Orbital Mechanics Competitions as Experiential Learning Opportunities for Undergraduates

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Abstract

This paper describes the development of an undergraduate research program in which orbital mechanics competitions are used as a basis for applying and integrating knowledge that undergraduate students gain throughout the mechanical engineering curriculum. Since 2017, four students from freshman through senior levels have been included in this endeavor. The approach to these competitions leverages basic physics and programming concepts to attack a complex problem. Thus, even freshmen-level students can meaningfully contribute to forming problem solutions. As students further their education, more complex analyses can be performed using numerical methods. In addition to a curriculum-wide analysis directed at identifying learning objectives that can be bolstered by these competitions, this paper also discusses the mapping of learning outcomes to ABET student outcomes. These competitions pose a significant challenge, but also present a great experiential learning opportunity for undergraduate students as well as provide a path to gain research experience.

Keywords

Undergraduate research, space mechanics, GTOC

Introduction

This paper describes the development of an undergraduate research program in which orbital mechanics competitions are used as a basis for applying and integrating knowledge that undergraduate students gain throughout the mechanical engineering curriculum. Since 2017, four students from freshman through senior levels have been included in this endeavor. The approach to these competitions leverages basic physics and programming concepts to attack a complex problem. Thus, even freshmen-level students can meaningfully contribute to forming problem solutions. As students further their education, more complex analyses can be performed using numerical methods. In addition to a curriculum-wide analysis directed at identifying learning objectives that can be bolstered by these competitions, this paper also discusses the mapping of learning outcomes to ABET student outcomes. These competitions pose a significant challenge, but also present a great experiential learning opportunity for undergraduate students as well as provide a path to gain research experience. **Since research in the space mechanics arena began at INSTITUTION, two competitions have been entered: the Global Trajectory Optimization Competition (GTOC) 9[1], the Chinese Trajectory Optimization Competition[2], and GTOC X[3]. GTOC 9 and GTOC X will be discussed in this report.**

Competition Overview

The first competition that was entered was GTOC 9 where the problem statement detailed 123 pieces of orbital debris that inhibit future space flight. In this competition, the mission was to find the optimal path for a spacecraft(s) to take in order to rendezvous with each piece of debris, deorbit it, and then move to the next targeted debris. This process involved extensive matrix sorting to evaluate which pieces of debris minimized the amount of fuel needed to reach it.

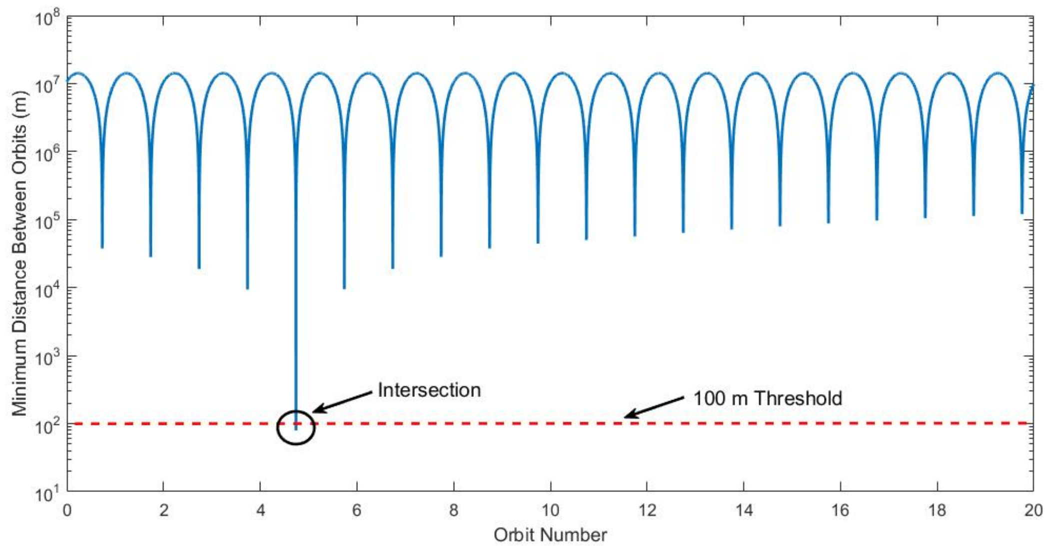

Figure 1: Minimum distance determination between spacecraft and target debris (ref: 4)

In order to find an efficient path for a deorbiting satellite to travel between pieces of space debris, the distance between the orbits of the satellite and individual pieces of space debris was calculated over time. Figure 1 shows a plot of INSTITUTION's GTOC 9 results, which represents the distance between the deorbiting satellite and the instantaneous orbit of a particular piece of debris. The dashed line is the threshold for an intersection to occur between the orbits. As indicated, just before the fifth orbit around the Earth, there is a direct intercept between this piece of debris and the satellite. At this point, a fuel consumption analysis would be conducted to see if it was efficient to target this piece of debris further for additional rendezvous maneuvers and eventual deorbiting of the space debris. This process was repeated with other debris targets until the optimal target was decided on.

