CSF 407 – ARTIFICIAL INTELLIGENCE

Optimization of Spacecraft Trajectories for Precision Navigation and Control

Using

D* Algorithm, Monte Carlo Tree Search (MCTS), Particle Swarm Optimization, Genetic Algorithms, MPC, Sequential Quadratic Programming (SQP)

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INTRODUCTION

SPACECRAFT TRAJECTORIES

Exploring the vast expanse of our universe requires innovation, precision and accuracy along with a deep understanding of the complex dynamics, laws that govern the movement of spacecraft. Spacecraft trajectories are the heart of every successful space mission, be it interplanetary exploration, rendezvous with celestial bodies, or even navigating around space stations and satellites.The ability to chart optimal trajectory paths for these vessels as they traverse the cosmic sea is of paramount significance in the field of space exploration. Over the years, scientists and engineers together have delved into the delicacies of spacecraft trajectory planning, seeking solutions that guarantee safe passage and also optimize fuel consumption along with minimizing the total mission time. Through the combined report, we embark on a journey through the astounding advancements in spacecraft trajectory planning and optimization.

The realm of space exploration is witnessing a strong revolution in computational methods thanks to the ever growing technologies and methods developed like application of hybrid algorithms combining swarm optimization with Legendre pseudospectral methods to tackle complex time-optimal trajectory planning, implementation of Monte Carlo Tree Search (MCTS) for automated interplanetary mission planning. These methods hold the potential to revolutionize how we plan and execute missions in the cosmic void.

We also explored innovative approaches which promised increased efficiency and helped us cover a larger area for the future. Methods such as Direct-Adaptive Model Predictive Control (DAMPC), which combines adaptive and optimal control systems to navigate through asteroid-rich regions, and Genetic Algorithms (GA) for optimizing low-thrust interplanetary trajectories.

Spacecraft trajectory optimization is a multidisciplinary field that touches upon mathematics, physics, and computer science. It required a delicate balance between mathematical modeling, heuristic search algorithms, and real-world engineering constraints.Whether it was steering through the gravitational fields of celestial bodies or avoiding collisions in the vastness of space. Spacecraft trajectory optimization poses a diverse range of profound challenges. As we ventured further into the cosmos, the pursuit of optimal spacecraft trajectories became not only a scientific endeavor but also a testament to human curiosity and also to our unquenchable thirst for exploration. The report helps in solving the mysteries of space with an intricate web of algorithms, models, and simulations that guide humanity's quest to reach the stars and beyond. In the pages that follow in this report, we have dived deep into the methods and technologies that make these wild journeys possible.

Some goals we try to achieve from this is to have a working model, expressed as an executable code, which can predict, estimate and do similar tasks.

1. Optimization of Spacecraft Trajectories
2. Efficient Space Exploration
3. Adaptive and Autonomous Control
4. Interplanetary Mission Planning
5. Application of Computational Methods
6. Multi- Objective Optimization

We will be looking at various algorithms to help us in our venture. The study of spacecraft trajectories is a multifaceted field that strives to optimize the paths of space missions with a diverse range of objectives and constraints of the cosmic world. It will be evident from the provided papers that researchers have made significant progress in developing advanced optimization techniques, adaptive control systems, and collision avoidance strategies to enhance the efficiency and safety of space exploration.

The application of computational methods, such as Genetic Algorithms and Monte Carlo Tree Search, has enabled the solution of complex trajectory planning problems, while the integration of mathematical models and consideration of uncertainties are pivotal for precise and accurate navigation. Furthermore we will see the emphasis on multi-objective optimization and the accomplishment of mission goals with minimal fuel consumption underscore the ongoing efforts to extend the reach and capabilities of space missions. Overall, the research presented in the report showcases the dedication and passion of scientists and engineers together in advancing the field of spacecraft trajectories to unlock the mysteries of the cosmos and enable ambitious human interplanetary probes.

LITERATURE SURVEY

In this section, we will provide an overview of several recent research endeavors that leverage knowledge extracted from clinical data sources to achieve a wide range of objectives.

