Multi-Disciplinary Capstone Design and Implementation of Orbital Debris Removal System

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Abstract
The goal of this multidisciplinary capstone design project is to promote and sustain undergraduate research at the University of Minnesota Duluth (UMD) through a fundamental design competition focused on innovation and technology development for USA Air Force Research Lab. The design project and competition are accomplished with two semester senior design capstone teams that is flexible enough to allow for successful project completion.

The region commonly known as lower earth orbit (LEO) is a spherical volume around the earth which extends 2000 kilometers into the earth's atmosphere. Low earth orbit is critical when launching satellites, rockets, and other space systems. There are currently thousands of pieces of debris in low earth orbit that pose a threat to future space operations. The United States Air Force Research Lab (AFRL) proposed design challenge among US Universities to design and implement a prototype to remove spent rocket bodies and other debris from LEO. Though there is no current perfect solution for clearing the debris, the AFRL has decided to deploy a drag enhancing device from a satellite payload to remove the debris.

This report presents a finalized design, an Active Orbital Debris Removal (AODR) device for the 2018 Air Force Research Laboratory University Design Challenge. Because the test of the AODR device will occur on Earth, both gravity and tropospheric conditions will have to be accounted for. Accounting for gravity will be accomplished via a hex copter which will lift the payload off the launch pedestal and deliver the payload to the rocket body. The proposed AODR device will use two cameras, a pair of stereoscopic cameras, a lidar detector, and an Artificial Intelligence (AI) controlled image mapping program to identify and track the rocket body. As the device approaches the rocket body the mechanical arms will deploy and grapple the rocket body. After attachment, the drag enhancement analog will be deployed on the rear of the device. The OADR device was designed, prototyped and tested over two semesters of capstone design courses within Mechanical & Industrial Engineering and Electrical Engineering Departments at University of Minnesota Duluth.

Keywords: Capstone, Undergraduate Design, Interdisciplinary Pedagogy, Undergraduate Research

1. Introduction

There is urgent need to develop effective solutions to address existing space debris because increasing number of satellites in Earth orbit will continue to increase their number and will eventually pose a serious hazard to near-Earth space activities. Earth-orbiting satellites will typically occupy either low earth orbits (LEO) or geostationary orbits. The satellite debris and rocket upper stages in LEO may be removed by lowering tier altitude to 650 km or less from where they will eventually re-enter the atmosphere and burn up. Geostationary orbit altitude is too high to allow this approach of debris removal, so in this case, the effective disposal method is to raise further the orbital altitude of satellite remnants by 300 km or more to disposal orbits that are of no practical use (Nishida and Kikuchi 2010). Capture is an indispensable task for the retrieval of large space debris (Nishida and Kikuchi 2010). On-orbit satellite capture experiments have been carried out successfully by the ETS-VII satellite in 1999 (Sanmartin, Martinez-Sanchez et al. 1993) and (Oda, Nishida et al. 1999). The key technologies being explored by researchers for implementing debris removal include: efficient orbital transfer technology - electro-dynamic tether; Navigation to and around the debris object - machine vision/image processing; and Robotic capture - simple light weight arm to capture the debris object.

The multidisciplinary senior design capstone class of Mechanical & Industrial Engineering (MIE) and Electrical Engineering (EE) at UMD has compared these alternative design concepts with decision matrix and chose to focus on robotic capture design concept for the 2018 Air Force Research Lab (AFRL) Design Challenge on orbital debris removal. The proposed solution will use two cameras, a pair of stereoscopic cameras, a lidar detector, and an Artificial Intelligence (AI) controlled image mapping program to identify and track a debris and will deploy mechanical arms to grapple the rocket body upon contact.

2. Description of Course and Team

The Senior Design course at Mechanical & Industrial Engineering Department of University of Minnesota Duluth uses real world engineering problems to teach students engineering design, analysis, communication, and project management. The students' teams provide real consulting services to real clients and begin their long rewarding career as engineers. They work in teams learning responsibility, professionalism, and manners. In some cases, the projects increase probability of receiving job offers from industry clients. The AFRL Challenge is one-year program that seeks breakthroughs in military operations and capabilities through goal-oriented competitions that attract, inspire and challenge the most brilliant, innovative and practical minds on earth. In the 2017-2018 academic year, AFRL Challenge theme was development of novel solutions to low orbit debris removal.

