Demostracion de Optimizacion mediante AG de un Modelo de Sistema de Tres Cuerpos

October 21, 2025

1 Evaluación del caso “Binaria + planeta cerca del radio de Hill”

En esta sección medimos cómo afecta la optimización al exponente de Lyapunov del sistema. Partimos de un estado base (masas en el centro de sus `mass_bounds`) para obtener un de referencia y lo comparamos con el mejor individuo que devolvió el GA.
Luego integramos la trayectoria con las masas óptimas y visualizamos el comportamiento de los tres cuerpos, poniendo especial atención a los encuentros cercanos del “planeta” con el binario.

> **Interpretación** - Un más pequeño indica una dinámica menos caótica. - El gráfico permite comprobar si el planeta logra mantenerse en órbita o si termina inestable por la proximidad al radio de Hill.

1.1 Preparación del entorno

Aseguramos que el directorio raíz del proyecto esté disponible en `sys.path` para poder importar los módulos internos sin problemas, independientemente de desde dónde se ejecute el notebook.

[1]:
```
import sys
from pathlib import Path

repo_root = Path.cwd().resolve().parents[1]  # …/collision_of_two_bodies
if str(repo_root) not in sys.path:
    sys.path.insert(0, str(repo_root))
```

1.2 Dependencias principales

Importamos los componentes clave del pipeline: - `Config` y utilidades de seeding. - El controlador híbrido (GA + refinamiento). - Herramientas de visualización y simulación REBOUND. - `numpy` para cualquier análisis adicional.

[2]:
```
from two_body import Config, set_global_seeds
from two_body.core.telemetry import setup_logger
from two_body.logic.controller import ContinuousOptimizationController
from two_body.presentation.visualization import Visualizer
from two_body.simulation.rebound_adapter import ReboundSim
import numpy as np
```

[3]:
```
import logging
from IPython.display import display, Markdown

class NotebookHandler(logging.Handler):
    def __init__(self):
        super().__init__()
        self.lines = []

    def emit(self, record):
        msg = self.format(record)
        self.lines.append(msg)
        print(msg)  # aparece en la celda conforme avanza

handler = NotebookHandler()
handler.setFormatter(logging.Formatter("[%(asctime)s] %(levelname)s -␣
 ↪%(message)s"))

logger = setup_logger(level="DEBUG")
logger.handlers.clear()          # quita otros handlers previos
logger.addHandler(handler)
logger.setLevel(logging.DEBUG)
```

1.3 Configuración del escenario "Binaria + planeta cerca del radio de Hill"

Definimos la escena de estudio: - Dos estrellas de masas distintas orbitando el baricentro. - Un planeta tipo Júpiter ubicado cerca del radio de Hill. - Hiperparámetros del GA y de la fase continua orientados a detectar combinaciones de masas que mitiguen el caos.

[ ]:
```
# ["Binaria con planeta (Hill)"]
case = {
    # Simulación
    "t_end_short": 200.0,
    "t_end_long": 4000.0,
    "dt": 0.25,
    "integrator": "ias15",
    "r0": (
        (-0.333, 0.0, 0.0),   # estrella 1 (1.0) orbitando el baricentro
        (0.667, 0.0, 0.0),    # estrella 2 (0.5)
        (1.2, 0.0, 0.0),      # "planeta" ~Júpiter cerca del límite de Hill
    ),
    "v0": (
        (0.0, -0.912, 0.0),   # velocidad circular ajustada (signo opuesto a la␣
 ↪otra estrella)
        (0.0, 1.824, 0.0),
        (0.0, 0.75, 0.0),     # ligeramente sub-circular para inducir encuentros
    ),
```

```
    # Parámetros físicos
    "mass_bounds": (
        (0.95, 1.05),          # estrella 1 alrededor de 1.0
        (0.45, 0.55),          # estrella 2 alrededor de 0.5
        (8e-4, 1.2e-3),        # planeta tipo Júpiter ~10 ⁻³
    ),
    "G": 1.0,
    "x0": (-0.333, 0.0, 0.0, -0.912, 0.667, 0.0, 0.0, 1.824),

    # Algoritmo genético
    "pop_size": 96,
    "n_gen_step": 4,
    "crossover": 0.85,
    "mutation": 0.25,
    "selection": "tournament",
    "elitism": 2,
    "seed": 321,

    # Optimización continua
    "max_epochs": 80,
    "top_k_long": 12,
    "stagnation_window": 6,
    "stagnation_tol": 5e-4,
    "local_radius": 0.03,    # radio pequeño: ajusta finamente las masas
    "radius_decay": 0.85,
    "time_budget_s": 1500.0,
    "eval_budget": 4500,

    # Backend / cache
    "use_gpu": "false",
    "batch_size": 128,
    "cache_exact_max": 500,
    "cache_approx_max": 1500,

    # I/O
    "artifacts_dir": "artifacts/hill_planet",
    "save_plots": True,
    "headless": False,
}
```

