Development of a High-Performance, Low-Profile Translation Table with Wire Feedthrough for a Deep Space CubeSat

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Abstract

NEA Scout, a 6U cubesat and secondary payload on NASA's Space Launch System Exploration Mission (EM-1), will use an 85-m^2 solar sail to travel about 1 astronomical unit (about 1.5 x 10^8 km) to a near-Earth asteroid for observation and reconnaissance[1]. A combination of reaction wheels, reaction control system, and a slow rotisserie roll about the solar sail's normal axis were expected to handle attitude control and adjust for imperfections in the deployed sail during the 2.5-year mission. As the design for NEA Scout matured, one of the critical design parameters, the offset in the center of mass (CM) and center of pressure (CP) proved to be sub-optimal. After significant mission and control analysis, the CP/CM offset was accommodated by the addition of a new subsystem to NEA Scout. This subsystem, called the Active Mass Translator (AMT), would reside near the geometric center of NEA Scout and adjust the CM by moving one portion of the flight system relative to the other. The AMT was given limited design space - 17 mm of the vehicle's assembly height - and was required to generate ±8 cm by ±2 cm translation to sub-millimeter accuracy. Furthermore, the design was required to accommodate a large wire bundle and coax cables fed through the center of the mechanism. The bend radius, bend resistance, and the exposure to deep space environment complicated the AMT design and operation and necessitated a unique design to mitigate risks of wire bundle damage, binding, and cold welding during operation. This paper will outline the design constraints for the AMT, discuss the methods and reasoning for the design, and identify the lessons learned through the design, breadboard and test phases for the low-profile translation stages with wire feedthrough capability.
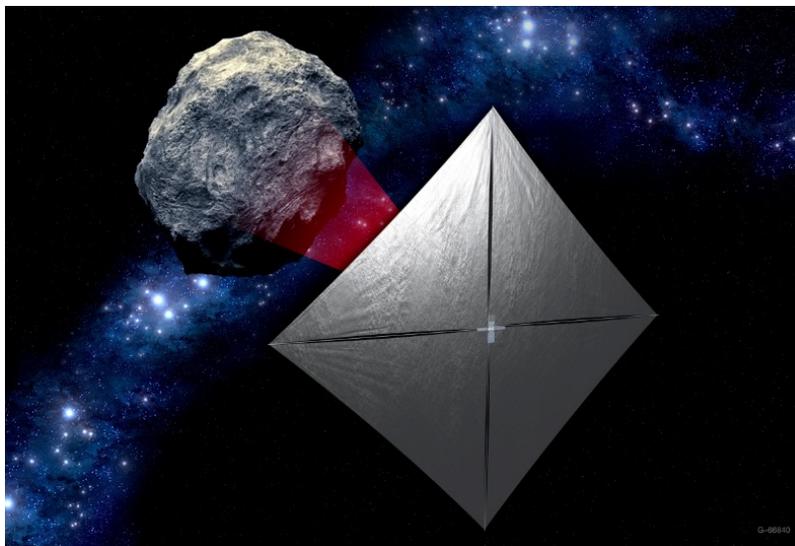
Figure 1. NEA Scout concept design[1]

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Introduction

CubeSats were developed with the intention to bring spaceflight designs and capabilities to academia. Early in their development, academic institutions composed a majority of the market but a decade later government agencies and large businesses noticed the opportunity to produce big science at low costs. This adaptation of the CubeSat intent required these high-capital entities to compress the form factors of conventional satellites into those outlined in the CubeSat Design Specification. With the growing popularity and development of CubeSats, designers, analysts, and manufacturing specialists noted that the requirements given in the CubeSat Design Specification demanded complicated, miniature systems to accomplish difficult tasks[2]. Numerous CubeSat programs became acquainted with this reality. Thanks to the growing market and development of low-cost launching capabilities for micro- and nano-scale satellites, universities, private industries, and government agencies have maneuvered large programs to take advantage of the CubeSat technology. Many of these CubeSats have the potential to become engineering marvels - they encounter technical issues (thermal, mechanical, and power limitations) similar to larger scale projects, but develop solutions at fractions of the cost. NEA Scout follows this suit. NEA Scout will employ the largest deployed solar sail to date to fly to a near-earth asteroid. The science instrument aboard NEA Scout will then characterize the asteroid by gathering shape, location, inertial properties and compositional information. The collected information will fill strategic knowledge gaps and lay the needed groundwork for future missions and the eventual human exploration of asteroids[1].