At UMD, the one-year AFRL project was split into two semesters work of 15 weeks per semester. The mission of the first semester's team was to research, develop and analyze three alternative solutions to the different design aspects of the project. The first semester's team tested their design concepts with preliminary prototypes. The second semester's team picked up the chosen design of the first semester's team as their baseline design and sought alternative solutions too. The mission of the second semester team was to develop full scale prototype that was tested and represented UMD at the 2018 AFRL design competition. On the first semester's team were one sub-team of mechanical & industrial engineering seniors (6 students) and one sub-team of electrical engineering seniors (6 students). On the second semester team were one sub-team of mechanical & industrial engineering seniors (6 students) and the same sub-team of electrical engineering seniors because electrical engineering program at UMD has one-year program for its capstone course. The design was decomposed into components as illustrated in Fig 3 for the teams involved in the project to allow assessment of students individually and as teams. The teams in the two engineering departments work with their senior design course instructors to accomplish their design tasks. Everyone including the instructors meet once per week to discuss overall project progress and challenges. Three design review meetings were held with AFRL personnel through teleconference over the duration of the project.

During the design phases, decision matrix was used to select the best design among alternative concepts brought forward by the teams. Table 1 is a design alternatives decision matrix used to choose the debris engagement, drag enhancement, and gravity compensation methods for the debris removal system.

Table 1 Design Alternatives Decision Matrix

	Criteria								
	Size	Weight	Safety	Function	Usability	Innovation	Project Cost	MFG	Score
Weight Percentage	2	2	3	3	1	2	3	3	
Engagement									
Mechanical Arms	3	3	5	5	5	2	5	4	78
Shape Memory	3	4	5	3	2	5	2	1	59
Electromagnetic Net	1	4	5	3	2	2	2	3	55
Photoreactive Polymer	4	4	5	3	1	4	1	2	58
Drag Enhancement									
Balloon	3	5	5	5	5	2	5	4	82
Electromagnetic Tether	2	3	4	4	3	3	3	5	67
Gravity Compensation									
Quadcopter	3	4	4	5	4	3	1	3	63
Scissor Arm	1	1	5	4	2	1	1	2	44
Glider	2	4	3	2	1	3	3	2	49

3. Final Design Solution – Robotic Arm Capture

The final design of the OADR device consists of a custom manufactured carbon fiber box with three mechanical arms that are used to grapple onto a rocket body. Each arm consists of three links which are constructed using carbon fiber and held together using specially designed aluminum connecting pins. Torsion springs positioned on the aluminum connecting pins of each link are used to drive the motion. Each arm is actuated by pilot controlled servo motors connected to customized bow release mechanisms. Once the payload has engaged the rocket body three more servo motors release the payload delivery device from the payload.

The pilots will be aided electronically by an identification system that contains a live vision system, LIDAR unit, ultrasonic sensor, and limit switches. The identification system will quantify the position of the payload as it approaches the rocket body and provide the pilot with target zones for attachment. The final design solution is detailed in the following sections highlighting critical subsystems of the payload and payload delivery device. Throughout the design, the competition constraints and associated risks were all considered. The final payload design is shown on Fig. 1. Figure 2 shows the device during capture of a debris (21 ft. length and 3 ft. diameter). Table 2 was used to evaluate different design metrics for the final design. Safety considerations, performance, usability, innovation/creativity, total weight, and size were all considered per AFRL requirement.