[5]:
```
cfg = Config(**case)
set_global_seeds(cfg.seed)
logger = setup_logger()
```

1.4 Ejecución del optimizador

Inicializamos el controlador con la configuración anterior, habilitamos el registro de eventos y lanzamos el proceso completo de optimización. Al finalizar, presentamos los logs capturados junto

con el resultado agregado (mejor combinación de masas encontrada y métricas básicas).

[7]:
```
controller = ContinuousOptimizationController(cfg, logger=logger)
results = controller.run()
display(Markdown("### Logs capturados"))
display("\n".join(handler.lines))
results
```

```
[2025-10-21 20:54:34,001] INFO - Starting optimization | pop=96 | dims=3 |
time_budget=1500.0s | eval_budget=4500
[2025-10-21 20:54:37,754] INFO - Epoch 0 | new global best (short)   -0.000261
| masses=(0.976395, 0.456018, 0.000943)
[2025-10-21 20:54:47,241] INFO - Epoch 0 complete |  _short  -0.000261 | evals
short/long=96/12 | total evals=108 | radius=0.0300
[2025-10-21 20:55:00,588] INFO - Epoch 1 complete |  _short  -0.000052 | evals
short/long=96/12 | total evals=216 | radius=0.0300
[2025-10-21 20:55:13,499] INFO - Epoch 2 complete |  _short  -0.000239 | evals
short/long=96/12 | total evals=324 | radius=0.0300
[2025-10-21 20:55:26,848] INFO - Epoch 3 complete |  _short  0.000173 | evals
short/long=96/12 | total evals=432 | radius=0.0300
[2025-10-21 20:55:39,832] INFO - Epoch 4 complete |  _short  0.000015 | evals
short/long=96/12 | total evals=540 | radius=0.0300
[2025-10-21 20:55:52,727] INFO - Epoch 5 complete |  _short  -0.000098 | evals
short/long=96/12 | total evals=648 | radius=0.0300
[2025-10-21 20:55:56,404] INFO - Epoch 6 | new global best (short)   -0.000435
| masses=(1.038867, 0.464502, 0.000991)
[2025-10-21 20:56:05,391] INFO - Epoch 6 complete |  _short  -0.000435 | evals
short/long=96/12 | total evals=756 | radius=0.0300
[2025-10-21 20:56:08,941] INFO - Epoch 7 | new global best (short)   -0.000455
| masses=(0.985017, 0.457462, 0.001074)
[2025-10-21 20:56:17,673] INFO - Epoch 7 complete |  _short  -0.000455 | evals
short/long=96/12 | total evals=864 | radius=0.0300
[2025-10-21 20:56:29,874] INFO - Epoch 8 complete |  _short  -0.000311 | evals
short/long=96/12 | total evals=972 | radius=0.0300
[2025-10-21 20:56:42,284] INFO - Epoch 9 complete |  _short  -0.000134 | evals
short/long=96/12 | total evals=1080 | radius=0.0300
[2025-10-21 20:56:54,514] INFO - Epoch 10 complete |  _short  -0.000362 | evals
short/long=96/12 | total evals=1188 | radius=0.0300
[2025-10-21 20:57:06,368] INFO - Epoch 11 complete |  _short  -0.000293 | evals
short/long=96/12 | total evals=1296 | radius=0.0300
[2025-10-21 20:57:18,357] INFO - Epoch 12 complete |  _short  -0.000118 | evals
short/long=96/12 | total evals=1404 | radius=0.0300
[2025-10-21 20:57:21,787] INFO - Epoch 13 | new global best (short)   -0.000566
| masses=(1.041211, 0.454195, 0.00095)
[2025-10-21 20:57:30,036] INFO - Epoch 13 complete |  _short  -0.000566 | evals
short/long=96/12 | total evals=1512 | radius=0.0300
[2025-10-21 20:57:42,011] INFO - Epoch 14 complete |  _short  -0.000209 | evals
short/long=96/12 | total evals=1620 | radius=0.0300
```

```
[2025-10-21 20:57:53,884] INFO - Epoch 15 complete |  _short  -0.000416 | evals
short/long=96/12 | total evals=1728 | radius=0.0300
[2025-10-21 20:58:05,476] INFO - Epoch 16 complete |  _short  -0.000159 | evals
short/long=96/12 | total evals=1836 | radius=0.0300
[2025-10-21 20:58:17,642] INFO - Epoch 17 complete |  _short  -0.000130 | evals
short/long=96/12 | total evals=1944 | radius=0.0300
[2025-10-21 20:58:29,456] INFO - Epoch 18 complete |  _short  -0.000260 | evals