Solar sails create propulsion without propellant, but the physics that makes them excel in efficiency and endurance also limits their ability to accelerate and decelerate quickly. Solar sails produce thrust by reflecting solar radiation with large areas of lightweight material. The reflected light produces solar pressure, which then propels the vehicle with control forces on the magnitude of $\mu N/m^2$ of sail material. The thrust, though miniscule in size, can produce large velocity deltas over a multi-year mission. These small forces also create disturbance torques caused by misalignments in the CM and CP. Although the CM and inertial properties can be easily measured or calculated, the CP of the solar sail is less exact. Guidance, navigation and control engineers have estimated the CP location with considerable margin due to the possibility of sail tears, asymmetry and non-planar shaping. NEA Scout's estimated CP/CM offset is large enough (about 2 cm at beginning of mission and 4 cm at end of mission) to overload the control systems and requires a mechanical system to adjust the center of mass and trim the spacecraft. This mechanical system became the Active Mass Translator (AMT).

Design Constraints

Volume, Mass and Power
The AMT's early design activities acquainted the design and analysis team with numerous design constraints and complications. The first few parameters - volume, mass, and power - commonly limit the design space on flight systems and were considered the highest level requirements for the AMT due to the vehicle's size, mission, and risk level. Again, the nuances of the AMT design further complicated these three requirements. First, the AMT could occupy a volume no larger than 22.6 x 10.0 x 1.7 cm (x y z coordinates, respectively). Within this design space, the complete system, including all thermal and electrical components, could weigh no more than 320 grams. This design correlates to less than 5% of the vehicle volume and less than 2.5% of the NEA Scout's mass. As with many other orbiting and deep space vehicles, individual systems' power demands are limited and carefully monitored. The AMT was allowed 0.5 W during standby and 12 W when operating during cruise. The power requirement included the control board, motors, sensing, thermal blankets, and locking mechanisms. These components were chosen accordingly.

Feedthrough Bundle and Mobility
The next lower level requirements were levied by the AMT's neighboring systems. The AMT resided in between the deployer for the solar sail and booms and the avionics box.
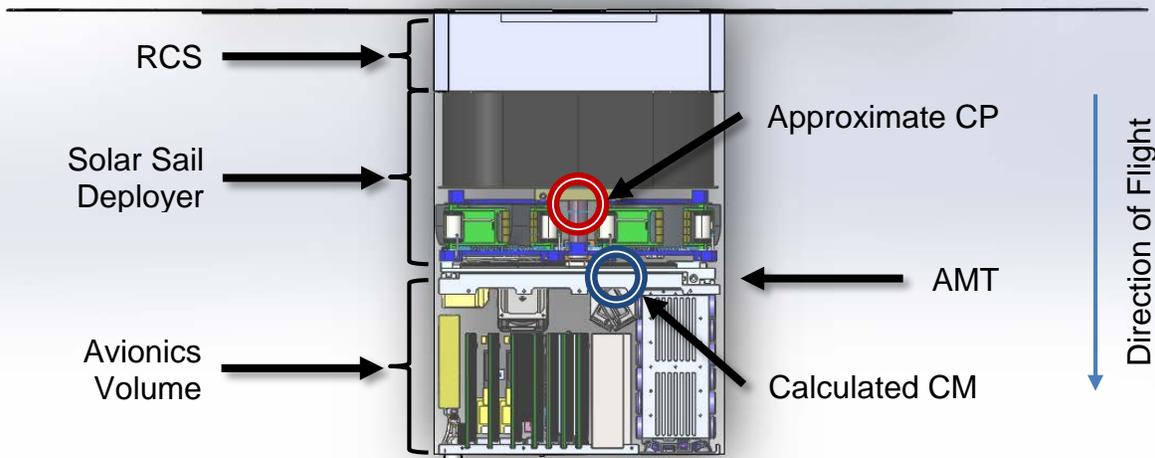
Figure 2. Current NEA Scout configuration

