Ut ProSat-1: A Repeatable Passive Deployer Mechanism for Testing Carbon Fiber Tape Spring Booms

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ABSTRACT

This paper presents the design, production, and testing of a mechanism to passively deploy a bistable coiled tape spring in a controlled, reliable, and repeatable manner on a SmallSat. The design has the tape spring wrapped around a spool that can be connected and disconnected from a motor to allow passive deployment through its stored elastic energy along with motorized retraction. The design went through several iterations before a workable prototype made of 3D-printed ABS and resin was developed. The prototype utilized a threaded clutch mechanism to transfer rotational motion from a servo to linear motion that allows two gears to move toward and away from each other. These two gears are attached to the spool and motor respectively, and their separation allows the motor to be disconnected from the spool to avoid influencing the deployment. The final prototype was capable of autonomous deployment and retraction with proper supporting software. Repeated tape spring deployments allow for automated reliability testing of a tape spring deployer, and the clutch mechanism to facilitate this can also be used in other applications.

INTRODUCTION

Virginia Tech's upcoming CubeSat mission Ut ProSat-1's primary payload is a tape spring deployer, based on work from the previous ThinSat mission, Vt ThickSat[1]. In an improvement of this last mission, the new deployer is designed to retract itself after deployment, while retaining the passive deployment. This allows for multiple deployments from one mission in order to better qualify the reliability of such a deployer. The deployer is designed to fit inside the 3U CubeSat that will be used for the mission. Development is ongoing, and multiple designs were conceived and tested, some of which are presented here.

Tape Spring

The deployer has been made to work with a larger tape spring than was used in VT ThickSat which has very different properties. The new tape spring is parabolic across its cross-section, with an arc length of 86 mm. Furthermore, it is bistable, so in addition to the stable energy state of a flat parabolic boom, it is also stable when flattened and coiled in a ring of a diameter of approximately 90 mm. The deployer prefers the uncoiled state, uncoiling just a few centimeters of the tape spring will cause it to quickly transition the rest of the boom into the uncoiled state. This boom that was used had a length of 2 feet. During later testing, this tape spring also proved to be much more resilient to stresses, as it did not degrade at all over repeated deployments, likely du to its relatively simple geometry. This tape spring was provided by the NASA Langley Research Center[2].

Figure 1: Tape Spring Profile, Coiled, and Extended

INITIAL TESTING

The initial tests were to characterize the behavior of the tape spring. The greatest initial concern was the size of the tape spring's coiled state. If the undeployed state involved coiling the tape spring around its stable diameter, it would be rather close to the size constraints of the CubeSat. Based on the design of VT ThickSat[3], an initial testing deployer was developed to see if the size of the boom would be a problem and if further constraining the tape spring would mitigate the issue. This deployer consisted of one of three sizes of spool which the tape spring would be coiled around, which would in turn be held on both sides by 2 panels. The connection between the two panels was fortified with four bridges, in addition to four rollers at each of the corners. The rollers were intended to minimize friction for the deployment. There were 3 different slots for each roller to fit into in order to match each size of spool. The three diameters of spool chosen were 90 mm, same as the stable diameter, and the smaller 70 mm and 50 mm.