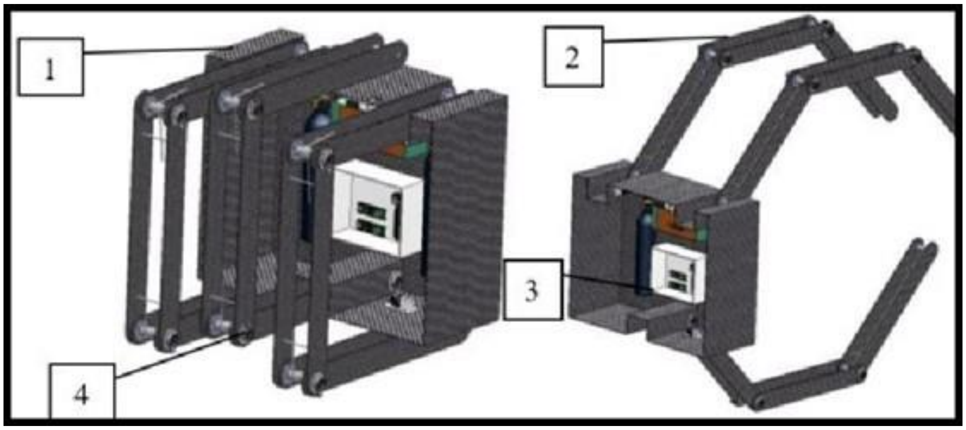


Figure 1**:** the payload case (1), mechanical arms (2), electronic brain box (3), and the Ratcheting System attached to the connecting pins (4)

Figure 2: Picture of device grappling a statically hanging large debris (21' X 3') upon contact

Table 2: Design Metrics for the System

Metric	Description	Quantity	Opinion
Safety Consideration	Uni-directional grappling motion and safety release keys		10
Performance	Based on preliminary testing of AODR		10
Usability	Easy to use? Comfortable? Hinder operators' mission? Training required?		10
Innovation/ Creativity	How creative do you feel your design is?		9
Total Payload Weight	All equipment on AODR device	12 lb	
Volume	All equipment combined (volumetric space required).	1.4 ft^3	

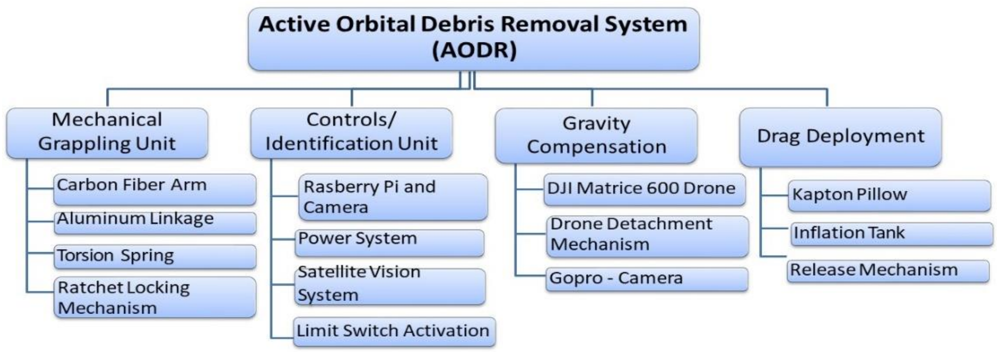


Figure 3 Debris Removal System Design Decomposition Diagram

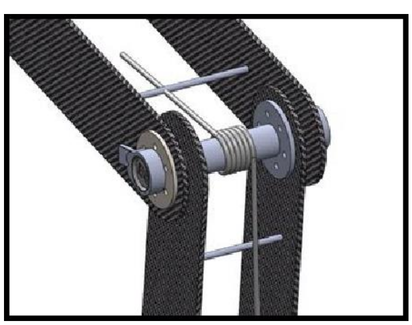
4. Payload and Grappling

4.1 Payload Case

The carbon fiber payload case was manufactured by the MIE students from a custom-built mold and will be used as the central mounting location for all other payload subsystems. Three layers of carbon fiber were used for the faces and up to nine layers were used in areas of high stress to improve design toughness. Case dimensions are a height of 13″, width of 22″, and depth of 8″. These dimensions can be reduced to minimize payload mass if mass reduction is needed. Additional layers of carbon fiber will be laid in areas under high stress, such as the torsion spring mounting locations, for added support and improved load distribution. The internal components of the payload, such as the microcontrollers and batteries, were mounted using 3D printed bracketing systems.

4.2 Mechanical Grappling System

The mechanical grappling arms were built by the MIE students and used to secure the rocket body. The three arms consist of three carbon fiber links secured together with aluminum pins. The carbon fiber arms were secured to the aluminum connecting pins using machined screws. Three specially designed torsion springs were inserted on to the internal section of the aluminum connecting pins to propel the arm. On the exterior of each pin a socket wrench head was welded onto a washer which will connect the outside carbon fiber arm. The socket wrench was used as a ratchet device which will restrict motion of the arms to one direction. The torsion springs and joints will close and lock the arms around the target object. In total the design consists of five individual elements the springs, screws, ratchets, washers, and connecting rods. Figure 4 below shows a close-up of the aluminum connecting pin with the ratcheting system.



