Mechanical Design of a Hopper Robot for Planetary Exploration

In Proceedings of the 9th ESA Workshop on Advanced Space Technologies for Robotics and Automation
'ASTRA 2006' ESTEC, Noordwijk, The Netherlands, November 28-30, 2006

MECHANICAL DESIGN OF A HOPPER ROBOT FOR PLANETARY EXPLORATION

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ABSTRACT

The Canadian Space Agency is investigating technologies for lowering the cost of planetary exploration missions through miniaturization of landed platforms. Such a change of paradigm could enable a revolution similar to that which has shaken the satellite business with the advent of small satellites and micro satellites. Such spacecrafts now provide space mission opportunities with price tags several orders of magnitude below classical satellites.

One of the consequences of miniaturization is that traditional locomotion schemes such as wheels are not appropriate any more. To a small rover, even the very small obstacles become insurmountable. Alternate locomotion schemes must then be investigated to overcome this problem and enable miniaturized missions. Another consequence of miniaturization is that electric energy obtained through solar panels becomes very scarce.

In light of these constraints, a hopping robot for Mars exploration is being designed and prototyped. This robot uses diurnal variations of temperature at Mars' surface as a source of power. The hopping mechanism is based on a novel cylindrical scissor mechanism. This paper presents the results of trade study on miniaturization of Mars landers, introduces the main requirements to be met by such a system and describes the concept of operation of the hopping robot. The design of the main components of the hopping mechanism is described in detail.

INTRODUCTION

The last decade has seen a revolution in the miniaturization of satellites for Low Earth Orbit (LEO) applications. The advent of small satellites and micro-satellites has changed drastically the cost models associated with space operations. The cost of micro-satellites in LEO has historically been orders of magnitude lower than that of traditional spacecraft. Organizations with modest budgets can now afford to develop and launch their own spacecraft.

A similar revolution in space exploration could have a dramatic impact on the affordability of exploration and on the kind of science that can be conducted on the surface of other planets. In addition, the availability of micro-spacecraft for planetary landed missions would open the door to the conduct of network science missions that require large geographic coverage and simultaneous measurements over large areas.

Finally, the low cost associated with such missions would allow redundant spacecrafts to be sent thus increasing the chances of success in two ways. First, this provides resilience through redundancy: each lander is going through a different Entry Descent and Landing (EDL) sequence. Second, it increases the probability of scientific breakthrough by allowing the same set of instruments to examine different sites on the planet.

Miniaturization trade study

A trade study was conducted to assess the benefits of conducting small landed Mars exploration missions. The trade-off has clearly demonstrated that there are advantages to miniaturizing landed planetary exploration missions. Data from past programs and current programs shows that the ratio of scientific instrument mass to entry mass increases dramatically as entry mass decreases.

Figure 1 and Figure 2 demonstrate that, based on past missions and on current designs, the EDL systems for Martian landers scale in a quasi-linear fashion over the full range from large missions such as the MER rovers to the small DeepSpace2 impactors. A linear regression was performed on the overall mission data set as well as on the reduced subset of missions under 120kg. In each case, a regression index superior to 0.93 was obtained (superior to 0.99 over the entire data set). The only exception to this linear progression is the Beagle2 lander, which was subject to failure upon Mars entry.