Yufei Z. et.al (2014) have proposed a hybrid algorithm combining swarm optimization with Legendre pseudospectral method (LPM) to solve the time-optimal trajectory for two-input underactuated spacecraft. The time-optimal trajectory planning problem involving the Hamilton-Jacobi-Bellman (HJB) equations of higher dimension nonlinear dynamics in rigid spacecrafts has been a question of interest in the last decades.An optimized solution for this problem should have the ability to converge to a global optimum and make the requirement of suitable initial guesses. Initially, evolutionary algorithms (EAs) such as genetic algorithms (GA), differential evolution (DE) and particle swarm optimization were implemented successfully in the real world nonlinear optimal problems, but dude to their poor numerical accuracy and difficult constraint handling hybrid methods like PSO algorithm generating initial solutions to gradient based direct trajectory optimization along with LPM have been proposed. The primary aim is: first, the PSO algorithm serves as a start engine which quickly converges to the approx region of global minimum with a randomly generated initial solution. Optimal solutions are obtained in flat output space to be mapped back to the state and control input spaces. The simulation results show that the proposal is competitive in convergence rate, global searching capability and robustness than single PSO and classical optimization algorithms with gradient information.

Mingming Wang et.al(2015) throws light on free-floating space robots and their particular trajectory planning techniques to work out the dynamic coupling between the space manipulators and spacecraft in this paper. Previously proposed solutions were improvised for non-holonomic redundancy, a new method for trajectory planning issue of kinematically redundant manipulator was proposed. The joint trajectory shape is represented by the Bézier curve for its simplicity and normalization and the ability to limit the values of joint range, rate, and acceleration. PSO with adaptive inertia weight and various fitness functions are implemented to find out the optimal solution for the problem. The sequence of problem solving is: initializing the population of particles; known position of particle and swarm's position(global); movement of particles is guided with local and global positions and updated in each generation; generation by generation repetition is performed until an optimal solution is found. In the future, Collision detection and avoidance is planned to be incorporated.

Asma Seddaoui et.al (2021) talks about use of robots for different services on the ISS and different spacecraft as a means of performing most of the work and communication. This servicing and assembly missions will require space robots capable of maneuvering safely around the target. This imposes several challenges like collision free approach to the target and motion redundancy. Many algorithms like Artificial Potential Field (APF), the Rapidly exploring, Rapid Tree (RRT), Model Predictive Control (MPC) have been used to solve but pose challenges in redundancy. The paper proposes a new optimal collision-free and singularity-free trajectory generator for a CFSR.

Daniel Hennes et.al(2022) present a heuristic-free approach based on Monte Carlo Tree Search (MCTS) for automated trajectory planning. Most interplanetary missions require a well-designed trajectory that guides the spacecraft through a number of gravity-assist maneuvers, also called fly-bys. Fly-bys are executed to steal some of the planet's orbital energy in order to limit fuel consumption. MCTS is used for finding the correct planetary sequence and time schedule that allow for the minimization of fuel consumed. MCTS goes through four steps for the required optimization: Selection, Expansion, Simulation, and Backpropagation. The evaluation of a trajectory is based on the total change in velocity during all the maneuvers. The best sequence of approach found by this model was very close to the actual approach in the case of the Cassini-Huygens mission while the trajectory options suggested in the case of the Rosetta mission were incomplete.

Haibin Huang et.al(2022) present an optimal trajectory for formation reconfiguration in deep space missions. Formation reconfiguration is undertaken to determine a set of optimal transnational trajectories allowing a spacecraft to transfer its state with the required performance index.The Legendre Pseudospectral Method (LPM) is employed to convert the optimal reconfiguration problem into a parameter optimization nonlinear programming (NLP) problem.Particle Swarm Optimization (PSO) is implemented to solve the NLP. Every particle of the swarm updates their velocity based on the personal best solution and the global best solution.Collision avoidance constraints are enforced by ensuring that the particles stay apart by a certain threshold distance. To check for collision, few test points are inserted between two Legendre-Gauss-Lobatto (LGL) points where there is a likelihood of collision. Finally, it can be inferred from the results that the PSO method could avoid most collisions during whole maneuvers. So, the trajectory found without enforcing collision constraints were near to the optimal trajectory with collision constraints.

Huaijiang Zhu et.al(2022) found an efficient approach to object manipulation planning using Monte Carlo Tree Search (MCTS) to find contact sequences.Interaction forces and contact switches are the main challenges faced during object manipulation planning.An ADMM based trajectory optimization algorithm is used to evaluate the feasibility of possible candidate sequences. If the contact surfaces are known, then the forces and contact locations can be found efficiently. At most one end-effector can touch a contact surface and each end-effector can utmost touch only one contact surface.Only one end-effector can break contact at each time step.The method is evaluated based on the force and torque error between the desired and generated solution and the computation time for first feasible solution. This method is capable of solving both short-horizon and long-horizon tasks. The major limitation of the approach is that the object motion must be provided. The approach assumes perfect knowledge of the object and environment which is not practically feasible.