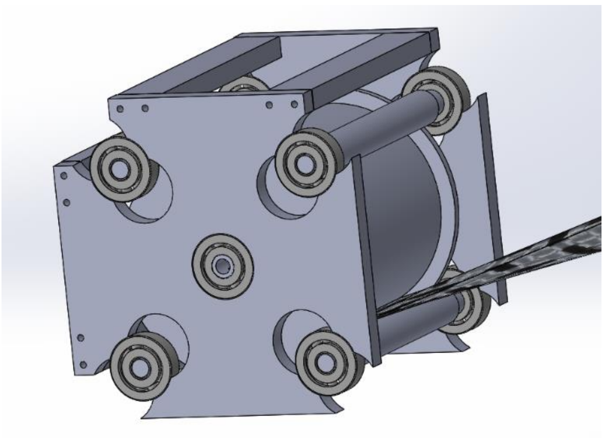

Figure 2: Initial Testing Deployer with 70 mm Spool

The first test was with the 70 mm, wrapping the boom tighter than its coiled state. In this configuration its bistability had no impact on its performance, and it deployed similarly to the deployer on VT ThickSat, although since the tape spring was larger it had more constrained energy and deployed very readily. Switching the spool to the 90 mm diameter, the tape spring no longer needed the rollers to help constrain it, and only retained one roller to guide the direction of deployment. However, it was somewhat less energetic on the deployment, likely because it started in a lower energy state, its unconstrained coiled state. Furthermore, this test showed that the tape spring can fit inside a 96mm squared cross section while coiled, without risking leaving that area and impacting any walls. Eventually, using a spool that was the same size as the bistable diameter was chosen in order to also demonstrate bistability, to help differentiate this boom from the last.

COMPONENT SELECTION

Motor Selection

In order to allow for repeated deployments during one mission, a mechanism was needed to retract the tape spring and return the deployer to its starting configuration. At first, a low rpm DC motor was considered as the energy efficiency would be useful on a satellite and it would still be controllable if the rpm was low enough. However, the higher reliability was considered to be more valuable later on, and its lower efficiency would be compensated by attempting the deployments less often, which were already going to be most limited by the amount of data that can be transmitted to the ground throughout the duration of the mission.

In order to choose the right motor, the required torque to actually retract the tape spring also had to be determined. Instead of choosing a collection of motors to test individually to determine a workable range, the exact torque required was determined through the use of a winch attached to the axis of the spool. A fishing line was spun around the winch and then a bag was hung from it. The bag was filled up with weights until the tape spring started retracting from the torque applied through the winch. Given the known radius of the winch and the weight of the bag when retraction started, the required torque was determined to be 3.1 N-cm. A large factor of safety of 2 for absolute assurance of retraction was used in selecting the motors. However, testing with the motors indicated that they did not perform as well as they were rated, so in despite of previous testing, each motors viability had to be tested individually.

Clutch Design

Just as important as the motor is how it is attached to the deployer. The motor will have to be attached directly to the spool in some manner to allow it to retract the tape spring. However, it cannot always be attached to the spool as just having it attached even when not powered will add some torsional friction to the system. This will influence the deployment by causing it to be slower, or if the motor is large enough, prevent it from happening altogether. As such, a clutch mechanism is required to detach the motor when it is time for deployment, and then reattach when it is time to use the motor for retraction.

INITIAL DESIGNS

Initial Concept

The first design conceived of used 3 bevel gears to transfer power from the motor to the central spool. A gear was attached to the spool shaft and the motor shaft, and the third gear connecting the two was attached to a solenoid. The solenoid was chosen as it was a simple mechanism to disconnect the two gears from each other. Its default position would have allowed the gear to connect between the spool and the motor, allowing them to transfer power. Powering the solenoid would move the middle gear away from the other two, breaking the connection, and allowing the tape spring to deploy without interference from the motor. The design, however, never left the conception stage without being improved on. The bevel gears, while the best option for this design, just wouldn't be anywhere near reliable enough to allow the deployer to operate autonomously, as there is a high chance that the motors would not mesh properly when the solenoid is disengaged. Furthermore, rotating the motor gear would likely push back against the solenoid, potentially disconnecting it when it was not supposed to. More effort was put in a more elaborate clutch mechanism that would be more reliable and followed up with a prototype.

The apparatus surrounding the spool was also updated in this concept and would remain the standard going forward. The number of rollers was reduced to the one that guides the deployment. The side panels were made slightly thinner to save on the limited volume, and smaller ball bearings were selected to fit into this frame. Three bridges were used at the corners instead of the four to provide more clearance for the spool.

First Design

The new mechanism was designed making use of two face gears as the method of transferring power from the motor to the spool. The first gear is attached directly to the spool axis, with the second attached directly to the motor shaft. Critically, the attachment to the motor shaft was through an insert that went all the way through the gear, allowing it to slide back and forth across the shaft. The insert extends beyond the face gear into a long shaft which is also inserted into a ball bearing. The ball bearing itself is inserted into a movable holder that will drive the clutch mechanism. In the initial design, this holder is directly attached to two solenoids wired together so that they would operate synchronously. This is to balance the force on the holder and prevent any torque from interfering with the smooth operation of the mechanism. The motor itself would be mounted to a frame that will in turn be connected to one of the side panels of the spool holding part of the deployer. The frame had a rectangular extrusion that would fit into a matching rectangular slot on the panel, as well as holes for up to 5 countersunk screws, however in testing the rectangular insert was secure enough. The screws would only have been used for a final version. Additionally, there was a stand on the frame near the motor that helped prevent the entire deployer from tilting over from the weight of the motor in gravity.

