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RESETTABLE BINARY LATCH MECHANISM FOR USE WITH PARAFFIN LINEAR MOTORS

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ABSTRACT

A new resettable Binary Latch Mechanism has been developed utilizing a paraffin actuator as the motor. This linear actuator alternately latches between extended and retracted positions, maintaining either position with zero power consumption. The design evolution and kinematics of the latch mechanism are presented, as well as development problems and lessons that were learned.

BACKGROUND

The increasing use of resettable paraffin linear actuators on spacecraft as operators of covers, apertures, caging and other mechanisms has created a need for latches designed to utilize the unique characteristics of paraffin actuators. Of particular interest is a latch which can utilize the multiple-operation capability of the actuator and which allows the output from a single actuator to alternately latch between extended and retracted positions while maintaining either position with zero power consumption.

For mechanisms with multiple in-flight operation requirements, this would offer advantages in weight and size over the electric motor and gear drive systems currently used. For single release applications, such as caging devices, the resettability of the latch during preflight testing would offer advantages over pyrotechnic devices that require replacement, discharge material and deliver considerable shock to instruments.

This type of mechanism was developed as the aperture driver on the ISTP/Geotail Comprehensive Plasma Instrument, built by the University of Iowa. Their requirements for multiple operation, weight, force, stroke and power consumption fit the performance of the SRC IH-5055 actuator but included zero power latching in the extended position. The available physical envelope for a latching mechanism was small: about 2.3x4.2x3.2 cm (.90"x1.65"x1.25"), including a limit switch.

Marshall Space Flight Center concurrently had a similar requirement for the VIS instrument on the ISTP/Polar spacecraft. Their requirement allowed more space for the mechanism but included 2 limit switches. The mechanism described in this paper was developed for these and subsequent similar requirements.

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LATCH REQUIREMENTS

The mission applications generated the following specific requirements:

1) Limit mass to a maximum of 95 grams with one switch, 120 grams with two switches.

2) Limit the single-switch latch dimensions to 2.3x4.2x3.2 cm (.90"x1.65"x1.25").

3) Provide dynamic load-moving capability of 23 kg (50 lbf).

4) Provide static or latched load-holding capability of 23 kg (50 lbf).

5) Operate with an overtravel of less than .19 cm (.075") (overtravel is the amount of additional stroke required to affect the change of latch state).

6) Provide a stroke between latched positions of at least 1.2 cm (.45").

7) Have a lifetime of more than 2,500 extended/retracted cycles.

8) Sustain launch vibrations of 20G in any direction.

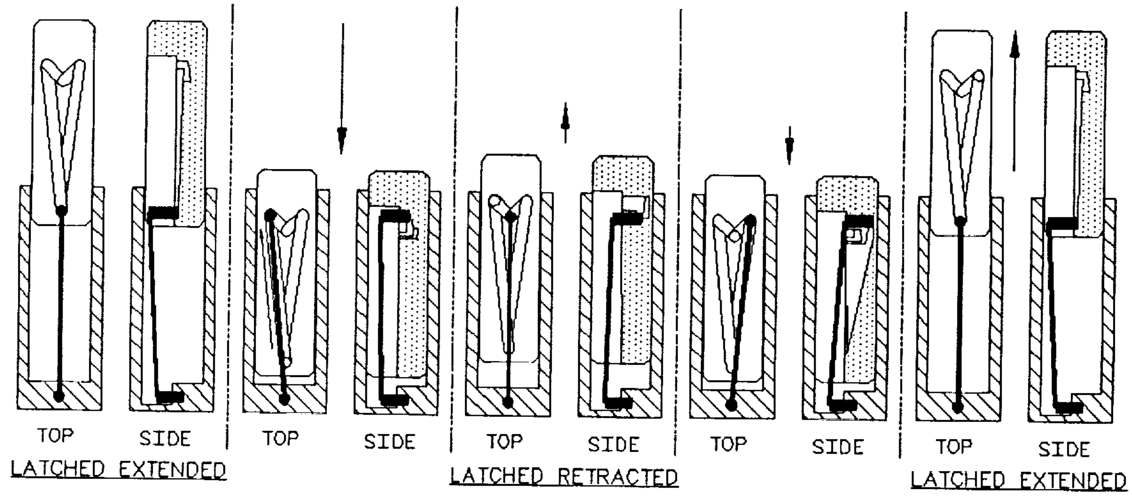
DESIGN APPROACH

Binary mechanisms are devices that allow an output to latch alternately between two mechanical states, extended and retracted, when repeatedly actuated with the same input. An example in everyday life of such a mechanism is the ball-point pen. Repeated actuations cause the pen point to alternate between extended and retracted positions.

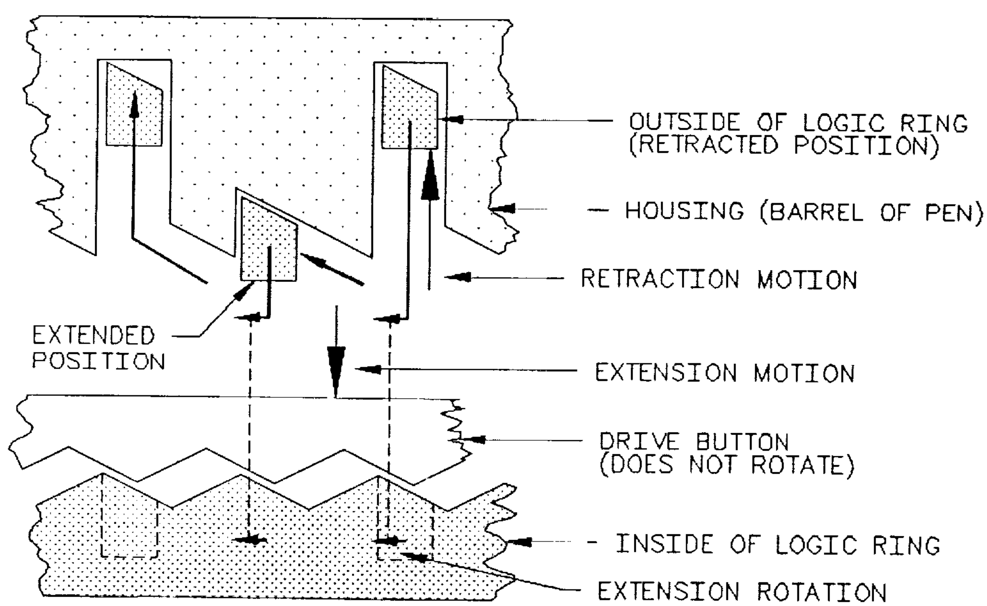
SRC research was unable to identify precedents for the use of binary mechanisms on spacecraft. To establish the state-of-the art in binary mechanisms, an extensive evaluation of commercial latches (including ball-point pen mechanisms) was performed.