short/long=96/12 | total evals=2052 | radius=0.0300
[2025-10-21 20:58:41,344] INFO - Stagnation detected; reseeding around best
candidate.
[2025-10-21 20:58:41,344] INFO - Epoch 19 complete |  _short  -0.000124 | evals
short/long=96/12 | total evals=2160 | radius=0.0255
[2025-10-21 20:58:52,230] INFO - Epoch 20 complete |  _short  -0.000095 | evals
short/long=96/12 | total evals=2268 | radius=0.0255
[2025-10-21 20:59:03,343] INFO - Epoch 21 complete |  _short  -0.000399 | evals
short/long=96/12 | total evals=2376 | radius=0.0255
[2025-10-21 20:59:14,471] INFO - Epoch 22 complete |  _short  -0.000208 | evals
short/long=96/12 | total evals=2484 | radius=0.0255
[2025-10-21 20:59:25,582] INFO - Epoch 23 complete |  _short  -0.000333 | evals
short/long=96/12 | total evals=2592 | radius=0.0255
[2025-10-21 20:59:36,726] INFO - Epoch 24 complete |  _short  -0.000266 | evals
short/long=96/12 | total evals=2700 | radius=0.0255
[2025-10-21 20:59:47,874] INFO - Stagnation detected; reseeding around best
candidate.
[2025-10-21 20:59:47,874] INFO - Epoch 25 complete |  _short  -0.000041 | evals
short/long=96/12 | total evals=2808 | radius=0.0217
[2025-10-21 20:59:58,705] INFO - Epoch 26 complete |  _short  -0.000411 | evals
short/long=96/12 | total evals=2916 | radius=0.0217
[2025-10-21 21:00:09,700] INFO - Epoch 27 complete |  _short  -0.000387 | evals
short/long=96/12 | total evals=3024 | radius=0.0217
[2025-10-21 21:00:20,704] INFO - Epoch 28 complete |  _short  -0.000065 | evals
short/long=96/12 | total evals=3132 | radius=0.0217
[2025-10-21 21:00:31,664] INFO - Epoch 29 complete |  _short  -0.000277 | evals
short/long=96/12 | total evals=3240 | radius=0.0217
[2025-10-21 21:00:42,560] INFO - Epoch 30 complete |  _short  -0.000198 | evals
short/long=96/12 | total evals=3348 | radius=0.0217
[2025-10-21 21:00:53,513] INFO - Stagnation detected; reseeding around best
candidate.
[2025-10-21 21:00:53,513] INFO - Epoch 31 complete |  _short  -0.000358 | evals
short/long=96/12 | total evals=3456 | radius=0.0184
[2025-10-21 21:01:04,585] INFO - Epoch 32 complete |  _short  0.000086 | evals
short/long=96/12 | total evals=3564 | radius=0.0184
[2025-10-21 21:01:15,765] INFO - Epoch 33 complete |  _short  -0.000160 | evals
short/long=96/12 | total evals=3672 | radius=0.0184
[2025-10-21 21:01:26,788] INFO - Epoch 34 complete |  _short  -0.000312 | evals
short/long=96/12 | total evals=3780 | radius=0.0184
[2025-10-21 21:01:37,900] INFO - Epoch 35 complete |  _short  -0.000099 | evals
short/long=96/12 | total evals=3888 | radius=0.0184
```

```
[2025-10-21 21:01:48,729] INFO - Epoch 36 complete | _short -0.000345 | evals
short/long=96/12 | total evals=3996 | radius=0.0184
[2025-10-21 21:02:00,051] INFO - Stagnation detected; reseeding around best
candidate.
[2025-10-21 21:02:00,051] INFO - Epoch 37 complete | _short -0.000254 | evals
short/long=96/12 | total evals=4104 | radius=0.0157
[2025-10-21 21:02:11,277] INFO - Epoch 38 complete | _short -0.000095 | evals
short/long=96/12 | total evals=4212 | radius=0.0157
[2025-10-21 21:02:22,460] INFO - Epoch 39 complete | _short -0.000499 | evals
short/long=96/12 | total evals=4320 | radius=0.0157
[2025-10-21 21:02:33,694] INFO - Epoch 40 complete | _short -0.000214 | evals
short/long=96/12 | total evals=4428 | radius=0.0157
[2025-10-21 21:02:44,723] INFO - Epoch 41 complete | _short -0.000333 | evals
short/long=96/12 | total evals=4536 | radius=0.0157
[2025-10-21 21:02:44,723] INFO - Optimization completed | epochs=42 | evals=4536
| best   -0.000566 | wall=490.7s
```