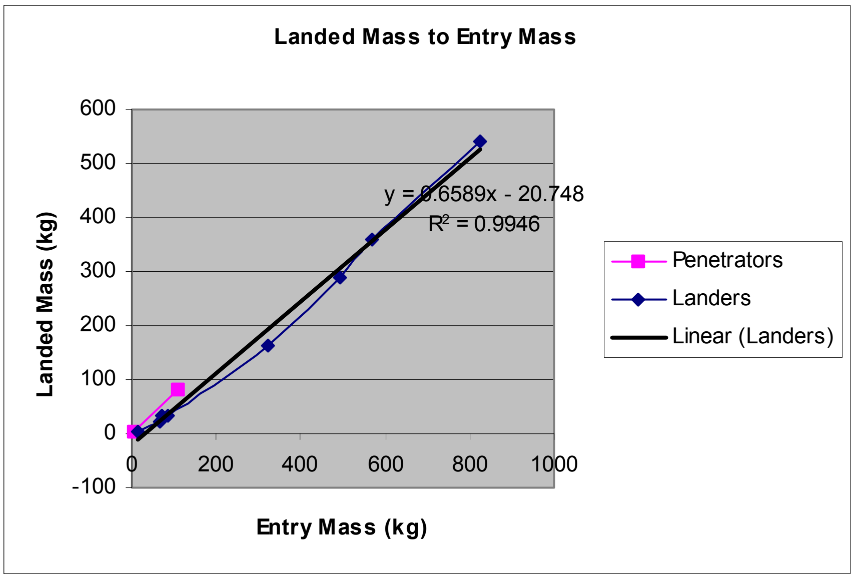

Figure 1 - Landed Mission Scalability

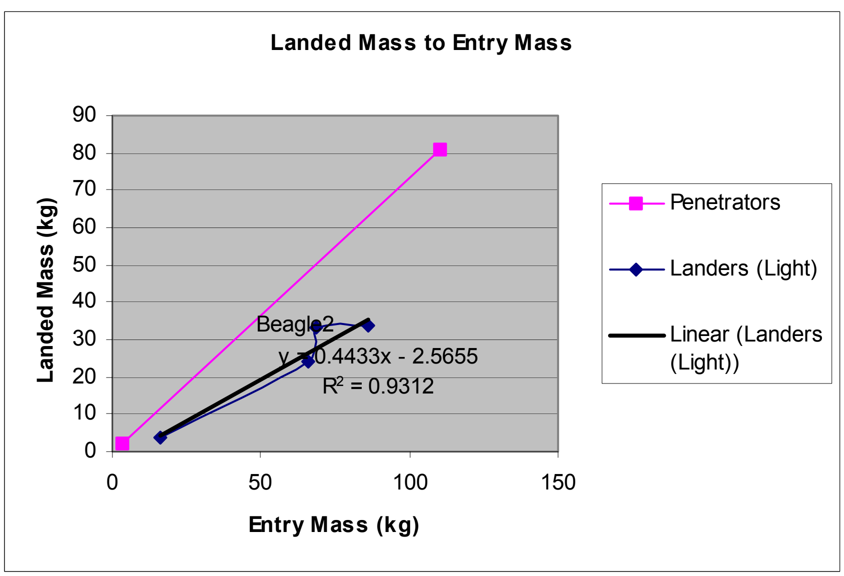

Figure 2 - Landed Mission Scalability (Light Class Missions)

Figure 3 clearly shows that lighter missions have historically carried a much larger proportion of their entry mass as scientific payload. This is explained by the fact that larger platforms have typically provided much more functionality than small platforms. For example, the MER rovers, although carrying a smaller mass fraction of scientific instruments, provided mobility, which has proven critical to the success of the mission.

An exponential curve was fitted to the data and shows extremely good match with the data. The only two exceptions are Beagle2 and Mars Polar Lander, which were both extremely aggressive missions from a mass and cost perspective and which have both failed to survive EDL. This curve cannot be used to extrapolate precisely the ratio of instrument mass to entry mass for micro-missions. However, there is a clear trend in the analyzed data set showing that smaller missions have a historically had a higher percentage of their mass dedicated to science instruments.