This evaluation included database and literature searches as well as a patent search and review. Commercial latches were acquired, disassembled inspected, and analyzed.

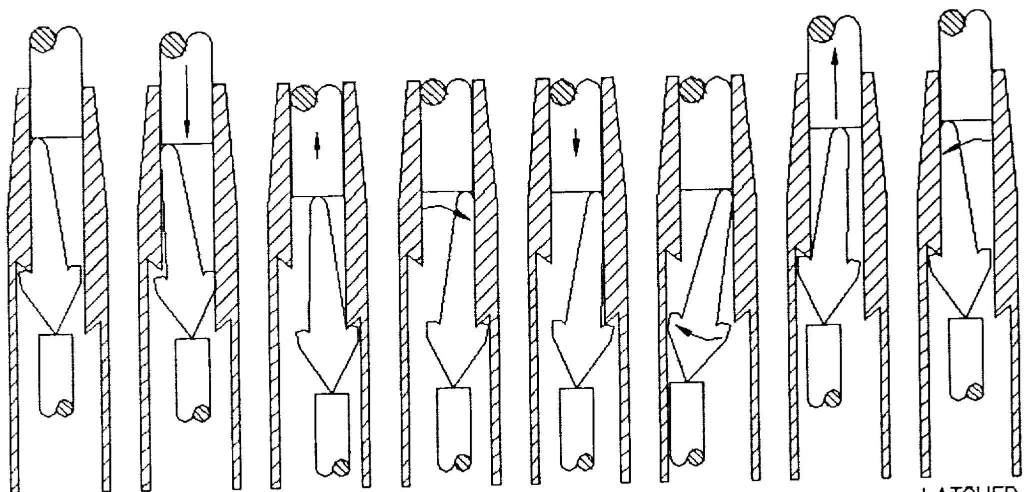
The following diagrams of several common binary latch mechanisms illustrate their operation:



Pin in track
The logic element, in this case a spring-loaded pin, is guided through a track that moves with the output shaft. Steps in the z-axis in the track create a non-reversible motion of the pin. The pin is moved alternately between the extended and retracted positions by the extension and retraction of the input. The size of the pin determines the load-carrying capability and the overtravel.



Typical ball-point pen
The logic element, in this case a ring with ramps that interface with the drive button and the pen housing, is guided in a rotating pattern. The "out of phase" interaction of the ramps translates some of the axial movement of the drive button into rotation of the logic ring. The logic ring latches in extended and retracted positions in the housing. Contact surfaces are small and overtravel is large.



Flipper ball-point pen

The output load is carried through the logic element, a flipper. The action of this load creates lateral forces that cause the flipper to flip or rotate about pivot points that engage features in the housing. The flipper thus moves through a non-reversible pattern of positions in response to the reciprocating input. The extended and retracted position latching is accomplished by engaging the flipper in the housing, thereby blocking the motion of the output shaft. Overtravel is very high and contact area small.

The following generalizations were made for the theory of operation underlying these binary mechanisms:

1) One part can always be identified as the logic element. When a reciprocating input is provided, the other components direct the motion of this element through a non-reversible pattern or series of positions.
2) The logic element locks up or latches the output in the extended and retracted positions.
3) The non-reversible pattern of movement of the logic element by the latch components translates the single input into two opposite movements, retraction and extension, and two latched positions, extended and retracted.
4) The latch component motion can usually be described as a 2-axis motion (x-y). Motion and force along another axis creates the non-reversibility.

It was determined that the existing latches reviewed were not suited for application to spacecraft mechanisms in general or the latch requirements in particular. Problems included:

1) None of the latches reviewed was designed to transmit high loads. They all carried the load through the latch components and many carried the load through the logic element. It was concluded that sizing the latch components to carry high loads would produce a bulky mechanism. In addition, high loading of the surfaces of the moving logic element would produce high wear and friction. Using self-lubricating polymeric materials for the latch components would further exacerbate the problem because of their lower compressive strengths and therefore larger size requirement.

2) Typical overtravel was high, usually greater than .4 cm (.15"). The overtravel was typically a function of latch component size and therefore would only become greater if the latch components were enlarged to handle high loads.

Evaluation of a prototype of a conventional ball-point pen mechanism modified to carry high loads and fabricated of metal components confirmed the preliminary assessments. High loading on the logic element created high wear and friction, which ultimately limited lifetime and decreased reliability.

After careful review, it was concluded that combining load-carrying structural and mechanical logic function into a single component created these problems. The opposite approach was explored as a possible solution. Function was separated and each component was optimized to function as either a structural or logic component. While this approach introduced more components, an improvement in reliability and lifetime was expected.

DESIGN

A new approach for the mechanism was proposed, the mechanical analogue of a relay. A small, lightly loaded binary latch would control a larger latch transmitting high loads. The component geometries of the lightly loaded binary latch could then be optimized to minimize overtravel, and the load-carrying latch could be sized to handle the high throughput loads. This would allow the mechanism to carry high loads with minimal overtravel.