1.4.1 Logs capturados

```
'[2025-10-21 20:52:45,331] INFO - Starting optimization | pop=96 | dims=3 |␣
↪time_budget=1500.0s | eval_budget=4500\n[2025-10-21 20:52:49,219] INFO - Epoch␣
↪0 | new global best (short)   0.000063 | masses=(1.041211, 0.454312, 0.
↪00095)\n[2025-10-21 20:52:57,881] INFO - Epoch 0 | new global best (long)   0.
↪000000 | masses=(1.041211, 0.454312, 0.00095)\n[2025-10-21 20:52:57,881] INFO␣
↪- Epoch 0 | new global best (long)   -0.000003 | masses=(1.027446, 0.465782, 0.
↪00084)\n[2025-10-21 20:52:57,881] INFO - Epoch 0 complete |  _short  0.000063 |␣
↪evals short/long=96/12 | total evals=108 | radius=0.0300\n[2025-10-21 20:53:
↪01,566] INFO - Epoch 1 | new global best (short)   -0.000224 | masses=(1.
↪043921, 0.545591, 0.000873)\n[2025-10-21 20:53:10,797] INFO - Epoch 1 complete␣
↪|  _short  -0.000224 | evals short/long=96/12 | total evals=216 | radius=0.
↪0300\n[2025-10-21 20:53:23,308] INFO - Epoch 2 complete |  _short  -0.000052 |␣
↪evals short/long=96/12 | total evals=324 | radius=0.0300\n[2025-10-21 20:53:
↪36,591] INFO - Epoch 3 complete |  _short  0.000026 | evals short/long=96/12 |␣
↪total evals=432 | radius=0.0300\n[2025-10-21 20:53:49,513] INFO - Epoch 4␣
↪complete |  _short  -0.000077 | evals short/long=96/12 | total evals=540 |␣
↪radius=0.0300\n[2025-10-21 20:54:01,669] INFO - Epoch 5 complete |  _short  -0.
↪000193 | evals short/long=96/12 | total evals=648 | radius=0.0300\n[2025-10-21␣
↪20:54:14,954] INFO - Epoch 6 complete |  _short  0.000127 | evals short/long=96/
↪12 | total evals=756 | radius=0.0300\n[2025-10-21 20:54:27,976] INFO -␣
↪Stagnation detected; reseeding around best candidate.\n[2025-10-21 20:54:
↪27,976] INFO - Epoch 7 complete |  _short  -0.000100 | evals short/long=96/12 |␣
↪total evals=864 | radius=0.0255\n[2025-10-21 20:54:34,001] INFO - Starting␣
↪optimization | pop=96 | dims=3 | time_budget=1500.0s |␣
↪eval_budget=4500\n[2025-10-21 20:54:37,754] INFO - Epoch 0 | new global best␣
↪(short)   -0.000261 | masses=(0.976395, 0.456018, 0.000943)\n[2025-10-21 20:54:
↪47,241] INFO - Epoch 0 complete |  _short  -0.000261 | evals short/long=96/12 |␣
↪total evals=108 | radius=0.0300\n[2025-10-21 20:55:00,588] INFO - Epoch 1␣
↪complete |  _short  -0.000052 | evals short/long=96/12 | total evals=216 |␣
↪radius=0.0300\n[2025-10-21 20:55:13,499] INFO - Epoch 2 complete |  _short  -0.
↪000239 | evals short/long=96/12 | total evals=324 | radius=0.0300\n[2025-10-21␣
↪20:55:26,848] INFO - Epoch 3 complete |  _short  0.000173 | evals short/long=96/
↪12 | total evals=432 | radius=0.0300\n[2025-10-21 20:55:39,832] INFO - Epoch 4␣
↪complete |  _short  0.000015 | evals short/long=96/12 | total evals=540 |␣
↪radius=0.0300\n[2025-10-21 20:55:52,727] INFO - Epoch 5 complete |  _short  -0.
↪000098 | evals short/long=96/12 | total evals=648 | radius=0.0300\n[2025-10-21␣
↪20:55:56,404] INFO - Epoch 6 | new global best (short)   -0.000435 | masses=(1.
↪038867, 0.464502, 0.000991)\n[2025-10-21 20:56:05,391] INFO - Epoch 6 complete␣
↪|  _short  -0.000435 | evals short/long=96/12 | total evals=756 | radius=0.
↪0300\n[2025-10-21 20:56:08,941] INFO - Epoch 7 | new global best (short)   -0.
↪000455 | masses=(0.985017, 0.457462, 0.001074)\n[2025-10-21 20:56:17,673] INFO␣
↪- Epoch 7 complete |  _short  -0.000455 | evals short/long=96/12 | total␣
↪evals=864 | radius=0.0300\n[2025-10-21 20:56:29,874] INFO - Epoch 8 complete |␣
↪ _short  -0.000311 | evals short/long=96/12 | total evals=972 | radius=0.
↪0300\n[2025-10-21 20:56:42,284] INFO - Epoch 9 complete |  _short  -0.000134 |␣
↪evals short/long=96/12 | total evals=1080 | radius=0.0300\n[2025-10-21 20:56:
↪54,514] INFO - Epoch 10 complete |  _short  -0.000362 | evals short/long=96/12␣
↪| total evals=1188 | radius=0.0300\n[2025-10-21 20:57:06,368] INFO - Epoch 11␣
↪complete |  _short  -0.000293 | evals short/long=96/12 | total evals=1296 |␣
↪radius=0.0300\n[2025-10-21 20:57:18,357] INFO - Epoch 12 complete |  _short  -0.
↪000118 | evals short/long=96/12 | total evals=1404 | radius=0.
↪0300\n[2025-10-21 20:57:21,787] INFO - Epoch 13 | new global best (short)   -0
```