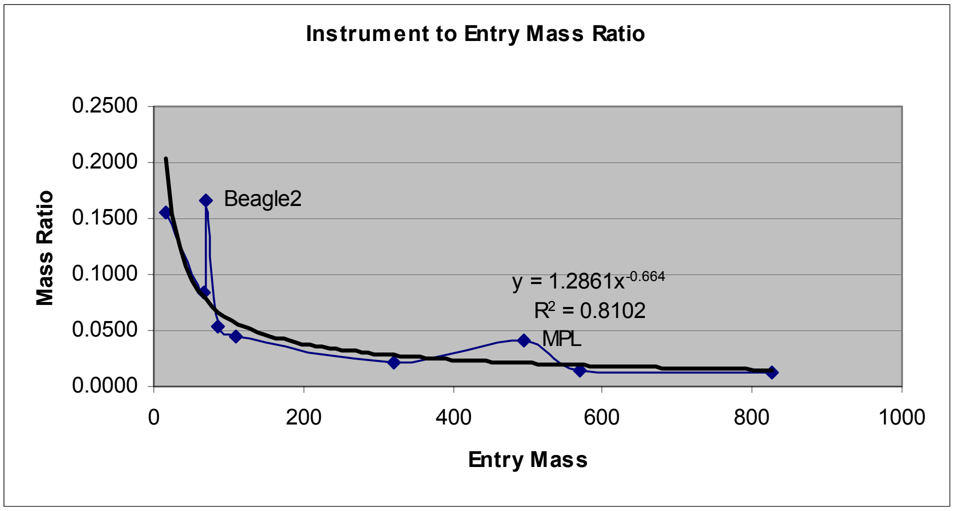

Figure 3 - Ratio of Instrument Mass vs Lander Mass

In response to the conclusions of the miniaturization study, the Canadian Space Agency is currently investigating the feasibility of building micro-landers of 1-2 kg to perform scientific measurements on the surface of Mars.

Micro-robot requirements

A set of requirements has been developed for such platforms in cooperation with selected members of the planetary science community. The main set of requirements imposed on the platform is that it should be capable of transporting a scientific payload on the surface of Mars. The micro-lander is expected to receive commands and transfer its telemetry through an orbital relay of the same class as the current family of Mars orbiters (e.g. Odyssey, Mars Express).

The total landed mass should not exceed 2 kg and an allocation of 250 grams is made for the science payload. Examples of instruments to be carried by such platforms include a microscopic imager, a panoramic imager, a meteorological sensor suite and magnetic field sensors. The micro-landed platform is expected to provide continuous operation for a period of 150 sols with a design goal of one Martian year (668 sols).

Several challenges must be overcome to enable such missions to be successful. One of the most important challenges to be faced by such a mission is its survival to large swings in the Martian thermal environment. The diurnal temperature cycle on Mars can range between –125 Celsius at its coldest and +25 Celsius at the hottest time of the day. Given the small size of lander being considered, active thermal control is almost impossible. The lander must therefore be able to survive such temperature variations.

Another important challenge for micro-landed platforms is the scarcity of electric power. For reasons of simplicity, it is preferable to rely on photovoltaic arrays for electric energy generation. However, the solar panels on such platforms are small by necessity and provide very low levels of power and energy. A large portion of the electric energy is required for communications to send scientific data back to a relay station (possibly in orbit).

To ensure robustness, it is therefore preferable to avoid any dependence on electric power for functions related to survival such as thermal control, environmental protection and mobility away from permanently shadowed regions.

Finally, the last challenge is mobility. To a robot whose size is of the order of a decimeter, almost every pebble is an insurmountable obstacle. One potential solution to mobility at such a scale is hopping. Concepts using hopping as a mobility scheme for planetary exploration were proposed as far back as the late 1960's [1][2][3]. Recently, hopping has been investigated for Mars exploration [4][5] and for the exploration of asteroids [6].

The purpose of introducing mobility on such platforms is to increase the diversity of the scientific data, in particular the microscopic images obtained while looking under the robot's footprint. The robot is not expected to be capable of jumping accurately to a given target destination. The requirements imposed on the hopping mechanism are such that each jump should be at least 1 meter high to be able to clear most obstacles on the surface. The robot should be capable to traveling the equivalent of 3 meters per sol with at most one hop per day.

CONCEPTUAL DESIGN

To maintain the priority on low cost borrowed from the micro-satellite philosophy, the main assumption underlying the design and operations concept of the micro-hopping robot is simplicity. Therefore, trade-offs performed in the design of the platform generally favour simplicity over performance.

The geometry of the micro-hopping robot is based on a regular tetrahedron. This geometric configuration has been selected because the hopping robot can land in any orientation at the end of a jump. A regular tetrahedron provides robustness to recover from landing on any of its faces. Three of the faces are petals that open to roll the robot to its vertical configuration. The interior of the petals is covered with photovoltaic cells to provide. The fourth face is used to locate the hopping mechanism that will provide locomotion. Such a configuration has been proven on the Pathfinder and Mars Exploration Rover missions to provide the ability of the lander to right itself up after the completion of the landing sequence.

To enhance robustness, it was decided to avoid dependence on electric power for the opening/closing of the petals and for the locomotion. A Shape-Memory Alloy mechanism is therefore used to drive the petals and to charge a mechanical accumulator storing the energy for jumping. A single SMA actuator is necessary to store the energy within a torsion spring (accumulator) and to put the robot back on its base after a jump.