Edward N. Hartley used model predictive control (MPC) to review the recent advances in spacecraft rendezvous missions. MPC is a control strategy based on on-line constrained optimisation of control inputs based on future trajectories. In a rendezvous mission, there is an active vehicle (chaser) and a passive vehicle (target). The target moves in a fixed orbit, while the chaser needs to be actively controlled to transfer it into the target's orbit, then it is made to approach the target at a safe terminal velocity. For perfect rendezvous, collision constraints are enforced. Also, a scenario has been taken into consideration where a single thruster must be re-oriented, so over-exertion must be avoided. There are multiple state constraints which lead to infeasibility. So, either the constraints need to be softened and accept a degree of constraint violation or systematically tighten the constraints based on the bounds of disturbance. MPC works well for fixed horizon, time-invariant rendezvous missions.

Madhuri Tiwari et.al(2022) proposed a modified control system to generate and track trajectories in the vicinity of asteroids. The novel system proposed here is a combination of the benefits of adaptive and optimal control systems. Adaptive control is used as a feedback controller and an MPC is used as feed-forward controller.The asteroid shape and inertia are assumed to be unknown while the total mass and its angular velocity are known.This control mechanism is called Direct-Adaptive Model Predictive Controller (DAMPC). The adaptive control increases the robustness of DAMPC.The MPC stabilizes the system and generates sub-optimal trajectories to be fed into the adaptive control. Dynamic, thrust and ellipsoidal constraints have been enforced for obstacle avoidance and to avoid overshooting the trajectory. DAMPC was numerically tested for the case of asteroid Kleoptra, for a rest-to-rest maneuver. The controller was able to generate and track collision-free trajectories and was also adept at handling noise.

John W. Hartmann et.al(1998) applied the Pareto Genetic algorithm for optimisation of low-thrust interplanetary spacecraft trajectories.Low-thrust trajectory optimisation has gained interest due to high-propellant efficiencies of the system which would allow cost-cutting. Pareto optimization is a multiobjective optimization which combines multiple objectives into a single objective by using weight vectors. Genetic algorithms used here employ selection, crossover and mutation to perform evolutionary search. Niching is also done to distribute members over large portions of search space and avoid premature convergence to a single solution. Based on the degree of proximity of the members, they are penalized at the end of each generational cycle. A solution is Pareto optimal if there exists no set of solutions that is superior to the current solution in all objectives. The Pareto Genetic algorithm is a non-dominated sorting genetic algorithm (NGSA). In each iteration, a Pareto front is assigned then the penalties are calculated. This continues till all individuals are assigned a front. The algorithm worked optimally for three simulations: Earth-Mars flyby, Earth-Mars rendezvous and Earth-Mars rendezvous on-demand.

Lorenzo Casalino et.al(2009) applied a hybrid evolutionary algorithm to the optimization of space missions with multiple impulses and gravity assists. Evolutionary algorithms (EAs) are procedures which search for the global optimal solution in the given search space for the given function. The algorithms used in the paper are Genetic algorithms (GAs), differential evolution (DE), particle swarm optimisation (PSO) and tabu search (TS). Information is shared amongst algorithms used in hybrid EAs, to improve the performance. The population of the Hybrid EA is the set of candidate solutions, and a cost/merit function determines their suitability to the environment and evolution occurs accordingly. GA chooses the best suited solution to be part of the next generation. DE generates new solutions by taking the weighted difference of existing ones. PSO modifies the solutions based on the personal and global best value.TS generates a list of promising solutions whose elements are centers of these promising regions and new solutions are added only if they don't belong to these regions. This combination of models is highly efficient and robust for optimizing spacecraft trajectories with multiple impulses and gravity assists as compared to the individual models.

J.Kponyo et.al(2014) in their work establish that ant colony optimization can efficiently improve the traffic situation in any environment and hence, can also find the optimal path to be taken to reach the destination. A Dynamic Travel Path Optimization System (DTPOS) establishes a vehicular ad hoc network and uses communication amongst vehicles to relay traffic status information. DTPOS is based on ant colony optimization (swarm intelligence), where ants use pheromone to relay information about the optimum path from a food source back to their nest. Its aim is to minimize both the total mean transit time and total variance in transit time. An improvement in ACO, is the previous path replacement (PPR). PPR involves comparing the best path with any new path found and then storing the best of the two. Results of their work clearly indicate that DTPOS with PPR provides the most efficient solution followed by DTPOS without PPR, followed by just PPR, and finally no ACO.