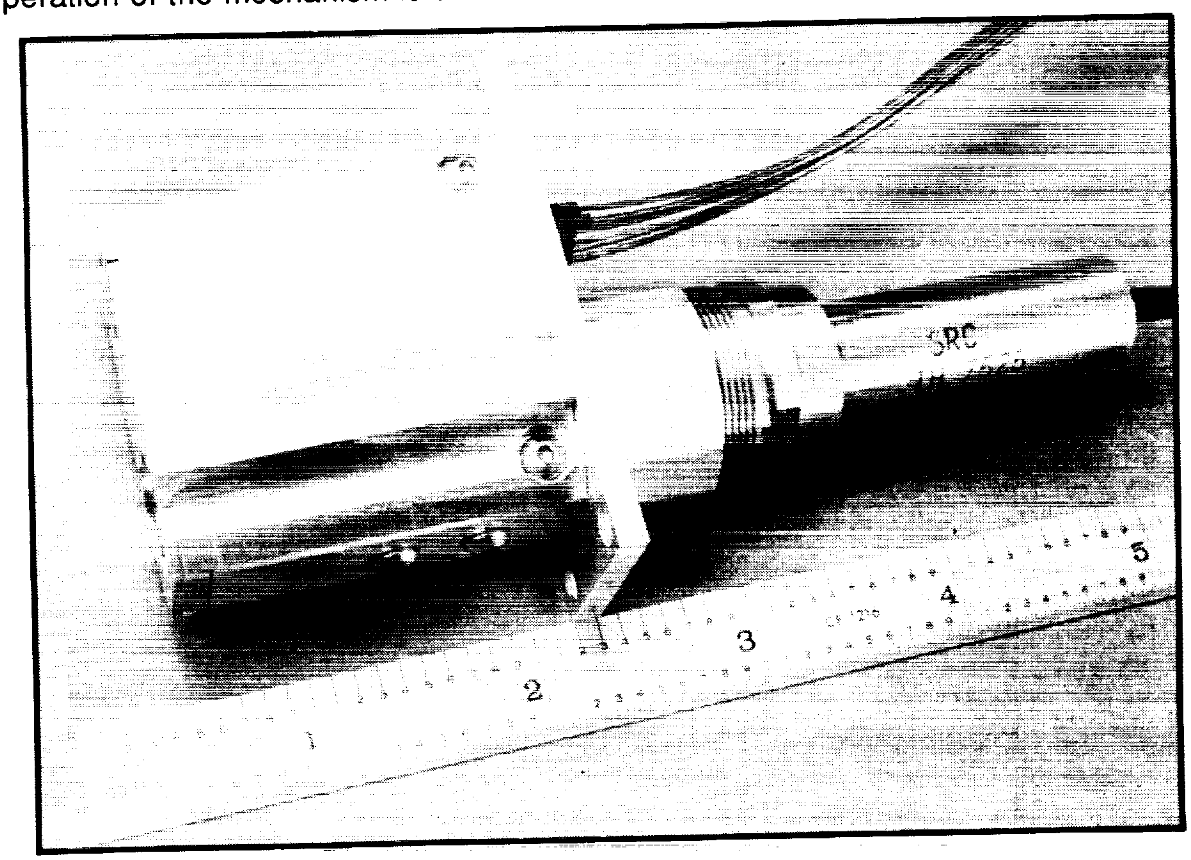
A series of mechanism concepts was developed and evaluated for concurrence with the design objectives and particularly for simplicity and low part count. The concepts evolved through several intuitive steps which were facilitated by the thorough understanding of binary latch principles gained from the previous state-of-the-art research.

The final concept placed the binary latch inside the load-carrying components. The logic element of this latch would position itself to interfere with the movement of the load-carrying components relative to the housing when they were in the extended position, thereby latching the mechanism. This arrangement simplified the design by having different parts of one component serve two functions, as a low-force logic element and as a high-force latch.

This final design has the following characteristics:

1) To latch and unlatch the mechanism, the logic element, called the "toggle," moves between a series of stable positions.
2) The toggle moves through the series of positions by pivoting about different features of the toggle. These movements are created by a separate low-force spring, the toggle spring, rather than by the throughput loads.
3) The toggle does not carry loads during actuator extension or retraction. It locks up the load-carrying components when in the latched position. No motion, and consequently no significant wear, can occur when the toggle is loaded.
4) The shapes of the toggle and latch components are optimized to minimize overtravel. Overtravel ideally can be limited to only what is required to accommodate tolerance stack-up.
5) None of the output loads is translated to sliding surfaces during extension or retraction, eliminating significant wear points in the mechanism.