Therefore, large power and data wire bundles required passage through the AMT. This wire bundle consisted of an estimated 40 power and data leads and 3 coax cables. Furthermore, they required flexibility and resistivity to radiation and extreme temperatures. The AMT was required to translate ±8 cm by ±2 cm. The wire bundles had to pass through the AMT as it translated between any two points within the translation envelope. Not only did the dynamic envelope house the wire and cable bundle service loop, but also the connector locations, which had to be positioned so that there was no potential interference or tangling. Thanks to the oversight of many experienced mechanical designers, the feedthrough bundle received much attention in early design stages. The AMT designer was presented with many technical papers regarding the performance and degradation of flexible wire bundles in moving systems, including a previous AMS publication "Lessons Learned to Avoid Coax Cable Failure in Moving Mechanical Mechanisms", by Sheah Pirnack. This paper suggested what types of coax cable designs were more resistive to cold welding between conductor layers and provided suggestions to cable lots for workmanship and contamination, as these parameters influenced cold welding. Furthermore, the paper discussed when cold welding tends to occur and how to design and test cables accordingly[3]. In turn, the design was modified to include ribbon cables for data and power and accommodate for the largest possible bend radii for the three coax cables. Currently, options are being investigated to route the coax cables outside of the AMT and reduce the probability of cold welding altogether.

Locking Mechanism
As with many translating or articulating mechanical systems, locking features are required for launch and some orbiting maneuvers. The AMT was no different. The system presented a clear weak point and introduces more failure modes to the vehicle. During the launch phase of the mission, a locking mechanism was required to create a load path, reduce stress in fasteners, and constrain the translating components of the AMT during the deployment phase of the mission. NEA Scout's interface to the CubeSat Dispenser is a rail, and due to the discontinuity across the AMT, the interface was held to tight tolerances. The locking mechanism will help control this tolerance. Although this mechanism will operate independently of AMT, it was included as a subcomponent of AMT and therefore be contained within all AMT requirements. This will prove exceptionally difficult as the locking mechanism will inherently reduce the translation ability of the AMT.

Design Ideology and Testing
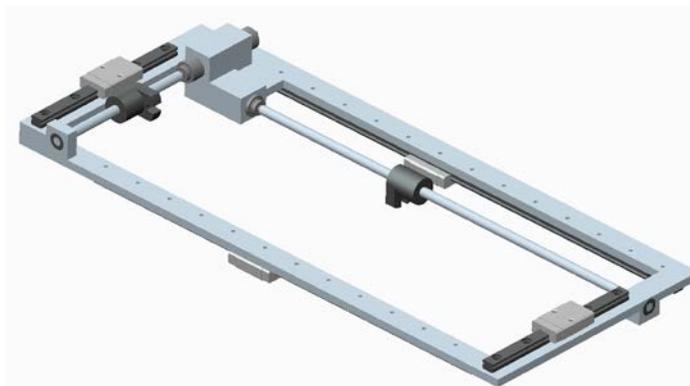
<u>Early Design</u>
Thus far, the AMT is the latest system added to the NEA Scout project. The surrounding systems, the solar sail boom deployer, and avionics box (reference Figure 2), had nearly one year's progress made at the onset of AMT design activities. Therefore, the interfaces for the AMT had some definition and rigidity. AMT had to accommodate the existing designs and make minimal impacts to these two neighboring systems and meet all previously-outlined requirements. Both the avionics box and boom deployer levied requirements for the wire bundle connector locations as well as the mechanical fastening points. In turn, the AMT levied requirements onto these systems regarding the locking mechanism location and fastening. After the interfaces were understood, the mechanical design work commenced.

The NEA Scout design team performed a detailed trade of 20+ concepts of varying TRLs for controlling the CP/CM offset. The concepts included rotation tables, gimbals, and sail tensioning systems, and varying reflectance materials. Each concept was scored according to the estimated ability to meet the AMT design constraints, and the trade concluded that a translation table combined simplicity, heritage, and capability. It quickly became clear that a COTS translation table could not meet the requirements for the AMT. Although many designs exist that can produce high-precision motion in low-profile assemblies (such as those for microscopes and other laboratory optical equipment), few designs could accommodate such a large translation envelope and none could deliver a wire feedthrough capability. Furthermore no space-qualified systems were found that could deliver translation capabilities within the same orders of magnitude as AMT and fit into the given volume. The AMT required an in-house design.