Arthur Richards et.al(2003). in their work discusses a newly developed form of Model Predictive Control (MPC). The drawback of existing MPC is that it requires the target to be an unforced equilibrium or the cost function imposes a penalty on the difference between the control inputs and the equilibrium forcing necessary to remain at the target. In the new MPC, firstly, MILP optimization is used, which allows the inclusion of non-convex constraints. Second, assurance of robust completion in finite time, for that assumption is taken of bounded disturbance. Then, 3 different forms of MPC were compared with one another and the glideslope algorithm in two test conditions, which are intrack approach and radial approach. In the first set of simulations no disturbances were taken and in the second set of simulations constant and random disturbances were considered. In all the cases MPC performed better than the glideslope algorithm.

Xiaoguang Di et.al(2013) discuss how ascending trajectory optimization can be done in the case of near-space airships while fully considering the disturbance caused by wind. Near space is the air space from 10km to 100 km above the sea level. The genetic algorithm performs better than the SQP algorithm in the case of complex non-linear programming and also the SQP algorithm is sensitive to the initial value of the problem. The whole trajectory is divided into 3 phases, the first is 0km-5km, the second is 5km-15km, and the third is 15km-22km. Using direct collocation, the dynamic optimization problem is then converted into a parameter optimization problem which can then be solved using the Genetic algorithm. The advantages of the Genetic algorithm in the following case include optimal solution from the beginning of a population instead of a point, no need of high order information and use of probability search which results in the global optimal solution.

Daniel Morgan et.al(2013) talks about the model predictive algorithm for the optimal guidance and configuration of swarms of spacecraft having lots of agents with limited capabilities. Sequential Convex Programming is not effective due to a high number of collision-avoidance constraints. So, Model predictive control-SCP i.e. MPC-SCP is used which decentralizes the communications required for swarm configuration with collision avoidance and also reduces the size of the problem resulting in less run time. Femtosat communication and computation are greatly reduced by decentralising the swarm guidance algorithm. The SCP algorithm is run multiple times to account for errors or uncertainties in the desired and actual trajectories when computing future trajectories which is the reason for some robustness as compared to running SCP one or two times. Later, a receding horizon was introduced and again MPC-SCP was applied, which decreased the number of variables and constraints which allowed smaller time steps in the optimizations.

Robert Smith et.al(2000) in their work discusses trajectory planning for multiple spacecraft. Generally, constraints like collision avoidance and limited fuel usage make the problem nonlinear and multi-modal, which does not allow us to use gradient descent or calculus. Also, a general solution can not be found when we are dealing with N spacecraft. Genetic Algorithm techniques can be used to find autonomous spacecraft trajectories as they serve as good global optimizers. Genetic Algorithm advantages include generating a large and diverse number of solutions from which one can be selected which performs best. Constraints for trajectory optimization for N-spacecraft problems are - collision-free, shortest path, minimum time and fuel usage and uniform fuel distribution at the end of maneuver. One problem with the genetic algorithm is that as it converges towards a single type of individual, the remaining population becomes unimportant. The Niched Pareto Genetic Algorithm which is a modified version of the genetic algorithm which solves this problem by maintaining a diverse and steady state population as the final result. This type of version can solve multi-objective optimization problems w.r.t. all criterias mentioned above.

KAILI XIE et.al(2020) discuss the safety and efficiency of aircraft during flight. A* Algorithm is used in a static environment for the purpose of trajectory planning, but in the case of a dynamic environment, Dynamic A* Algorithm that is D* algorithm is used. Since the D* algorithm is more complicated, Lifelong Planning A* (LPA*) is an extension of the A* algorithm and its search efficiency is higher which is achieved by multiplexing environmental information. Later, fast D* Lite was introduced with better search efficiency than LPA*. The key highlight of fast D* lite was that it completely or partially avoids re-planning and calculation of some nodes. The problem in D* Lite algorithm is that the path planned by it is very close to obstacles, in real-world scenarios making it unsafe. This paper proposes the improved D* Lite algorithm, in which nodes with obstacles around are not taken for node search calculations and to avoid increased path nodes and turning points, Euclidean distance is replaced by Chebyshev distance.