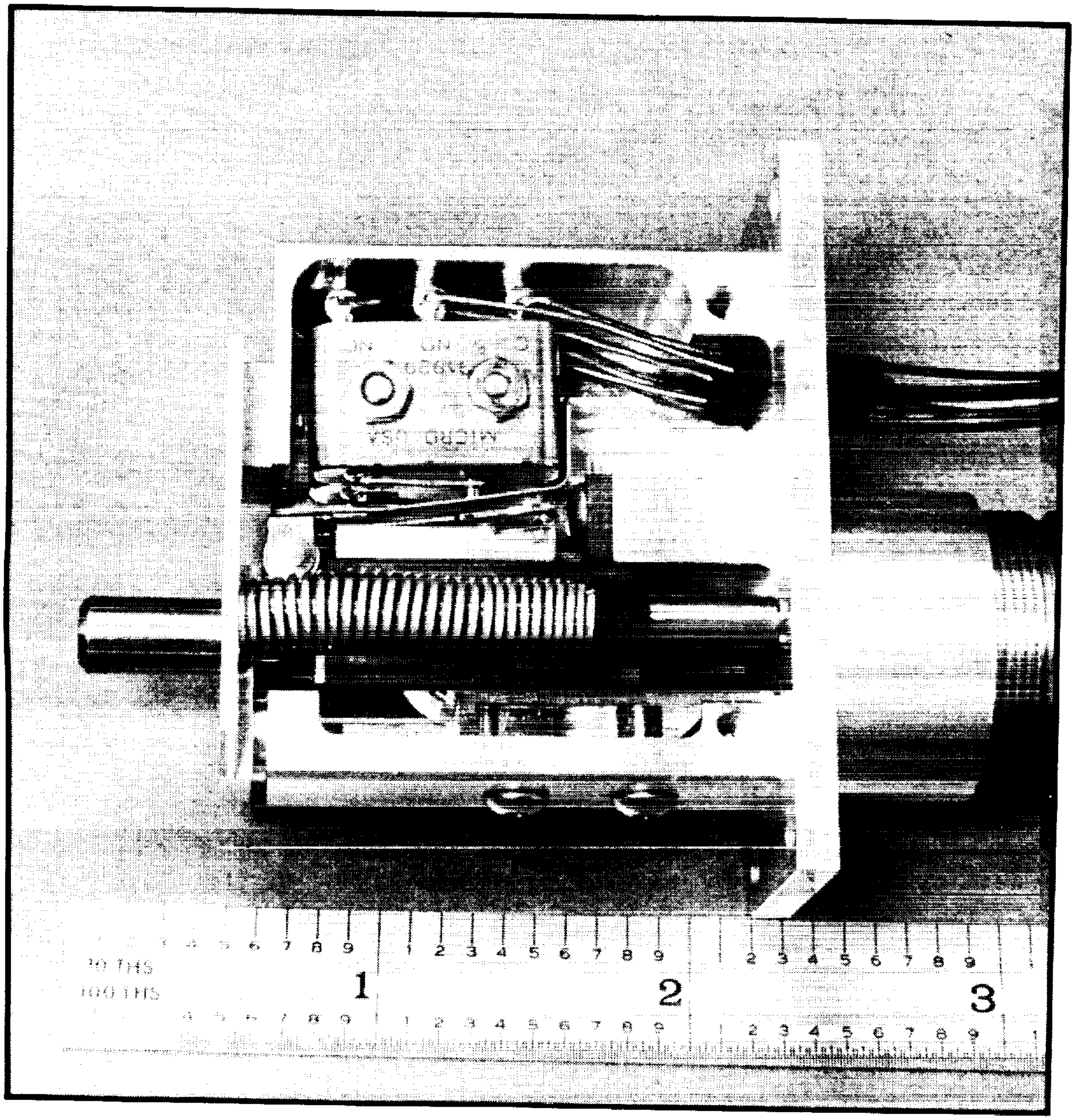
Operation of the mechanism is described in the following pictures and illustrations:



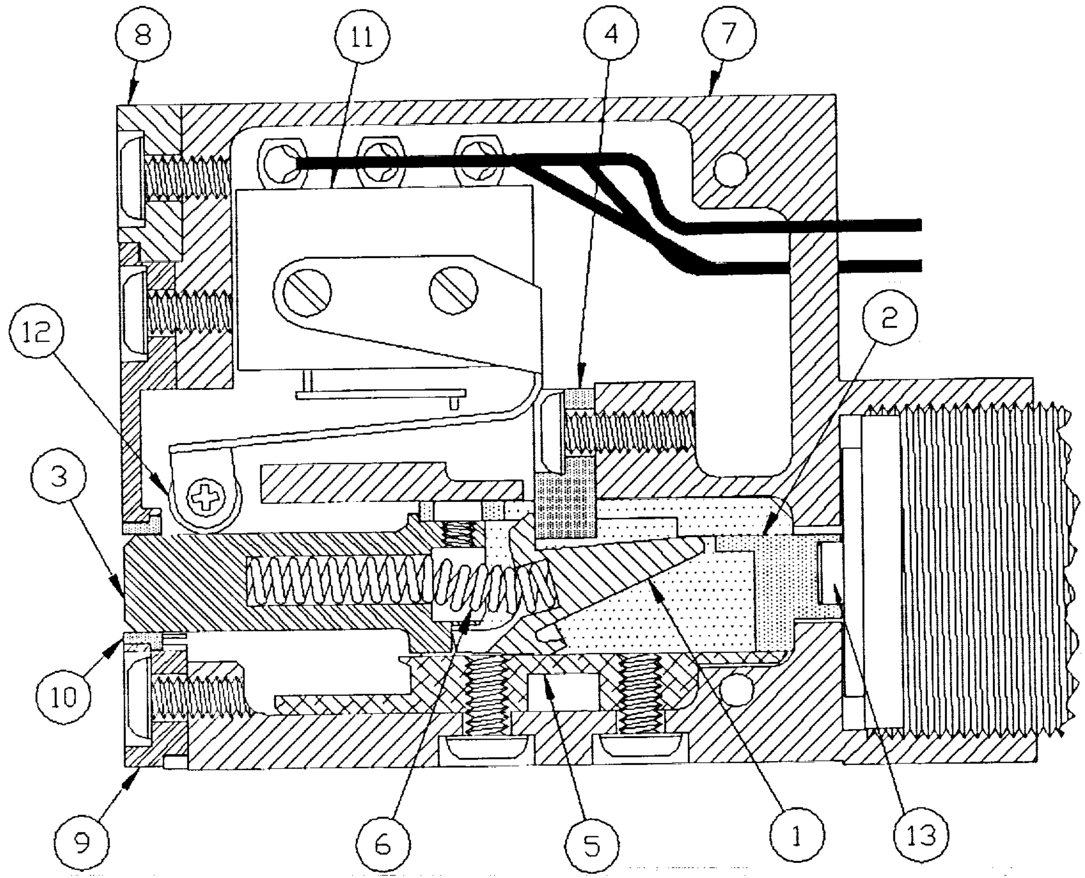
Latch mechanism (two switch version) with paraffin actuator