The second competition that will be discussed here INSTITUTION entered was GTOC X, where teams were tasked with developing a plan to colonize the Milky Way galaxy. The galaxy was considered to be a collection of 100,000 stars orbiting a black hole at the center of the milky way in circular orbits. Teams were to maximize the number stars settled within a 90 million year (Myr) period while maintaining an even spatial distribution of settled stars using minimal fuel.

As an optimization competition, success was measured through a reward function that calculated scores based on fuel efficiency, number of stars settled, and star distribution. Due to this reward function, there were two natural strategies for the competition. The first was to compute the paths to colonize as many stars as possible and then pare down the data set to maximize the spread of colonized stars in order to prioritize an evenly spread distribution. This required significant computational resources due to the sheer number of potential orbital paths calculated.

The second strategy was to focus on a minimal number of stars while utilizing efficient fuel burns. The second strategy proved to be more successful given our team's constraints.

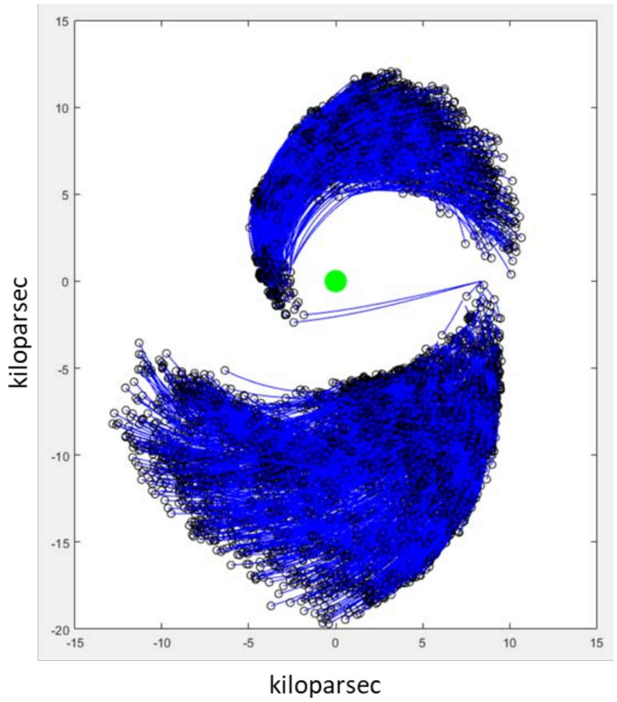

Figure 2: Bands of colonized stars surrounding the Milky Way Galactic Nuclei

Figure 3 shows results from GTOC X and is an overhead view of the Milky Way; each black circle represents a colonized star, each blue path is the trajectory a spacecraft took to get there, and the green dot is the center of the galaxy. The image represents 4340 colonized stars. Qualitatively, the angular distribution of colonized stars appears to be uniform. To quantitatively assess this approach, the actual special and angular locations of these colonized stars was plotted, as shown in Figure 4a-b. These plots show the angular and radial distributions of stars, respectively, as a function of time, with different colors indicating the stars settled by each original settler ship launched from our solar system and their descendants. In inspecting Figure 4a, the pattern of stars settled by each of the original ships maintains a narrow angular spread throughout time, which tends to form gaps in the axial star colonization. Conversely, the radial distribution of these colonized stars tends to become broader over time, forming a more uniform radial distribution, although some gaps do still exist. Based on the competition merit function, the result of this solution submission was a score of 70.5.