Early design concepts took conventional translation table designs and "inverted" them by moving the motors and transition components from a central location to the periphery of the system. Figure 3 illustrates the "inversion". Although this concept is not novel, the low mass requirement and translation ability made the concept unique. This modification freed a large internal volume that could be used to house a service loop for the feedthrough bundle, locking mechanisms, and sensing equipment. The design also allowed a small vertical profile, and made the AMT design much more appealing to NEA Scout. The trade, however, complicated the interfaces and required the stepper motors to reside one atop the other. The motors' location and the height requirement only allowed motors of 8-millimeter diameter or less to drive the translation of the AMT. The small motor size constraint required considerable investigation and testing for torque output, margins, and load capacity.
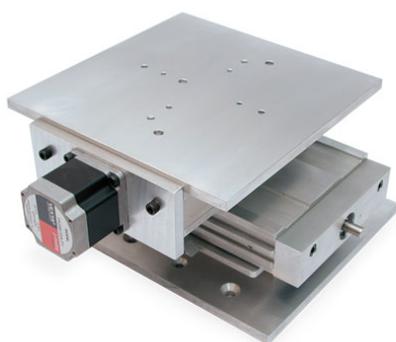
| Common XY Translation Table Design | "Inverted" Variation |
| (VELMEX, Inc. UniSlide XY Table) | (NEA Scout AMT) |

Figure 3. Comparison of translation table designs

The main design trade completed during the AMT design was for the driver motors. Stepper motors proved to be the best choice for a number of reasons. First, steppers have flight heritage on many spacecraft deployment mechanisms and solar array gimbals. These heritage systems have similar duty cycles, translation speeds and environments to NEA Scout. Secondly, the stepper motor design allows for microstepping, which when combined with gearboxes and lead screw drive systems, can produce very small, precise steps. Lastly, stepper motors can track motion by counting steps, so long as the detent torque is not exceeded, causing skips. This step counting could replace a positional sensing system as long as the motor is properly sized for the environment and loads[4].

In order to quantify the required driving torques needed for each of the two motors, the AMT designer used static and dynamic equations to calculate the friction forces and torques in the drive system. These equations combined inertial loads from the driven mass; friction from the bearings, lead screw and nut; motor efficiency; lead screw efficiency; and acceleration. The result produced a torque requirement for a particular set of motors, lead screws, nuts and bearings. These results were then documented and compared to the torque margins required by the organization.

Although the torque outputs for stepper motors and torque requirements for the AMT drive systems were relatively simple to calculate, there were many other elements of the calculations that were assumed (workmanship, degradation, feedthrough wire bending resistance, etc.). Therefore, a drive system test fixture was manufactured to simulate a single axis of the AMT, inertial loads and wire bend resistance. The fixture was then paired with a custom driver board to fine tune motor speed and current supplies. The test assembly is shown in Figure 4.
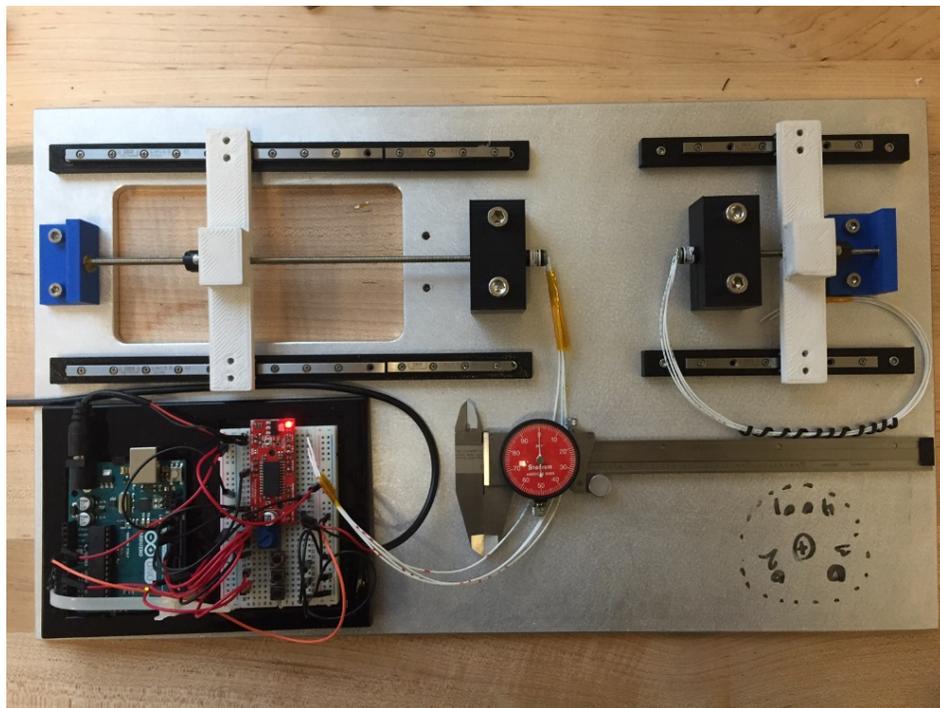