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

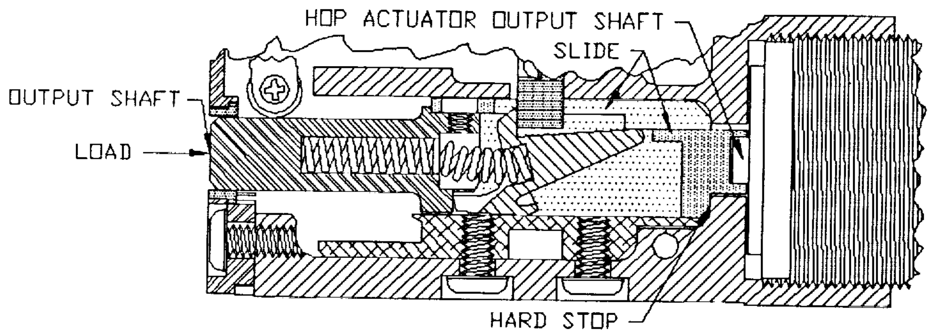


Latch mechanism with cover removed

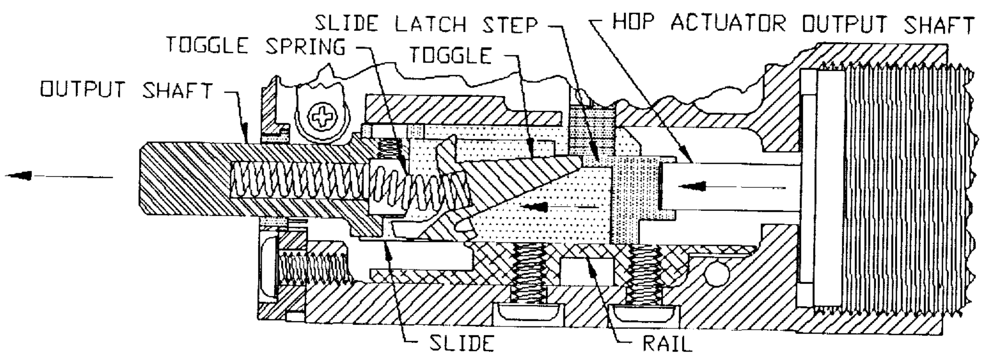


1) Toggle - The logic element of the mechanism. Moves inside the slide to latch the mechanism. (303 stainless steel)
2) Slide - Carries the throughput load from the output shaft around the toggle to the actuator shaft. (Envex 1115)
3) Output shaft - Carries the load to the slide and to the toggle in the latched position. Houses the toggle spring. (303 stainless steel)
4) Reset Plate - Resets toggle to its initial position. (Envex 1115)
5) Rail - End of the rail captures the toggle forcing it to pivot into the latched position. The toggle slides on the rail. (630 bronze)
6) Toggle spring - Applies an axial off-center load to the toggle, which forces the toggle to pivot through various overcenter positions. (18-8 stainless)
7) Housing - Houses components and mounts to spacecraft. Actuator mounts to housing. (6061-T6 Aluminum)
8) Cover - Encloses components after assembly and restrains bushing. (6061-T6 Aluminum)
9) End Cap - Captures bushing and supports output shaft. Allows visual access to components. (6061-T6 Aluminum)
10) Bushing - Guides the output shaft. (Envex 1115)
11) Limit Switch - Signals actuator extension. (Honeywell 9HM1)
12) Switch Blade and roller assembly - Interfaces with slide to actuate the limit switch. (Microswitch JS-151)
13) Actuator output shaft - Output of paraffin motor. (Nitronic 60)

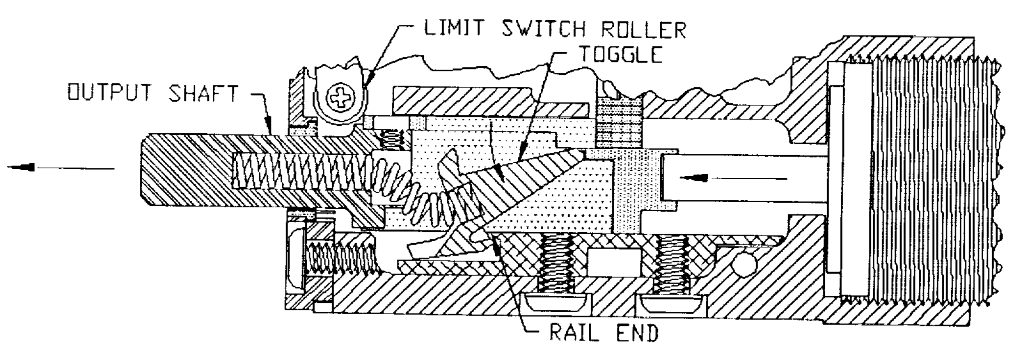
OPERATION



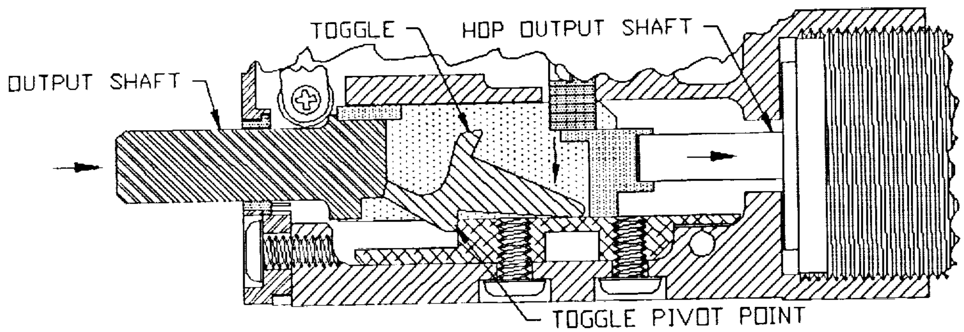
1) Initial position:
The actuator is fully retracted. Loads on the output shaft are carried by the slide around the toggle to an internal hard stop in the housing. The return springs (not shown) maintain this position during launch loads.