A typical day of surface operations therefore starts with the hopping robot righting itself up as the petals open under the influence of the warming temperature (see Figure 5). At the same time, the shape-memory alloy drive cranks the spring that will be used to deliver the impulse for the robot to jump. As the petals open, the solar cells get exposed to the sun and start loading an accumulator.

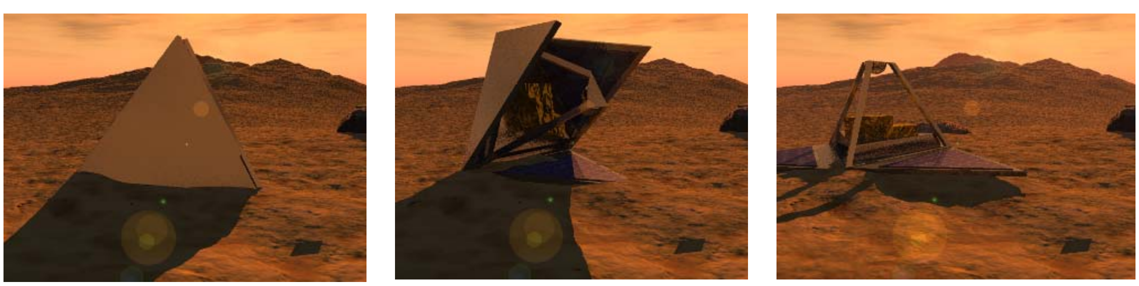

Figure 5 - Hopping Robot Righting Sequence

As the electric power increases, the robot electronics powers up and starts taking sciences measurements of the surroundings. These could include a panoramic view of the landing area, microscopic imaging of the ground underneath the lander in both visible and UV light, and atmospheric temperature. The data acquired from the scientific instruments is stored in a non-volatile memory for eventual uplink to an orbital asset. The robot has the capability to store data for a few sols of operation while waiting for a communication window, which is appropriately synchronized with the robot's power cycle.

As the Martian day draws to a close, the petals close, and the electronics shuts down. If the hopping mechanism has accumulated enough energy for a jump, the closing of the petals triggers the release of the impulse delivery mechanism. The robot executes a jump of a few meters in length and crash-lands back on the ground, protected by its closed petals. The next morning, as the petals open, the lander is automatically righted up and the cycle starts again. Table 1 shows the step-by-step sequence to be accomplished by the robot's mechanisms within a complete thermal cycle.

Table 1 - Sequence of mechanical actions in a complete cycle

Step	Tasks
1	Petals close for protection upon landing (triggered by cooling down of SMA)
2	Impulse delivered by hopping mechanism (at end of SMA cooling cycle)
3	Hopping mechanism retracted during flight
4	Robot lands on the planet surface
5	Petals open thus righting robot (triggered by warming of SMA)
6	Hopping spring recharged (end of SMA warming cycle)
7	Return to step 1

DETAILED DESIGN

Impulse Delivery Mechanism

The concept retained for the deployable mechanism that generates the thrust to jump is a cylindrical scissor mechanism as shown on Figure 6. The usage of a scissor mechanism to deliver the impulse is motivated by the fact that it applies the jumping force in a gradual manner. This reduces the risks of premature jump [4], which can occur when using a compressed linear spring.

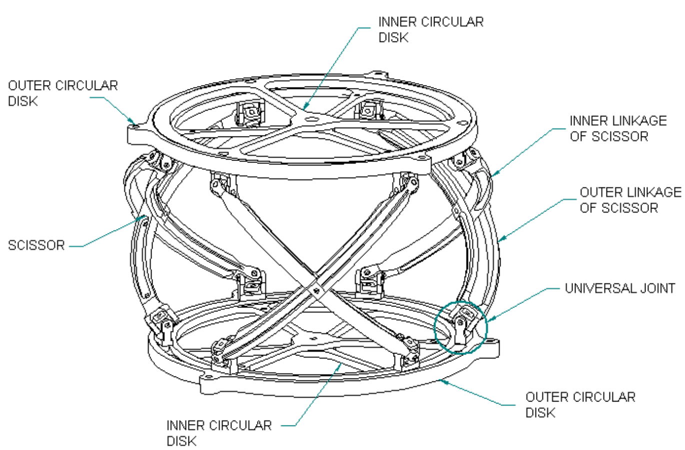

Figure 6- Cylindrical Scissor Mechanism used for Impulse Delivery

Figure 7 illustrates the difference between a traditional scissor mechanism and the proposed cylindrical scissor mechanism. A traditional scissor mechanism requires one of the legs to travel along a rail (from point C to point B in Figure 7). Laying the base of the scissor mechanism along an arc allows the sliding rail to be replaced by a rotational joint at the center of the arc. Such a configuration is more tolerant to dust and grit as the rails along which the base of the scissor moves can be designed with proper gaps to avoid gritting and the bearing can be sealed.