Figure 4. AMT test assembly

The test assembly was developed using stock ¼" (6.35-mm) aluminum plate and 3D-printed components to replicate the X and Y translation axes (the left and right side of the assembly, respectively) of the AMT. The 3D-printed components were designed and manufactured to fit all configurations outlined in Figure 5. The adjustability of this setup allowed for quick interchanging and controlled variations between tests.

Tests were conducted to combine three various motor sizes with two lead screws with varying pitch. The goal was to produce a balance of speed, size, and torque margin. Navigation and control designers required that the AMT move slowly to increase precision and reduce dynamics imparted into the vehicle. The design volume, driven greatly by motor diameter, limited the available height of the AMT. Lastly, the design requirements levied certain torque margins onto the system, which when compounded by conservatism in the preliminary thermal, mechanical and dynamic analysis, yielded driving torques far greater than expected. Nonetheless, the system had to be sized accordingly. Changes to the motor diameter directly affected the AMT vertical size constraint, while combinations of the motor and threads adjusted the speed and torque margins simultaneously. For example, a motor-thread combination could yield acceptable torque margins and size, but produce too rapid of motion. Adjusting to a higher pitched thread would increase the torque margins and reduce the driving speed - a single change benefiting two figures of merit.

A few of the combinations were ruled out by hand calculations. The largest motors (Configurations E and F from Figure 5) were too large for the design volume and had calculated torque margin at beginning of life magnitudes higher than required. Furthermore, when the final two motors were paired with both threaded rods, hand calculations again ruled out two more options. The smallest motor paired with a high pitch thread (Configuration A) and the middle-sized motor paired with the lower pitched thread (Configuration D) produced comparable speeds and margins, but different form factors. The test fixture was used to compare the final two motor and thread combinations and close the trade. The results were as follows:

Configuration Title		
Motor Size [mm]	Thread Pitch [threads/cm]	
	16.4	8.2
6	A	B
8	C	D
10	E	F

Configuration	Figures of Merit			
	Vertical Height Required	Translation Speed	Torque Required	Torque Available
A	13 mm	0.032 cm/s	1.5 mNm	35 mNm
B	13 mm	0.064 cm/s	2.5 mNm	35 mNm
C	17 mm	0.032 cm/s	1.5 mNm	120 mNm
D	17 mm	0.064 cm/s	2.5 mNm	120 mNm
E	21 mm	0.080 cm/s	1.8 mNm	200 mNm
F	21 mm	0.160 cm/s	4.2 mNm	200 mNm

Figure 5. Drive system configuration trade

At the conclusion of the trade, the AMT designer chose Configuration A. This motor-thread combination minimized the vertical profile of the AMT while also minimizing translation speed and retaining an acceptable torque margin. Despite the small motor size, the designer was surprised by the force produced by the system (an estimated 150 N). Originally, the 8-mm diameter motors served as a baseline design, yet this test led to a design change that will reduced the AMT's volume requirement.

Moving forward, there are options to modify the torque output and speeds pending engineering development unit test results. This will be done by modifying the gearboxes and control inputs. According to the tests, all configurations had large torque margins, with configurations E and F clearly oversized for the given application.

As expected, the test setup proved beneficial to the AMT design process. The designer gained confidence in the system's design, particularly with the pairing of the stepper motors, lead screws and rail guides. The motors, despite their small size, were capable to produce driving torques far greater than demanded, even

with the presence of wire bending resistance, gravity, and prototype-level workmanship (it should be noted that many of the components were 3D printed or hand machined).