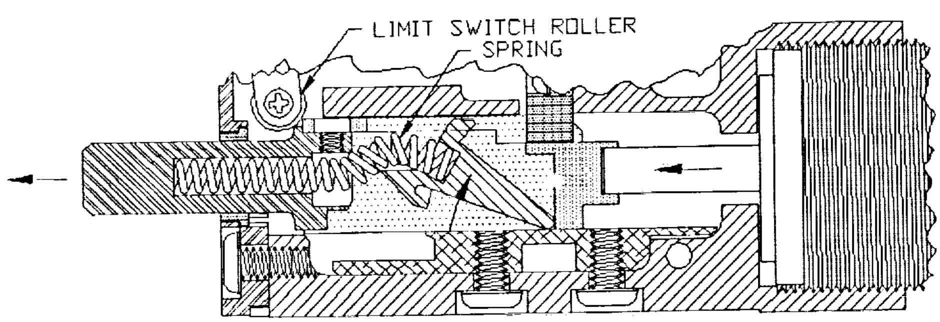
2) Actuator extending:
When power is supplied to the actuator, it slowly extends against a load carried axially from the output shaft through the slide to the actuator output shaft. The toggle spring establishes the position of the toggle and the direction in which it will rotate. It is held against the slide latch step and biased towards the rail during this phase.



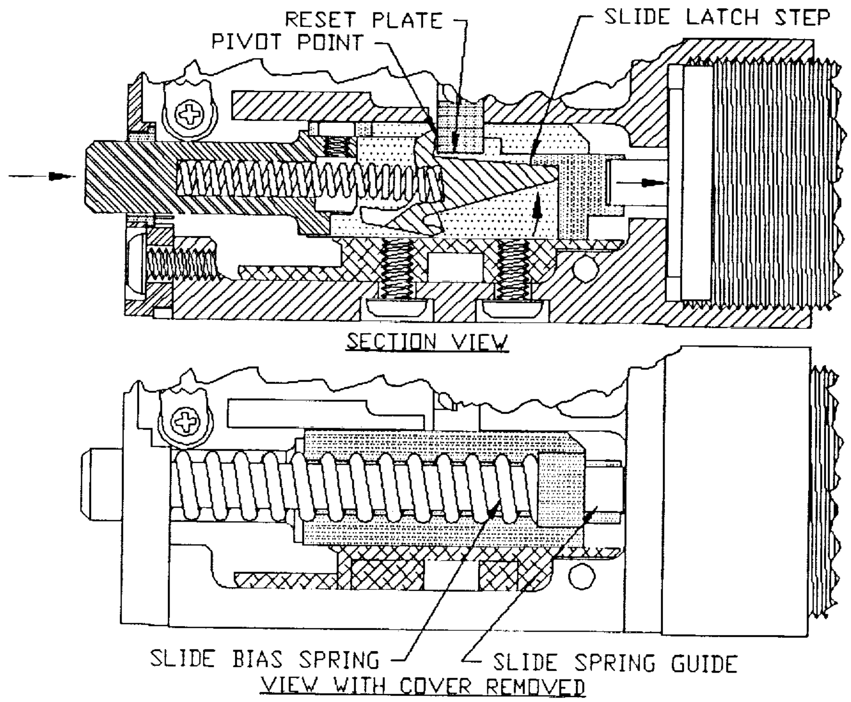
3) Prelatching:
The bias force on the toggle forces the toggle to pivot over the end of the rail. Actuator extension is signaled by the limit switches and the actuator is de-energized.



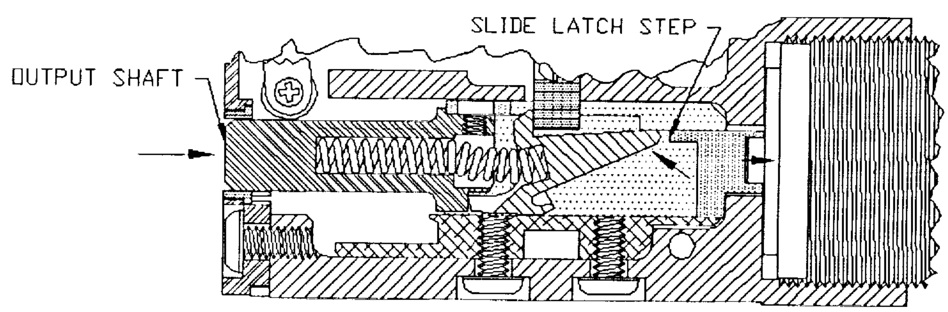
4) Actuator retracting:
The actuator begins to retract. Because the toggle is over the end of the rail points, it is captured and, under the action of the toggle spring, pivots about this point toward the rail. Friction forces alone are sufficient to maintain this position, however, .08 cm (.030") high points on the rail ensure that the toggle maintains this position under high vibration loads. As the output shaft continues to retract, loads are transferred from the output shaft through the latched toggle to the rail and retraction is halted. In this position, high loads are accommodated by this high-strength output shaft-toggle-rail load path. There is no wear because the load is applied to the toggle only after it is stationary. The pivoting of the toggle has shifted the direction of the toggle spring bias, preparing the toggle for the next step.



5) Unlatching:
When the mechanism is to be unlatched, the actuator is energized and begins to extend. Immediately the toggle is unloaded as loads are again transferred axially from the mechanism output shaft, through the slide, to the actuator output shaft. The toggle spring is now biasing the toggle away from the rail. As the slide advances, it moves the toggle forward, raising it above the rail points. Under the action of the toggle spring, the toggle pivots away from the rail to the far side of its housing in the slide. Actuator extension is again signaled by the limit switches and the actuator is de-energized.