An alternative version of this design was also developed that moved the clutch mechanism inside the spool. It was functionally similar; the only difference was that one of the face gears is integrated to the inside of the spool. The main advantage would be a significant saving of volume; however, the drawbacks prevented the alternate design from going much further. It would have required a very large ball bearing that could fit the motor through it, which could pose a hazard if it survives reentry. Furthermore, the solenoids could not be fit through the large ball bearing with the motor, so they would still have to be mounted outside the end of the spool, eliminating some of the volume advantages of the design. As a result, the design was scrapped, and all subsequent design would just keep the clutch outside the spool.

The solenoids proved to be the weak link in the original design, having trouble providing the force to push the holder forward. Improvements could have been made; however, a competing design necessitated the use of a servo for the clutch mechanism, and to simplify the compatibility for the electrical sub team, the mechanism was changed to make use of a servo to drive the linear motion of the face gear.

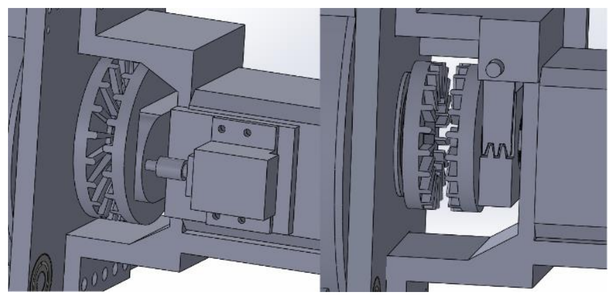

Figure 3: The Two Preliminary Designs for the Clutch Mechanism

Second Design

The second design had the servo attached directly to a shaft that would rotate with the servo. The shaft had two arms attached to it, with three gear teeth at the end. The holder was modified to have matching gear teeth on each side, allowing the arms to push and pull the holder as the servo rotated the shaft. While this method of transferring rotational motion to translation would stop if the holder was pushed too far, the holder only had to move at most 5 mm for this to work so it was not an issue for such a small angle that the servo would be rotating. However, the design would lose a lot of torque as the effective gear ratio was very high, so another design had to be used that could keep the torque of the servo.

FINAL PROTOTYPE

Description and Operation

The final design that was prototyped and tested made use of a threaded clutch. In this design, the frame holding the motor is modified; there is a cylinder that protrudes towards the spool from the center of the motor mount.

The cylinder is hollow, so that the motor shaft can pass through it without getting close to its inner walls. The cylinder protrudes 8 mm, and on the outside surface has 6 threads that rotate approximately 240 degrees. The holder has been modified, with the end opposite that of where the ball bearing goes now having an interior cylindrical space with threads matching the frame on the inside. As the holder is rotated, it moves back and forth due to the action of the threads.

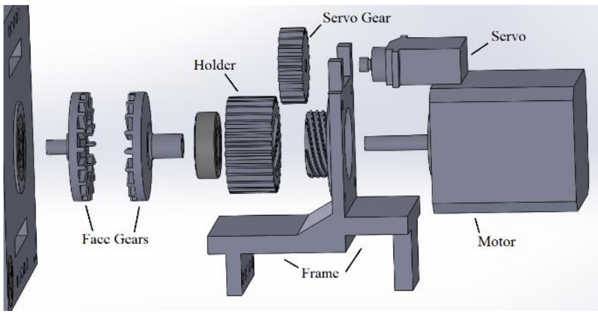

Figure 4: Exploded View of Clutch Mechanism with Labels

The outside of the holder is a long gear that extends down its entire length. This gear will be in contact with another smaller gear attached to the servo, with a gear ratio of 3:4, allowing a small gain in torque. Through the gears, the rotation of the servo can transfer into linear motion of the face gear while keeping the torque high. The servo chosen had a limited angle of freedom of 170 degrees, which meant all the necessary linear motion had to be achieved without turning the servo more than this. This meant the threads had to be a bit steeper than would be ideal, as well as preventing the gear ratio of the holder servo gear from being higher. The total length of threaded area is also longer than strictly necessary, in order to ensure the holder does not fall off, as was the case in initial testing when it was shorter.