Kun Y. et.al (2018) have proposed a solution to the problem of far-distance rapid cooperative rendezvous between two spacecrafts, specifically when two spacecrafts are orbiting on non-coplanar orbits and their apsidal lines are different. They found that PSO can’t be used here as it falls into local optimal and cannot converge to a global optimal solution.They concluded even if it did converge optimal fuel consumption would still be really large.The results of classical PSO are not stable to be initial values of

SQP.They put light onto using QPSO as it increased convergence speed , convergence accuracy and stability. It uses the ability to generate a rough range of optimal solutions quickly and precisely, but lacks the local search of SQP. They used QPSO-SQP by taking the initial value of it. The mean time of calculations came out to be 25.074 min for QPSO-SQP and 68.31 min for PSO-SQP.Overall it was found that QPSO can converge more rapidly and is hence most preferred.

Addis B. et.al(2011) have given the work for optimally designing a trajectory for space mission.GTOP database has been used on different models.They suggested that problems can be simplified using simple global optimization on standard models for local optimization. They have used Multiple Gravity Assist (MGA) , MGADSM Models for Multi- start algorithms where standard local searches are replaced by middle searches returning funnel bottoms. It was carried through Basin Hopping or Monotonic Basin hopping approach.They have used a technique called implicit-filtering algorithm(IF) using SQP code SNOPT.They incorporated Variable scaling and Periodic variables, everything was tested on ESA ACT. They tested out various space missions such as Rosetta , Cassini-Huygens,etc.Future research will be carried out to extend the range of applicability of Basin Hopping to space trajectory, and the final algorithm proposed is Differential Algorithm with Basin Hopping scheme.

Bradley J. Wall et.al (2008) have proposed hybrid optimal control problem solution algorithm, which works with GA’s and are employed in both inner-loop and outer-loop solvers.They used shape-based method which performed better than direct method in collocation with NLP(DCNLP) or RK parallel shooting(DTRK). The 4 asteroid sequence had 12 min using shape based and 7 hrs using DTRK solver. They suggested that for low-thrust arcs it's best to use GA outer-loop solver anc combine with inner -loop. The B & B tree for the GTOC2 problem had 910 one-asteroid sequences, 580,000 two-asteroid seq. And 230 million three-asteroid seq, and 41 billion 4-asteroid sequences.They found cause of this heavy computation they presented idea of pre-pruning such as sequences which go out to outer orbit then return back to inner orbit , they found it would eliminate 50% of 41 billion sequences of GTOC2 problem.Their final verdict was that GA+GA method for the solution of HOCP’s is better as it removes the work of pre-pruning of possible sequences.

Saber M. Elsayed et.al (2014) have worked on a newer path for genetic algorithms for solving optimization problems. They proposed GA with multi-parent crossover (GA-MPC) , its coming from heuristic crossover.They proposed a diversity operator , they didn't use mean centric probability distribution such as UNDX and SPX nor apparent-centric PCX. They describe a 24 known constrained benchmark problems such as Parameter estimation for frequency-modulated (FM) , Lennard-Jones potential problem , optimal control of a nonlinear stirred tank reactor, static economic load dispatch(ELD) etc.After using GA-MPC , it was 100% while SBX-NU was 89% on feasibility ratio and PCX-NU was 83%.They have also performed Wilcoxon Signed Rank Test to judge for differences between algorithms. Results showed GA-MPC , APF-GA,MDE and ECHT-EP2 reached optimal solutions for 22,17,20 and 19 problems , on this GA-MPC was better than APF-GA in terms of better average results. For future work , they intend to conduct further theoretical analysis of their proposed algorithm.

Alireza E.et.al (2022) have proposed a hybrid method for trajectory optimization of re entry spacecraft.They tried solving the problem of heat reduction in early phases of reentry. They have tried using 3 global optimization methods (ABC , GA and GA-PSO) and used them to determine the best profile of the bank angle and angle of attack.ABC is swarm based algorithm and for randomosity PSO-GA is used. Bank angle and angle of attack function was made using Polynomial and sine functions.They have divided 2 phases , first one being heat reduction and next one to satisfy final conditions , parameter k optimization methods.GA-PSO yielded the best results , their heat reduction was 6% lower, Heat Transmission in [140-250s] time period is lowered by 11%.they also found that current method reduces the maximum heat rate by around 12%, and final mistakes were less than 2%. The present study will be used to reduce the heat rate of an SRV without sacrificing final conditions.