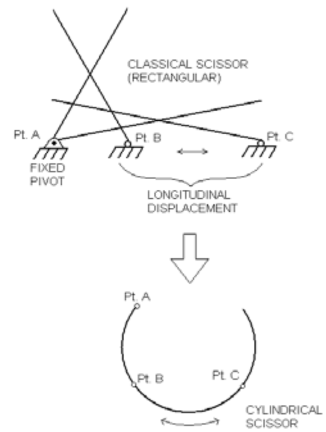

Figure 7 - Comparison of Rectangular Scissor and Cylindrical Scissor Mechanisms

In addition, as shown on Figure 8, the mechanism has the added advantage of offering a very compact configuration when stowed, which allows it to be located within the base of the hopping robot (as shown on Figure 9). The diameter of the circle on which the scissor assemblies are mounted on is about 150mm and the stowed height is on the order of 40-45mm.

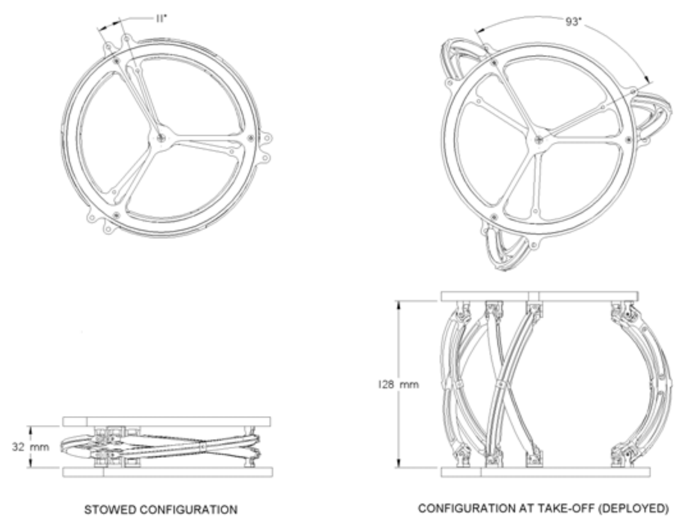

Figure 8 - Cylindrical Scissor Mechanism in Folded and Deployed Configurations

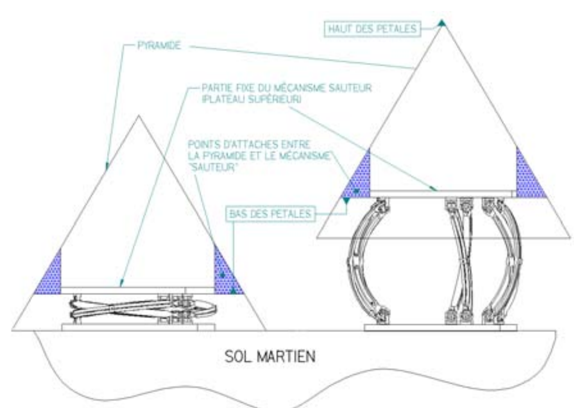

Figure 9 - Mechanical Configuration of the Hopping Mechanisms and Robot Body

As shown on Figure 6, the scissors are mounted on two concentric disks (spoked wheels) at either end. As the scissors deploy, the disks rotate with respect to each other. The energy necessary for the jump is accumulated in a torsion spring attached to the two disks at the top and a similar spring attached to the two disks at the bottom of the mechanism. One of the advantages of the selected configuration is that, as the scissors deploy, the rotary displacement of the lower disk pair is exactly the same as the upper disk pair: one of the upper disks does not rotate during deployment. Therefore, if the main body of the hopping robot is attached to the non-rotating disk, the mechanism will not impart any angular velocity on it before the end of the stroke. This maximizes the fraction of the potential energy that gets transferred from the spring into translational kinetic energy, thus maximizing the hopping distance.