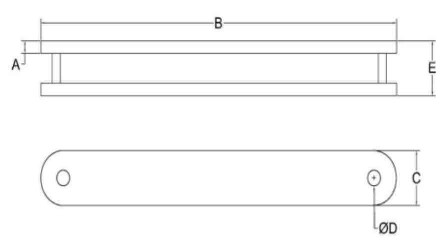


Figure 4 (left), Figure 5 (middle), and Figure 6 (right): Show the connecting pin, arm dimension and arm release mechanism respectively.

Each carbon fiber link will meet the following dimensions, Figure 5 above; A (thickness) - 0.035″, B (total length) - 18″, C (width) - 2″, ØD (outside diameter of hole) - 0.5″, and E (total thickness) - 3″. Arm actuation will be initiated by three servo motors attached to customized bow releases which will act as triggering mechanisms, Figure 6 above. The arms will be held in the cocked position by a barrel swivel locked in the bow release on one end while the other end is tied to the final connecting rod of the mechanical arm with braided line. The example release mechanism above is shown mounted on a test arm. The actual release mechanism will be mounted inside the payload box below the final aluminum connecting rod. This configuration will allow for a direct path between the connecting pin and the bow release.

4.3 Compressed Gas and Nozzles

The MIE students presented preliminary designs of the payload to incorporate the use of compressed gas for small maneuvering actions. Due to the weight constraints of the payload delivery device the compressed gas tanks and tubing system had to be omitted from the competition design. Additional connection points between the payload and the payload delivery device were added to replace the yaw control of the proposed compressed air system. Even though the compressed gas system is not included in the competition design the preliminary analysis of the system is detailed below.

Based on the competition information, it is assumed that the retrieval device will separate from a main parent satellite close to a piece of target debris and complete small maneuvering actions to achieve the best possible engagement position. Thruster nozzles using CO_2 as a medium were going be used to demonstrate this motion. The concept is similar to the Manned Maneuvering Unit (MMU) developed by NASA for untethered extravehicular activity (EVA) activities. The design goal for the payload was a simpler version incorporating only four thrusters. Two thrusters would be placed on the outer edges of the main body and two on the rear in the same relative position.

Calculations show that at 60 deg/s rotation the force required to stop the payload is 0.61 lbf. Using a nozzle with a throat of 0.25″, 10.56 lbf of thrust can be produced from each individual nozzle. The force produced by the nozzles is more than enough force to demonstrate maneuverability. To control the motion, bursts of gas will be used to slow or reverse rotation as needed. Preferably, they will be positioned at the midpoint along its face vertically to give the most stability while still contributing to the pivot about the vertical axis.

5. Identification Subsystem

5.1 Sensing

Proper sensing and identification of the rocket body and its movement is crucial for proper performance of the payload. The EE team designed a computer vision system that will be used to provide the remote payload operator with a clear view of the target. Additionally, a LIDAR unit, an ultrasonic sensor, and limit switches will quantify the position of the payload as it approaches the rocket body.

The pedestal, where the payload will originally start from, will be used to provide a third point of view for the pilot. It will serve as the basis for the satellite computer vision system that will perform stereo visual analysis using two SainSmart Wide Angle Fish-Eye Camera Lenses for Raspberry Pi to first detect the target and then the payload. Using visual analysis, the distance between the two objects will be computed by a laptop equipped with a NVIDIA GeForce GTX 1080 and displayed on the heads-up display. The image processing will compute the rate of rotation of the target and the distance to the target, which will provide the pilot target zones to aim for.

5.2 Communication and Computing

The design of EE team's communication network between the payload, pilot, and the pedestal is shown in Figure 6. Wireless communications between the payload and the operator is managed by a NETGEAR AC1000 wireless router. This router will provide secure and fast wireless communication over the distances needed for the competition.

A Raspberry Pi 3B microcomputer will serve as the central computational unit. The Raspberry Pi was chosen as the primary computational unit due to its high clock speed of 1.2 GHz. A Teensy 3.6 microcontroller was used to manage the controls and sensor input. The Teensy is an extremely small and lightweight microcontroller that has a large quantity of inputs and outputs making it ideal for managing the sensors. Allocating subsystem-level control to the Teensy board will ensure that the central Raspberry Pi never becomes overloaded with instructions, which would reduce its overall computational speed. The Teensy and Raspberry Pi communicate via a serial USB connection. Terminal blocks provide an interface to the outside world. The terminals provide control of the servos, communication between both the LIDAR and the ultrasonic sensor, and the digital signal from the limit switch.