V.M Becerra et.al (2007) have given a design of optimal multiple gravity assist trajectories with deep space maneuvers.They have located feasible vectors using local optimization and applied a clustering algorithm to find reduced bounding boxes. They have used the Global optimization method of Differential Equations. They have formulated problems into multi-stage optimization (MSOP) and used GASP(Gravity Assist Space Pruning) . It includes powered gravity assist at intermediate planets and braking manoeuvre.A model is made , a patched conic, and is assumed to be a two-body problem. They have found leg trajectory through the solution of 2 Lambert problems, using Battin's method for Lambert problems. 3 algorithms have been used , pruning the first phase , pruning the second phase and Global Optimisation on the pruned search space, in that they have used Stochastic global optimisation algorithm.A simple Earth - Mars mission has been designed to compare the results with Earth-Venus-Mars mission.For tolerance of lambert solver was 10^{-14} and 10^{-6} for differential Evolution Optimization phase.

Karla. R et.al (2022) have given an autonomous trajectory maneuver to de-orbit spacecraft back to Earth using collision avoidance techniques.They have compared two methods, sinusoidal and Pontryagin, they tracked Euler angle spacecraft and found differences. Pontryagin's trajectory had a 15 min lower computation time .Simulink was used to model Euler Angles, way-point guidance , controls , sensors and natural forces.The model was made (PID controllers) to handle quaternion kinematics along with Direction Cosine Matrix, to mimic spacecraft trajectory accurately.Sinusoidal Approximation and Pontryagin's Optimal Trajectory were performed , by minimising cost functions. They finally calculated the Way-Point Guidance Method , atan = miss dist/ for. Travel dist. Mass of 100kg was taken with altitude of 1000 km and total of 600s with 4 way-point guidance maneuvers. Overall it was found Pontryagin method was more optimal with 37.9% fuel conserving and 40.5% less time.They plan to expand their research by increasing the breadth of the simulation to include a touchdown model on Earth's Surface.

Deaconu. G et.al(2014) have proposed a Model Predictive Control(MPC) as a potent strategy capable of accommodating mission-specific constraints and minimizing fuel consumption. Feedback control MPC is used as feedback policies instead of control actions.It approaches for circular and eccentric orbits, leveraging static feedback terms and time-varying feedback policies. Tube-based MPC concepts are utilized to achieve robust fixed-time spacecraft rendezvous while considering navigation uncertainties and actuator constraints, aiming to minimize fuel consumption and ensure precise rendezvous.The variable change has been used ny Tschauner & Hempel to obtain linearised spacecraft relative dynamics for arbitrary eccentricity.They got final error e_N into computing the smallest ellipsoidal set $E(0,Q_f^{-1})$. Minimizing it enables problems linked to infeasibility when satellites get close range.They were able to use MPC disturbance feedback for better a priori for closed loop system behaviour for any value of uncertainty.

Wei Li. et.al (2023) have proposed a self learning Monte Carlo Tree Search(SL-MCTS) which can continuously improve its problem-solving ability in single-player scenarios.They have used a two-branch neural network (PV-Network), it outputs the selection probabilities p which is then evaluated by comparing it with optimal models.Evaluation is done using Proximal Policy Optimization algorithm , additionally they also compared other variants of algorithms such as MCTS , SP-MCTS, SP-MCTS-CRIPPA.Elo-rating is used for number of evaluations. SL-MCTS explores only 28.9% of the environment space and solves the problem in 25.48s, its simulation counts were 30 , compared to 50-150 for SP-MCTS. Results showed SL-MCTS can find the solutions with better quality in half the time required by MCTS-50.In future they want to further explore applying self-learning collective intelligence algorithms in the field of path planning problems.

Zheyao X . et.al(2019) have worked on guidance and control strategy for spacecraft rendezvous and docking specially with chaser spacecraft docking with a rotating target spacecraft.They have used a flying-around approach , Optimal energy guidance method, In the prior they have given that spacecraft can arrive at the dicking position and maintain a fixed relative position and also relative attitude to rotating target.As this approach is not efficient optimal energy guidance algorithm is used in which they have used front docking region to avoid collisions with solar panels, expands front docking range and has better angle of incidence for docking. A_r is used for ACD , AD and DM. Relative velocity equations are used for evaluation to make relative motion to be 0. The analytical expression of minimum energy guidance is solved based on Pontryagin minimum principle.They plan to use the proposed technique for a better docking system in spacecraft stations.