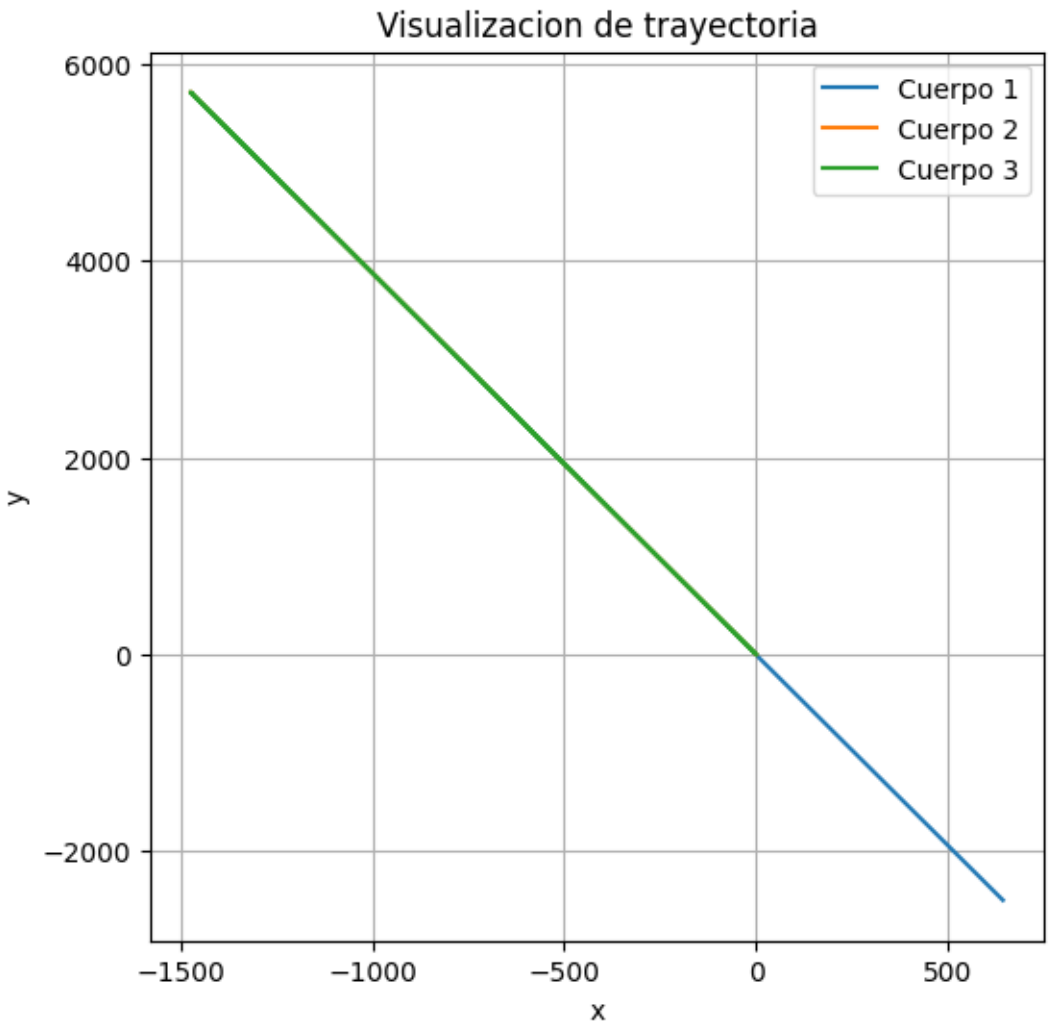
[7]:
```
{'status': 'completed',
 'best': {'masses': [1.041211032216705,
   0.45419474332579357,
   0.0009503809646476818],
  'lambda': -0.0005658586991704906,
  'fitness': 0.0005658586991704906,
  'm1': 1.041211032216705,
  'm2': 0.45419474332579357,
  'm3': 0.0009503809646476818},
 'evals': 4536,
 'epochs': 42}
```