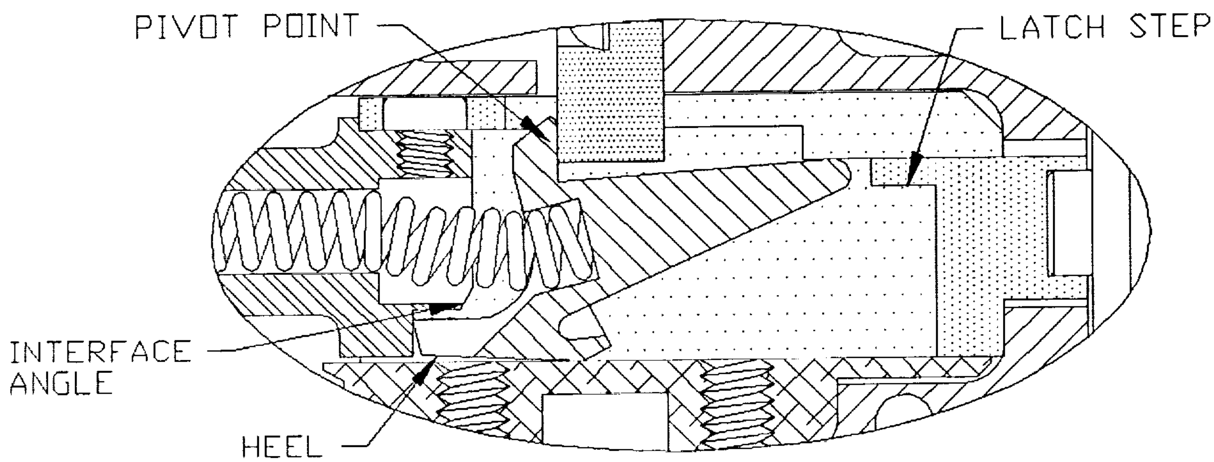
6) Retraction:
The actuator retracts, allowing the mechanism, under the force of the slide bias springs, to retract at a slow, controlled rate. A tab on the toggle encounters the reset plate near the bottom of the stroke. Retraction past this point allows the toggle spring to rotate the toggle away from the rail toward the slide latch step, towards its original position.



7) Full retraction:
As the mechanism fully retracts, the reset plate lifts the toggle onto the slide latch step, resetting all the components and completing the mechanism cycle.

DESIGN REFINEMENT

Reducing the design from a concept to component parts required determining the optimal toggle length, width, length-to-width ratio, the toggle side travel, the pivot locations, the toggle "heel" length, the heel pivot point, output shaft interface angle, the toggle pivot angle, the toggle spring position, the latch step height, etc. All these attributes interact with one another to define the latch performance and, most importantly, to establish overtravel.



An analytical approach to optimizing these attributes was precluded by the complexity of the geometric solutions. In other words, there were more variables than equations. An interactive, iterative approach was used as an alternative to analysis to determine these attributes and generate the final component dimensions.

1) A first approximation of the component geometry was laid out on a CAD system. The mechanism was drawn in different positions.
2) Manipulation on the CAD system of the components in different positions provided a better understanding of the relationships between the parts and their attributes.
3) Iterative modifications to the component shapes provided approximate solutions to the component geometry.
4) The CAD output was translated to pasteboard prototypes which allowed more detailed evaluation of the kinematics throughout the latching cycle.
5) A final geometric solution and assembly drawing was completed by repeating the CAD/pasteboard prototype loop several times.
6) Individual part prints were completed and prototype hardware was fabricated. Some components were fabricated of clear polycarbonate to allow visual inspection of part movement and loading during operation.
7) The prototype was observed during operational testing and components were modified to optimize for function and overtravel.
8) Material selection was completed, component design finalized and test hardware was fabricated.

RESULTS OF PROTOTYPE FABRICATION AND TESTING

As initially configured, all siding surfaces in the mechanism were metal on molydisulfide-impregnated polyimide (Vespel and Envex are trade names for Mil Spec versions of this material). This required the slide, rail and bushing to be made of polyimide. Fabricating these parts required developing machining expertise because of the brittleness of the material and its tendency to chip and split when in shear. Carbide tools, backing up edges, high tool speeds and high feed rates were necessary for fabricating the complex shapes required.

The polyimide rail failed during initial testing. The rail end points, around which the toggle pivots (see the Prelatching and Actuator retracting diagrams) fractured from unexpected high inertial loads. The toggle impacted the rail ends as it moved into the latched position and again when it rotated. Both motions and the associated impact led to a rapid brittle failure, breaking the ends off the rail. More tightly controlling the toggle movement might have eliminated this failure, but it was clear that a more durable material was required for this part to ensure reliability under all conditions.

Because limiting weight was important and because the rail experienced light loading from the toggle sliding along it, 6Al-4V titanium was initially substituted. Galling occurred within 100 cycles although contact surface loading was less than 25 psi against the stainless steel toggle. The galling produced progressively higher drag and could not be mitigated by smoother surface finishes. The titanium was therefore deemed unsuitable.

CDA 624 aluminum silicon bronze, CDA 655 silicon bronze and CDA 630 aluminum nickel bronze were tried next. After initial wear-in, approximately 50 cycles, the toggle was burnished from contact with the rail and neither part demonstrated significant wear during subsequent testing to 20,000 cycles. CDA 630 bronze was selected because of its resistance to corrosion and slightly better wear characteristics.

Thermal testing revealed interference between the output shaft and its bushing at low temperatures. The bushing, fabricated from polyimide, shrank onto the output shaft at -60°C and created friction. Enlarging the bushing bore corrected the problem.

Repeated latch operation at 80kg (150 lbf), greater than three times normal load, was performed. The mechanism functioned smoothly with no deformation or excessive component wear, confirming satisfactory strength margins for the latch and load-carrying components.

Standard mounting of the Honeywell Microswitch 9HM1 switch and its associated roller blade uses only the clamping friction created by torquing the switch mounting screws to 1728gm-cm (1.5 in-lb) to secure the blade in position. Because one of the mechanisms designed required stacking two 9HM1 switches on top of each other, there was a concern that the blades and therefore the switch actuation point might shift from vibration. The mounting security was improved by assembling the switches with urethane between all the parts, effectively bonding the assembly.