Abolfazl S et.al (2018) have proposed a review for solving spacecraft trajectory optimizations problems , they have divided it into 4 parts , of mathematical modeling of the problem, defining the objective functions, development of an approach and obtaining the solution of the problem.They have classified based on their characteristics. They have reflected on the previous work done by others.They found that there are various solutions to problems. Solution to the trajectory optimization problem that minimizes a cost function to nonlinear differential equations of motion and various types of constraint has been used. They concluded it majorly depends on what type of mission its there to use which algorithm to use, maybe genetic or particle swarm.They said viewing them as general ideas allowed a broader view of the problem and discovered similarities between structure and inner workings of methods.

Zich F .et.al (2019) have worked on Multiple-asteroid exploration with low-thrust propulsion.They have used FFS method to generate flight trajectory at very short computational time and the MCTS algorithm to determine the exploration sequence in multi-asteroid exploration.They have used Fourier approximation, the goal is to visit multiple asteroids which is time-free problem (NLP). MCTS have also been used where Earth is the root node, and each of the rest of nodes represent an asteroid.They have evaluated to visit whole sequence selection, MCTS was terminated by controlling the number of iterations.For simulations they have used GTOC-3 and had used traversal algorithm , Greedy Algorithm , Tree search algorithm with trimming strategy, MCTS algorithm. They found that for same sequence MCTS is 79% of traversal algorithm.When they reduced number of iterations to 9, MCTS took 71% of the computation time of the traversal algorithm to obtain the quasi-optimal solution with a probability of 88% and the suboptimal solution with a probability of 12%, and the difference between the two solutions is 9.5%.

Martin S. et.al (2015) have shed light on optimization of interplanetary space mission trajectories.They found that Ant colony Optimization (ACO) has been remarkably optimal in Ceriotti , Vasile and Schlueter.They have proposed a better approach Utopia-Nadir-Balance Decomposition, with parallelization framework ACOMOD (Master-Slave Model) . To test their model they have used an interplanetary design problem from ESA GTOP - 8 .They got 12635 non-dominated solutions for the 4 objectives.They saw that ACOMOD had similar results with HV indicator, whereas the proposed utopia-nadir had a small advantage of about 1%. In the area of weighted sum, utopia-nadir had 3% over ACOMOD. In the second level of two parallelizations, utopia-nadir had a 4.6% advantage over others.They hope that their work shows a new way of fully automated, deep space mission design planning which also takes in mission parameters at the same time.

Yanghua.LI et.al(2013) have proposed the idea on the implementation and application of quintic polynomial in the spacecraft trajectory planning.They have worked on to optimise the spacecraft's trajectory on basis of quintic polynomial, They have used a inertial coordinate system , centroid trajectory, attitude angle. They have also made an attitude kinetic model of spacecraft and have also implemented use of a PID controller (Proportional-integral-differential). They have devised a quintic polynomial to generate a continuous smooth trajectory; a linear function of parabolic fit has been used. SIMULINK has been used to simulate the trajectories to get a relative error of 0.2% between expected attitude angle and the actual angle. They think by this method they can generate a trajectory whose position , speed and acceleration are all smooth and continuous as they final result they had 60˚ wide-angle maneuver within 40 seconds with control accuracy of 0.1%.

Andriy Predmyrskyy et.al(2020) explores the application of differential evolution on simple adaptive control law formulation and compares it to techniques like selection particle swarm optimization(SPSO) and self adaptive differential evolution(SaDE). The final DE and SaDE optimized controller compared with the manually designed SAC was able to determine significantly lower cost controllers. DE converges on the model response very quickly, SPSO likely increased convergence by moving high cost agents closer to the lower cost agents. For SPSO, 50% of the agents were used to provide updated positions of the other 50% of agents.In the SaDE search the four trial vector generation functions described were used in strategy adaptation. In the future, work in this field may include the structure of cost functions used in conjunction with adaptive controllers, techniques to minimize the search space or determine characteristics of the cost function applied may greatly improve search speeds and results.

ZHU Kaijian et.al(2009) in the paper compares the different realistic global optimization algorithms, which include genetic algorithm, particle swarm optimization, differential evolution algorithm and two hybrid algorithms. Assumptions taken are square inverse gravity field between the planets, time of spacecraft passing through the influence sphere of the planet is negligible, spacecraft is considered mass point. GA cannot get an optimal solution for some benchmarks, because of the presence of more than 30 parameters to be optimized resulting in the invalidation of binary coded GA. Differential Evolution is similar to EA in structure but differs in case of generating new candidate solutions and using a greedy selection algorithm.It has lots of potential in numerical benchmark problems and real-world applications. In the hybrid algorithm of PSO and SA(simulated annealing) principle of SA is applied in the process of renewing the position and velocity of the individuals in the population. Another hybrid algorithm is composed of PSO and DE which takes advantage of both algorithms and delivers results which are very close to optimum.

