraction of the global solution seems to be very small because slightest changes in the steering result in "loosing the final constraint."
- Therefore, InTrance searches for more robust solutions w.r.t. changes in the steering.
- Therefore, InTrance should be hybridized with a local optimization method.
- Gravity assist trajectory optimization should be implemented into InTrance.
Generating the aiming point on the B-plane with the ENC

- the GA parameters are co-optimized by the EA.
- At every integration step a $\Delta$ is provided so that every GA is optimized.
- The task for the EA is extremely difficult!
Outlook: InTranceGA: Optimization of B-Plane Aiming with a Hill-Climber

GA maneuver optimization in 16 iterations
Outlook: InTranceGA Results – Pluto Flyby
Outlook: InTranceGA Results – Mercury Rendezvous