Lessons Learned and Forward Work

The preliminary design activities for the NEA Scout AMT required a significant amount of research and investigation, but in hindsight, too much time may have been spent creating design options and trade spaces. As the design process continued from preliminary sizing into component trades and final down selections, hand calculations and analysis were set aside for bench top testing. This approach proved to be the best use of time. Once the time was spent to design and build the test bed, the results came quickly and were easy to discern. In retrospect, testing should have commenced far sooner to save time and produce hard data. This mindset would have allowed more design iterations and taken advantage of the additive manufacturing capabilities available to the AMT designer. Furthermore, this methodology of "test early and often" would have followed common CubeSat development practices (analysis is less common in CubeSat-sized projects due to cost and staffing constraints).

Earlier testing would have also allowed the test bed to evolve. Once a design parameter - such as the motor size of thread pitch - was determined, another parameter could be tested. The test bed was designed with enough work space to test optical sensing and locking mechanisms, but due to "excessive" research and investigations into space rated components and flight heritage information, time did not allow. This is not to discredit engineering heritages or workmanship, but it is intended to reinforce the point that CubeSats and other micro/nanosatellites have limited heritage. Their comparable mechanical systems are often orders of magnitude different from traditional systems in volume, mass, and cost, thus limiting the comparisons. Other mechanical systems aboard NEA Scout, such as the solar sail and boom deployers, embraced this mindset sooner (partially due to age and design maturity) and the number of design iterations was staggering.

As NEA Scout moves into the next stages of development, the AMT is scheduled to deliver an engineering development unit in May. Before that time, positional sensors and locking mechanisms must be designed and tested. These two subsystems are not trivial and have the potential to greatly alter the current AMT design. It would have been beneficial to baseline structural designs for these components, but that is not the reality. The locking mechanism has numerous single point failure locations. Furthermore, if positional knowledge is lost during cruise, NEA Scout could lose its mission. In retrospect, the locking mechanisms and sensing systems should have been designed and tested in parallel with the linear motion systems. Moving forward, the AMT designer will have to become more flexible and adapt to the creative environment common among microsatellite projects. The designers should embrace a mentality to test, learn, and iterate as often as possible.
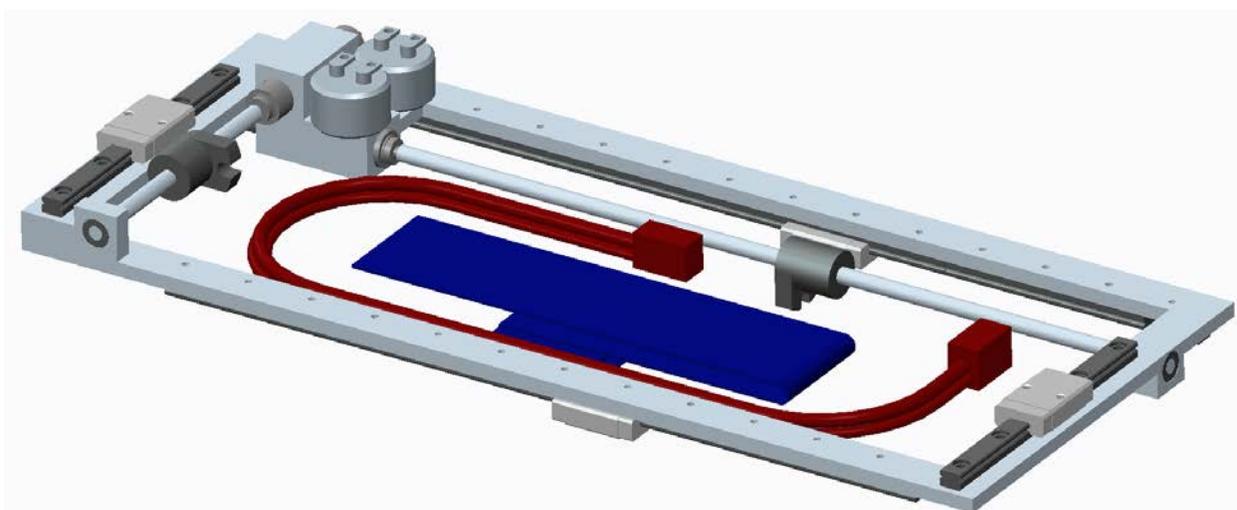

Figure 6. Current AMT design, and concept wire harnesses
(coax cables in maroon, power and data in blue)

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