Actuation Mechanism

As mentioned earlier, the actuation mechanism is base on a shape memory alloy actuator to increase mission robustness and avoid dependence on scarce electric energy. For the current prototype, the selected SMA material is a nickel-titanium (Ni-Ti) alloy. This choice is mainly motivated by the availability of this type alloy, its low density, and its super-elastic qualities. For a Mars mission, it would be possible to obtain a similar alloy with a transition temperature around –40°C. Such a transition temperature is superior to Mars nighttime temperatures and inferior to daytime temperatures over a broad range of latitudes and seasons.

To minimize stress on the actuator assembly, it was decided to use two identical actuator assemblies mounted in parallel: one mounted on the top disk assembly and one on the lower disk assembly of the cylindrical scissor mechanism. The two actuators must be confined inside the deployable mechanism in its stowed configuration, which represents a cylinder of 120mm diameter and approximately 32mm height.

The actuator is designed to benefit from the properties of a SMA straight wire, which are: a weak rate of elongation (4% - 6%), and a high force capacity in tension. Figure 10 shows the configuration of the actuator assembly. A single SMA wire is looped several times around an assembly of three pulley stacks and then wound around a drum, which is directly attached to the torsion spring linking the two disks of the cylindrical scissor mechanism. To completely retract the scissor mechanism, the drum must undergo a rotation of 82 degrees. Given a drum diameter of 85 mm and a conservative 4% strain on the SMA, the required SMA wire length is 1.52m. This is obtained by running the SMA wire over three stacks of four pulleys as illustrated on Figure 10.The wire diameter required to overcome the maximum torque of the torsion spring during the compression cycle is 0.24mm or approximately 0.010".

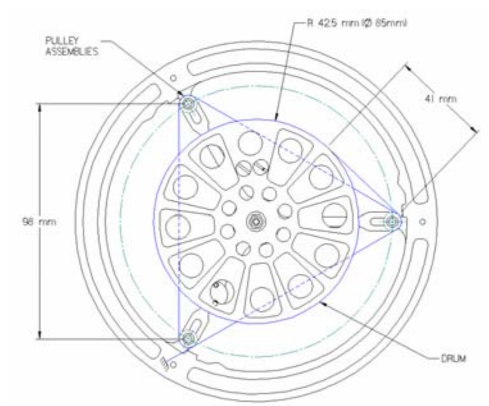

Figure 10 - Detailed Design of the Actuator Assembly

CONCLUSION

In an attempt to mirror the micro-satellite paradigm, the Canadian Space Agency is investigating technologies for lowering the cost of planetary exploration missions through miniaturization of landed platforms. A trade study was conducted to evaluate the scalability of planetary landers and to evaluate the benefits and disadvantages of such an approach. The study was based on the historical data of all Martian landed platforms launched between 1996 and 2003. Statistical evidence shows that, in the sampled set, the ratio of instrument mass to lander mass is higher for smaller spacecraft.

In response to the results of this trade study, a concept of a hopping micro-robot was developed. The target mass of the robot is on the order of 1-2 kg with 250g of scientific payload. The locomotion scheme developed for this micro-robot is hopping. To increase robustness and remove dependence on scarce electric energy, the hopping mechanism draws its energy from diurnal temperature variations through the use of shape memory alloy actuators to recharge a set of springs used for impulse delivery. The robot is therefore limited to a single jump per day.

The hopping mechanism is based on a novel cylindrical scissor mechanism. Scissor mechanisms are particularly suited to provide the impulse for hopping since they generate a gradually increasing force throughout their motion, thus reducing the risk of premature jump. The cylindrical scissor mechanism has the additional advantages of being compact and more tolerant to dust than traditional scissor mechanisms. The mechanism described in this paper uses a single actuator to drive all mechanisms.

At the moment, the fabrication of the mechanism is complete. The deployment of the cylindrical scissor mechanism has been proven and preliminary tests have been conducted. The springs used for these tests were slightly weaker than the design case. Yet, the mechanism was able to achieve a height of approximately 60cm in Earth gravity. Unfortunately, the fabrication has revealed some problems with interferences between the shape memory alloy actuator configuration and the sequencing mechanism. The actuation unit is current being re-designed to overcome these interference issues.

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