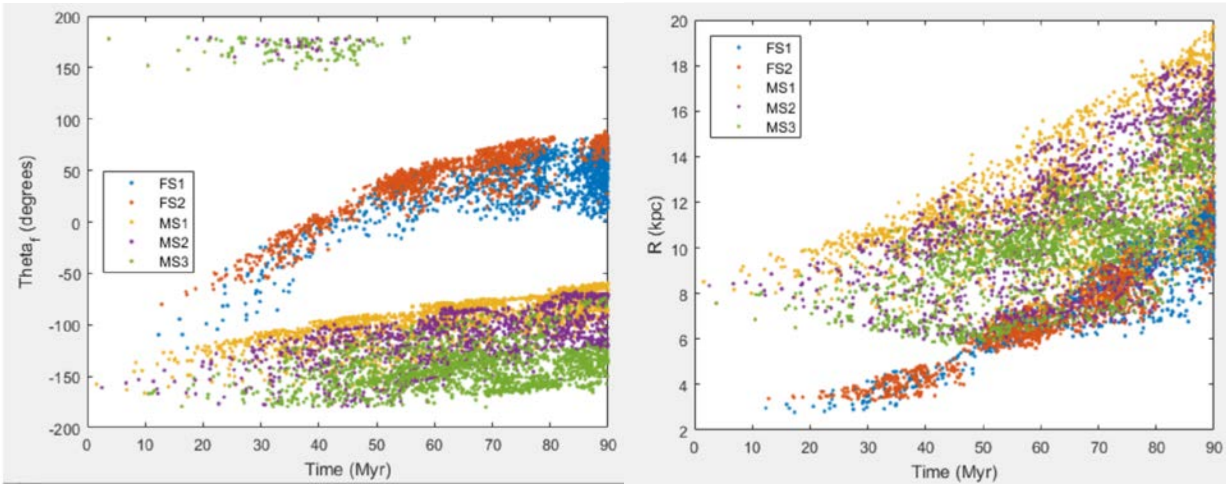

Figure 3: Analysis of a) axial and b) radial spread of colonized stars over an 80 Myr period

The best score for this team was gained by colonizing only two stars. The idea of this approach was to find stars that remained close to our sun throughout the 90 Myr timeline. This would allow a ship to make a very small fuel burn and travel very slowly to the nearest star to colonize it. This was done by analyzing nearby neighbor stars, within 0.25 parsec, at 0 Myr and then at 80 Myr for the same search area. This returned five possible target stars and the combination of two such stars utilized minimal fuel consumption, and earned our team's highest score of 173.7.

Student Outcomes

As students brainstorm ideas and develop methods for solving these orbital mechanics challenges, they gain experience with not just a specific set of tools, but with a variety of aspects of engineering. No place is this shown better than in the ABET student outcomes that are addressed as a part of these research projects. This section will show how the work needed to compete in these competitions aligns with ABET student outcomes.

1. An ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics

All aspects of this student outcome are addressed through these competitions. Students read the problem statement to identify the problem, they determine how to apply their engineering knowledge to formulate a solution and apply their coding skills to solve the problem. Given that the competitions are based on orbital mechanics, students are exposed to principles of astrophysics, dynamics, numerical methods, etc., covering a wide range of STEM fields.

2. An ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors

Each of these competitions places the engineering problem within the context of global or interstellar issues. One of themes for these competitions, for example, is orbital debris removal. The space environment is becoming increasingly crowded both with satellites that are placed on orbits and rocket bodies and corresponding detritus. Being able to safely operate in the space environment is critical for satellite systems like GPS. Unfortunately, the more systems we put in space, the more potential for increased debris. All of theses pieces need to be tracked so that any bits of debris that come close to a given satellite would require that satellite to maneuver in order to avoid a collision. A debris removal plan is in critical need and these competitions offer an opportunity to generate possible solutions for this task. As a real world example, in 2007, China purposefully destroyed one of its satellites on orbit to test anti-satellite missile technology which immediately generated thousands of pieces of space debris that now pose significant risk to other satellites in similar orbits.[6] A similar test was performed in 2019 by India[7], showing that these global, political issues exert a continued influence on real world science and engineering issues.

3. An ability to communicate effectively with a range of audiences

To date, the work done by the members competing on the team at INSTITUTION has resulted in three publications. Students have been included as coauthors on each of these publications.

4. An ability to recognize ethical and professional responsibilities in engineering situations and make informed judgments, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts

As with ABET Student Outcome 2, the competitions pose real-world problems with significant engineering challenges that will have a global impact if not addressed. This provides an opportunity for students to be exposed to these problems.

5. An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet obj.

Many tasks that needed to be accomplish and they were difficult to do by one person. There was a need to brainstorm all the items that needed to be addressed and then they were tasked out based on each team member's skill sets. Everyone's input was valuable no matter if they were first year students or faculty members. The competitions were ~30 days long and so these objectives had to be completed in a timely manner to generate a possible solution for submission.

6. An ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions

An interesting issue arose with how to translate the problem statement into Matlab code that could be used for solution testing. This process involved coding orbital mechanics calculations into Matlab, running the code, and then evaluating whether a given problem item was solved. For instance, in the GTOC 9 competition an orbital debris rendezvous occurred when the spacecraft was within 100 m of the target debris. Code was generated that would look at closest approach between the spacecraft and all 123 pieces of debris for a predetermined amount of time. If a closest approach was within the 100 m, the target debris was then analyzed further to see if the fuel required to move the spacecraft from its current location to meet the debris was within a certain threshold. To the best of the team's abilities, this process was automated to reduce the number of times the code had to manipulated during in situ during a testing scenario.