The mechanism was subjected to vibration testing at 20, 30, and 50G rms. There was no change in mechanism function and the latch stayed in position during vibration. The Honeywell 9HM1 limit switch point of operation shifted by .025cm (.010") after 20G vibration. This shift was due to changes in the internal components of the switch and was expected. Mechanism tolerance was sufficient to accommodate this shift and no further shifts were noted at the 30G and 50G vibration levels.

After establishing satisfactory performance, the mechanism and its parts were reviewed for structural margin and optimized for such manufacturing issues as tolerance, ease of fabrication, assembly, fasteners, etc. The final design was used for fabrication of qualification and flight assemblies.

FINAL CHARACTERISTICS OF THE LATCH MECHANISM

Size/mass

Final dimensions of the single switch version of the mechanism are 2.3x4.2x3.2 cm (.90"x1.65"x1.25") and mass is 86 grams. Dimensions of the 2-switch version are 2.5x4.3x4.5cm (1.0"x1.7"x1.75") and mass is 100 grams.

Output loads:

During extension and retraction, output loads are carried axially from the actuator shaft to the mechanism output shaft. None of the output load is translated to normal forces on wearing or moving surfaces. 100kg (220lbf) static load testing and qualification testing at 80kg (175lbf) dynamic load for 15 cycles produced no wear or damage to latch components. This testing established a margin of greater than three above the nominal rated operating load of 23kg (50lbf).

Overtravel/stroke:

As currently configured, .08cm (.030") of overtravel is required to operate the latch. An additional .08cm (.030") is required to operate the limit switches. A remaining .152cm (.060") of overtravel is used to ease part tolerance requirements, assembly tolerance, and to accommodate a large variation in environmental temperature. Total overtravel is .32cm (.125"). Overtravel was reduced to .19cm (.075") by utilizing a custom switch blade and by tightly controlling tolerances.

The use of an SRC IH 5055 actuator with 1.5cm (.575") of available stroke provided 1.1cm (.45") of stroke between the retracted and extended latched positions, even with the more generous .32cm (.125") of overtravel.

Reliability/lifetime/wear:
Outside of the output shaft assembly which transmits the throughput load, the actual latch mechanism contains one moving part, the toggle, which moves by the forces created by the toggle spring (approx. 1.5kg). The final mechanism configuration limits the sliding surfaces to four interfaces. The loadings listed are maximum limits that could occur with 23kg (50lbf) of throughput load:

Toggle/rail interface
303 stainless steel against 630 bronze with 2kg/sq.cm (25psi) loading.

Toggle/slide interface
303 stainless steel against molydisulfide-impregnated polyimide with 1kg/sq.cm (10psi) loading.

Slide/rail and housing interfaces
Molydisulfide-impregnated polyimide against 630 bronze and 6061-T6 aluminum with 2kg/sq.cm (20psi) loading.

Bushing/output shaft
Molydisulfide-impregnated polyimide against 303 stainless steel with 2kg/sq.cm (25psi) loading.

These surface loading levels are two-to-three orders of magnitude less than standard design limits for self-lubricated systems, therefore high-cycle lifetimes are expected. Lifetime testing for a total of 20,000 cycles was performed on the final prototype design at various temperatures and loads. The mechanism was disassembled, and the components were examined under a 20x microscope after initial wear-in and again after the test program. Mechanism wear was negligible after initial burnishing. The expected life of the device will exceed 100,000 cycles, based on testing and wear information. Testing to greater than 100,000 cycles will be completed this year.

Fatigue on all components is minimal. Strains on the toggle spring are well within design limits for infinite life. Strains on the internal bias springs used to reset the actuator and the slide are low and provide for a lifetime of 10^7 cycles.

Vibration:
All moving parts are retained in fixed positions by springs exerting forces approximately 100 times the component mass. Qualification testing at 50G rms random vibration along 3 axes has been performed with no change in mechanism performance.

Friction/lubrication/outgassing:
The normal loads on all sliding surface interfaces during operation are very low, less than 1kg (2lbf), therefore friction is negligible. No liquid lubricants are required because all sliding surfaces are self-lubricating and outgassing can be limited to negligible levels.

CONCLUSION

The project was successful from a technical standpoint, with the flight unit assemblies meeting or exceeding all the original design requirements. As with most design efforts, there were some surprises. Lessons that were learned during this process included:

1) Leave room to maneuver. The initial design requirements were aggressive in all areas, such as mass, size, and performance. This allowed few opportunities to trade off less important features for more important ones.

2) Having a full background understanding of a mechanism is worth the effort. Thorough state-of-the-art research, including non-aerospace commercial mechanism designs, greatly supports a design effort. Besides the obvious advantages of not having to "reinvent the wheel" or avoiding possible patent infringement, thorough state-of-the-art research:
   a) provides lateral leaps to new approaches.
   b) affords a "heads up" to possible problems.
   c) provides an broad-based understanding of a particular mechanism's design principles or philosophies and its suitability to the given requirements.

3) Iteratively designing a complex mechanism in CAD and using pasteboard mock-ups can be a more efficient process than detailed mathematical analysis of component geometries:
   a) Components can be visualized throughout their range of motion.
   b) Interferences can be identified and eliminated.
   c) Kinematics and component shapes can be easily optimized by simultaneously seeing the effect of changes in all positions.

PROJECT STATUS

Flight hardware was fabricated and delivered for the University of Iowa Comprehensive Plasma Instrument aperture cover driver in April 1990. The mechanism has successfully passed all qualification testing. The ISTP/Geotail spacecraft carrying the instrument is scheduled for launch in July, 1992.

Flight hardware is being fabricated and will be delivered in February 1991 to Marshall Space Flight Center for the Ultraviolet Instrument aperture cover and folding mirror driver to be flown on ISTP/Polar.

Flight hardware is being fabricated and will be delivered to Ball Aerospace for the caging mechanism and occulter for the Ultraviolet Coronagraph Spectrometer to be flown on ISTP/SOHO.