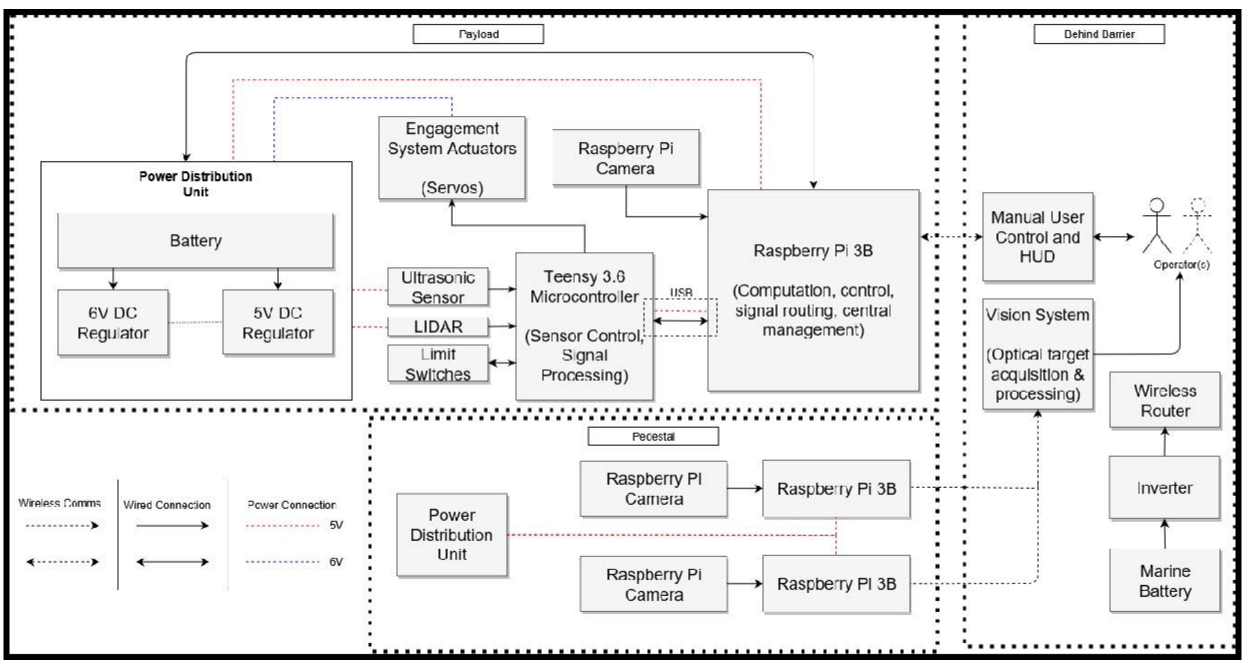


Figure 6 Communication Network

5.3 Heads Up Display

The MIE team designed a heads-up display system (HUD) that will provide the visual control interface for the remote operator. The HUD will contain live video feed from the payload and current sensor reading. The displayed sensor reading include the distance from the bottom of the payload to the ground, provided by the ultrasonic sensor, and the distance from the payload to the rocket body, provided by the LIDAR. Additionally, the status of each servo, designated as either cocked or released, will be displayed to the operator. The HUD is served wirelessly to an operator's computer as a standard web page. Using Node.JS in combination with web Sockets and Serial Port allows the communication between the Pi microcontroller and the server to be coded entirely in JavaScript. Web Sockets is used to provide near real-time data transmission to and from the HUD, while Serial Port is used by the Pi microcomputer to interface with the Teensy.