In GTOC X, the problem statement was loftier, but no less challenging to work through. Teams were asked to essentially colonize the Milky Way over the course of 80 Myr with 30 days to submit solutions. The starting point was Earth and up to five settlement spacecraft could be used for colonizing the galaxy, including three motherships and two fast ships. Scoring well ended up being based off how well teams could manage and code competing priorities related to fuel consumption, the number of stars colonized and the even distribution of colonized stars.

7. An ability to acquire and apply new knowledge as needed, using learning strategies.

For the undergraduate students, these competitions were typically their first exposure to the physics involved in astrophysics calculations. They had to acquire new knowledge in a short timeframe and then immediately apply it to form possible solutions or generate applicable code.

Curriculum Correlation

From a programmatic level, the space mechanics competitions offer an opportunity to utilize their education to solve real-world engineering problems. Courses throughout the curriculum enable students at every level of their academic careers, as will be discussed in this section.

MECH 102 – Engineering Computer Applications with Matlab

The bulk of the coding for these competitions has taken place with Matlab. Students develop a basic understanding of Matlab in MECH 102. They work with topics such as: matrix definitions and sorting, minimization, searches, and function generations. Each of these are critical functions that are used exhaustively in the overall code. It is this necessary base understanding that allows first-year students the ability to compete.

MATH 131/132/231 – Calculus I-III

Calculating position as a function of time is a somewhat nonintuitive process. There are no closed-form solutions which can be employed to find this information and when orbital perturbations like considering the Earth's oblateness make this process more difficult. To accurately calculate position, topics concerning numeric approximations of integrals must be utilized. Therefore, learning objectives in Calculus I-III and Differential Equations become essential for solution progression. Specifically, a Runge-Kutta approximation is typically used to integrate provided differentials to find position. Luckily, each of the competitions provide the time-dependent differentials as a starting point for developing a solution. The GTOC equations are outlined in the referenced problem statements. When coding these functions into Matlab and solving them, ode45 was used.

COMM 260 – Technical Report Writing

Being able to communicate complex ideas effectively is a powerful skill for an engineer. COMM 260 introduces how to author a technical document. For these competitions, discussing the outcomes of student work is important to publish so that others who may be interested in this topic can become engaged with it and participate as well. Therefore, it is important to publish the good and bad results, where possible. The faculty leadership on the team encouraged the undergraduate students to author their perspective on the competition and the approach that they used in solving the problems that were delegated to them. This has resulted in three publications.

PHYS 221 – Physics I with Calculus

Physics I provides a baseline for the topics applied in the competitions with the discussion of Kepler's Laws of Planetary Motion. For circular and elliptical orbits of satellites, general orbital ephemeris components like radius, true anomaly, and period can be calculated.

PMGT 401 – Project Management

Generating a possible solution for these competitions is a nonlinear process; there are many side tasks and subroutines that need to be accomplished in parallel to be eventually integrated together. Identifying skillsets and managing component development and integration in a time-constrained competition is thus key. Students learn these types of skills in project management where having visibility on all aspects of a process is essential for successful results.

481/482 – Senior Design I/II

Even though the mechanical engineering curriculum does not perfectly align with the skill set needed for a full understanding of the physics involved in the competitions, the fundamental knowledge for attacking the problem is there. Extending foundational knowledge to solve a problem is inherent to the senior design course and contributing to these competitions will give students a feel for this process before they are tasked to do it in their capstone project.

Conclusion

Being able to apply lessons learned to real-world problem is a critical skillset that faculty members strive to ingratiate into the students. However, finding these opportunities during the school year and outside of class time can be challenging. A great prospect for just such an outlet can be found in coding competitions, such as GTOC. These competitions offer avenues for undergraduate research where if there is a faculty advisor that is able to translate the problem statement into manageable task, then the barrier to enter is very low for students and even first-year students can play a valuable role in helping the team develop valid solution submissions.

This report showed that these specific competitions align well with achieving ABETs student outcomes and the mechanical-engineering curriculum path with showing how the course objectives from even first-year courses provide the foundation for student participation. It is therefore recommended that when faculty are trying to look for outlets for interested students to pursue which directly utilizes the lessons that they are learning in class that they explore these space-mechanics competitions. They are interesting, challenging, and offer a glimpse at the ideas that are necessary for solving today and tomorrow's issues regarding the space environment.

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