1.5 Evaluación comparativa y visualización

Contrastamos el exponente de Lyapunov del estado base (masas en la mitad de sus rangos) contra el obtenido por la solución optimizada. Por último, integramos la dinámica con las masas ganadoras para visualizar la trayectoria de los tres cuerpos y observar el comportamiento cerca del límite de estabilidad.

[8]:
```
from two_body.logic.fitness import FitnessEvaluator
from two_body.core.cache import HierarchicalCache
from two_body.simulation.rebound_adapter import ReboundSim

cache = HierarchicalCache()
evaluator = FitnessEvaluator(cache, cfg)

center = tuple((lo + hi) / 2.0 for lo, hi in cfg.mass_bounds)
baseline = evaluator.evaluate_batch([center], horizon="long")[0]
best_fit = results["best"]["fitness"]

print(f"  inicial = {-baseline:.6f},   óptimo = {-best_fit:.6f}")

sim_cls = ReboundSim

sim_builder = sim_cls(G=cfg.G, integrator=cfg.integrator)
sim = sim_builder.setup_simulation(tuple(results["best"]["masses"]), cfg.r0,␣
 ↪cfg.v0)
traj = sim_builder.integrate(sim, t_end=cfg.t_end_long, dt=cfg.dt)

viz = Visualizer(headless=cfg.headless)
viz.quick_view([traj[:, i, :3] for i in range(traj.shape[1])])
```

```
 inicial = -0.000004,   óptimo = -0.000566
```


Visualizacion de trayectoria
Cuerpo 1
Cuerpo 2
Cuerpo 3
6000
4000
2000
0
−2000
y
−1500
−1000
−500
0
500
x