CONCLUSION

Denouement

The extensive research that we did on the following topic of spacecraft trajectories has helped us understand the complex and intriguing word of space exploration and its complex problems involved in the process.We have learnt and explored a lot of optimization techniques, algorithms and mathematical models which has helped us to understand immense possibilities of computational methods that can be used in space exploration.We plan to implement and analyze these principles through code and real-world dataset.

One of the most significant takeaways from this extensive research we did was the wide variety of optimization techniques used to solve spacecraft trajectory problems. Genetic Algorithms, Particle Swarm Optimization, Monte Carlo Tree Search, and Differential Evolution are some of them, we also found it depends most of time on the space mission hence giving us flexibility. We also saw the crucial part of multi-objective optimization, we get a lot of problems such as minimizing fuel consumption, maximizing mission duration and ensuring collision avoidance. All these problems have been handled with multi-objective optimization.

The focus on Model Predictive Control (MPC) has been an important part of docking systems and spacecraft rendezvous, real time adjustments have been made possible due to control algorithms which were seen to increase the accuracy. Of course the safety is an important consideration in space exploration, algorithms such as Artificial Potential Field(APF) and Rapidly Exploring Random Tree(RRT) were seen to maintain safe distances between spacecraft and other debris.

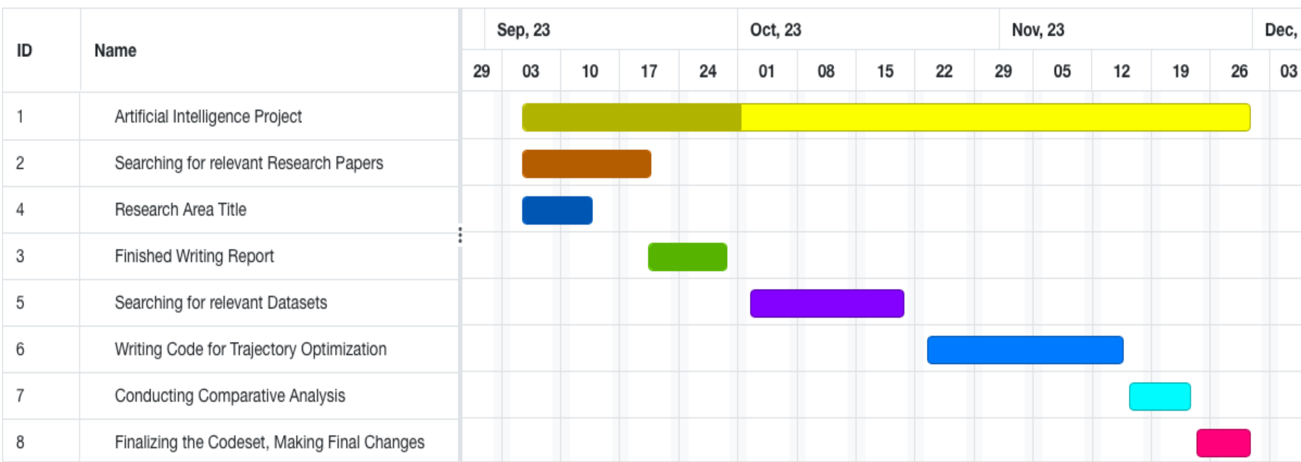
Plan for Implementation and Analysis

We aim to contribute to advancement of trajectory planning techniques, by simulating a real world dataset of problems of Global Trajectory Optimisation Competition (GTOC).

We plan to select a specific space mission like Cassini or Apollo for our implementation, which will also depend on the algorithms we plan to work with,We will be gathering relevant datasets from the internet which will contain initial conditions , spacecraft parameters , celestial body characteristics and mission objectives to help us in trajectory planning. We plan to work in C++ / Python to implement the algorithms discussed in the above research. For simulation we plan to use MATLAB/ SIMULINK so we can look after the parameters such as fuel consumption, mission duration and collision avoidance.

Then we plan to conduct a comparative analysis of performance of different algorithms by varying the parameters, we plan to do this by having 2D and 3D plots of spacecrafts path to understand the results properly.We will be documenting the code, datasets and results comprehensively to serve as a valuable reference for future space mission planners.

Gantt Chart



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