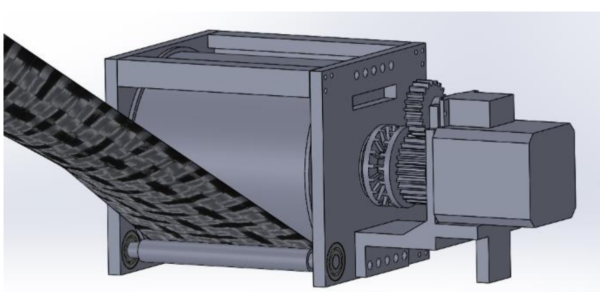

Figure 5: Final Prototype with Threaded Clutch

Prototype Testing

During initial testing the clutch mechanism had difficulty performing correctly. The initial threaded sections were too short and would result in the holder falling off near the end. Once corrected with new parts, there was instead difficulty with the interface between the servo gear and the holder gear. At several instances, it would get stuck, and the servo would fail to move the holder any further. The first issue that caused this was that the threads between the holder and the frame were a bit loose due to uncertainties in the printing process. Most of the original parts were printed with ABS, while the newer parts used resin, which had lower tolerances for dimensions. Fixing that solved part of the issue, and the next issue was similar, the servo gear did not fit onto the servo properly, as such it would shift away from the proper axis of rotation. Accounting for the now known printing uncertainties, a new servo gear was printed, and the clutch mechanism of the deployer worked very reliably henceforth.

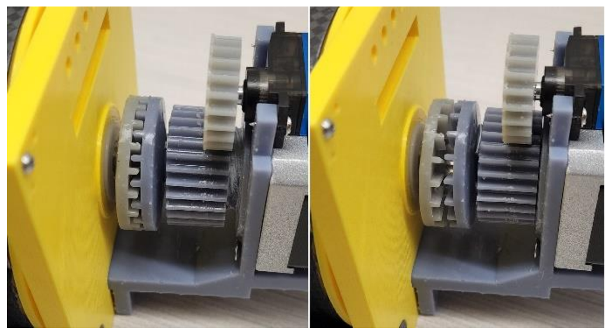

Figure 6: Closed Clutch on the Left, Open Clutch on the Right

Testing the deployer as a whole proved somewhat more challenging. While the clutch mechanism allowed the gears to attach to each other, and the motor was able to retract the boom when the clutch was engaged, there were a few issues that plagued smooth operation, and which could be improved on. In the instances where the teeth of the two face gears aligned, the geometry of the teeth was not sufficient in getting them to slide past each other. When this occurred, the torque of the servo was high enough that it started to flex the frame when the face gear couldn’t be pushed any further. If the frame was further stiffened, it would prevent the flexing, which would instead cause the servo to stall. This could be detected with a higher current draw from the servo, to let the microcontroller know that gear teeth are aligned. From there the software could tell the clutch to retract, spin the motor slightly, and try again for a better alignment. There were also issues with the gears meshing correctly, with the face gears not being completely parallel, however, it did not seem to severely affect the ability of the deployer to retract.

CONCLUSION

The final design in this paper is a functional demonstration of a deployer that can retract a tape spring boom after it was passively deployed under its own stored elastic energy. The threaded clutch mechanism that allowed the spool to disconnect and reconnect with the motor proved to be very reliable and was a great improvement on the previous designs. The bistability allows the boom to be coiled small enough to fit on a CubeSat, although more space needs to be allocated in at least one direction in order to fit the motorized components. The deployer can be used for many deployments without failure that can't be mitigated with correcting software.

There are improvements that can yet be made to the deployer. The final prototype was merely a demonstration of the mechanism and had not yet integrated the features and instrumentation that would be necessary for a spaceflight. Refinement to the sizes of the components to make everything fit better would improve the reliability of the deployer and the smoothness of its operation.

Acknowledgements

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