5.4 Power Management

The EE team designed power distribution unit as shown on Fig. 6. The payload is powered by a battery composed of 3 Lithium-Ion cells connected in series. The output of the cells is then fed into a 5v regulator, a 6v regulator, and an unregulated output. The cells are rated to produce a nominal 3.6 volts, with an energy capacity of 2600mAh, sufficient to power the onboard electronics for the proposed mission time. Further capacity can be added by connecting an additional 3 cells in parallel with the existing cell. Switching regulators were chosen over linear regulators to both reduce heat generation and, by extension, reduce weight by removing heat sinks from the design. The only linear regulator on the board is the 5v regulator providing power to the indicator LEDs and enable/disable transistors and was chosen over a switching regulator due to the low wattage passing through it (generating less heat), and lower cost/smaller footprint over a switching module.

6. Gravity Compensation

The MIE team designed a microgravity compensation system for testing the debris removal design. One of the challenges of the competition is compensating for gravity to demonstrate microgravity operation in earth’s atmosphere. NASA has developed many different compensation techniques including hanging a person or object from a point to compensate for gravity and simulate the freedom of microgravity during training. The DJI M600 drone was selected as the gravity compensation device to deliver the payload. The payload was connected to the drone via three connection points which will allow the pilot to control altitude, horizontal translation, and yaw. A release mechanism will be attached at each connection point on the payload. The release mechanisms will allow the pilot to detach the drone from the payload once the payload has engaged the target, protecting the drone from crashing.

Two associated concerns were identified with using the DJI M600 drone for gravity compensation. The first concern was the stability of the drone while delivering a weighted payload. This concern required the acquisition of a drone capable of carrying at minimum a 10lb payload. The DJI M600 Drone was selected due to its cost-effective payload capacity with the ability to carry a 13.25lb payload. Even with a higher payload capacity the stability and controllability were still in question. These concerns were mitigated through scheduled drone flying practice sessions. The second concern was how the pilot was going to operate the drone from behind a wall. This concern required outfitting the drone with a customized video system and an identification system.

7. Space Considerations and Future Improvements

Due to the conditions present during the AFRL competition the final payload is designed for use within a terrestrial environment leading to design features that would be unnecessary in LEO. Four major environmental differences were identified and analyzed on how the payload could be adapted for space operation: vacuum of space, presence of atomic oxygen, temperature extremes, and radiation. Each difference was first analyzed for how it would affect the currently designed payload. Changes to the design are then proposed to allow operation in LEO. The overall vacuum that is experienced in low earth orbit ranges from 10^{-6} to 10^{-9} torr. This vacuum can cause a process called outgassing, which is the release of gas trapped within a solid. This process reduces the effectiveness of material properties of the payload affecting the performance. A method to reduce the effects of outgassing is to bake the materials for 24 hours at elevated temperatures to reduce tolerance losses in space. Additionally, atomic oxygen (O) which is present in low earth orbit may also pose a problem. Atomic oxygen is produced when ultraviolet radiation reacts with oxygen gas molecules (O2); the average amount of energy released from this type of oxygen when it reacts with payload materials is about 5.2 eV. Atomic oxygen causes reactions, which in turn cause erosion and pitting to materials which are made of carbon, nitrogen, sulfur, and hydrogen bonds. Therefore, any materials in the payload design must go through atomic oxygen testing to see if the reactivity of the material is low enough to be suitable for use in low earth orbit. Extreme temperatures are found in low earth orbit ranging from -120°C to 120°C (-250°F to 250°F). The material selected must have thermal properties which can withstand the temperature range and still work effectively. The ultraviolet radiation found in low earth orbit is about 8% that of the solar constant (136.7 mW/cm^2). The heightened UV radiation causes materials to go through UV hardening which can damage polymers, making them weaker and less reliable. Damage due to UV radiation can be prevented by taking the material used in the payload and hardening the material with a radiation hardening bath.

8. Conclusion

The 2018 Air Force Research Lab design challenge on design of debris removal system provided an opportunity for the capstone class to promote and sustain multidisciplinary undergraduate research and development at the University of Minnesota Duluth (UMD). The UMD team comprising of mechanical, industrial, and electrical engineering seniors successfully presented a simple remotely operated active debris removal device as an effective design for capturing and de-orbiting spent rocket bodies of various diameters. Using a semi-autonomous identification system and the mechanical grappling system the presented payload serves as a strong base design for a future device capable of autonomous control and operation in space. The presentation and functionality of the designed prototype were judged at the 2018 AFRL design challenge at Arnold Air Force Base, Tennessee, USA. UMD team came out of the competition as first runner-up among the nationwide Universities that competed in 2018 AFRL University design challenge.

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