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# X–38 Bolt Retractor Subsystem Separation Demonstration

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## LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| BRS | bolt retractor subsystem |
| DPS | deorbit propulsion stage |
| fps | frames per second |
| FRL | Flight Robotics Laboratory |
| lbf | pounds force |
| LED | light-emitting diode |
| LMB | Large Mobility Base |
| LRF | laser rangefinder |
| LVDT | linear variable displacement transformer |
| MSFC | Marshall Space Flight Center |
| NASA | National Aeronautics and Space Administration |
| PSF | Pyrotechnic Shock Facility |
| SMB | Small Mobility Base |

## NOMENCLATURE

| | |
|---|---|
| $k$ | spring stiffness |
| $m$ | mass |
| $t$ | time |
| $x$ | displacement |
| $x_0$ | initial displacement |
| $x_{ic}$ | displacement of spring at point of interface crossing |
| $\tau_{ic}$ | time of interface crossing |
| $\omega$ | natural frequency |

TECHNICAL MEMORANDUM

# X–38 BOLT RETRACTOR SUBSYSTEM SEPARATION DEMONSTRATION

## 1. INTRODUCTION

In the late 1990s, the National Aeronautics and Space Administration (NASA) conceived the X–38 lifting body and deorbit propulsion stage (DPS) as a prototype for a full-sized crew return vehicle for the *International Space Station*. The lifting body was to act as a "lifeboat" for seven crewmembers in the event of a catastrophic emergency that required immediate evacuation from the Space Station. The DPS was designed to conduct the deorbit burn required for the lifting body to reenter the Earth's atmosphere and safely return the crew to Earth. After the deorbit burn was completed, the lifting body was to jettison the DPS prior to reentry. While the lifting body proceeded to a safe landing, the DPS would burn up in the Earth's atmosphere. A view of the combined lifting body/DPS assembly is shown in figure 1.

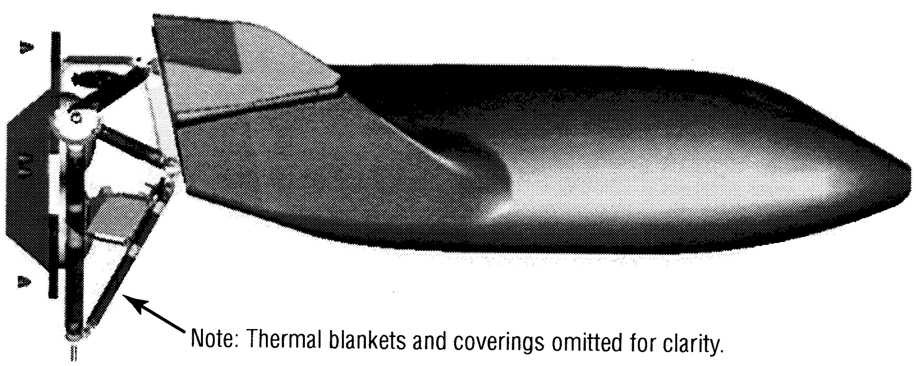


Figure 1. X–38 lifting body and DPS.

One of the major design challenges was creating a system that would reliably separate the DPS from the lifting body at minimal cost without posing danger to the crew and to anyone on the ground. The system that was chosen for the X–38 program used six separation bolts strategically placed at the interface between the lifting body and the DPS. These bolts were to be held in place by separation nuts, which were previously used as parachute release nuts in the Space Shuttle solid rocket booster program. The joint design is shown in figure 2. The X–38 project office determined that a sequence of two separation commands, each firing three separation nuts, provided the best probability of successful separation of the DPS from the lifting body. In this case, successful separation was defined as a complete disconnect of the two bodies with no recontact between them or catastrophic failure of the lifting body. After careful analysis of the separation event and preliminary testing of the separation nut/bolt

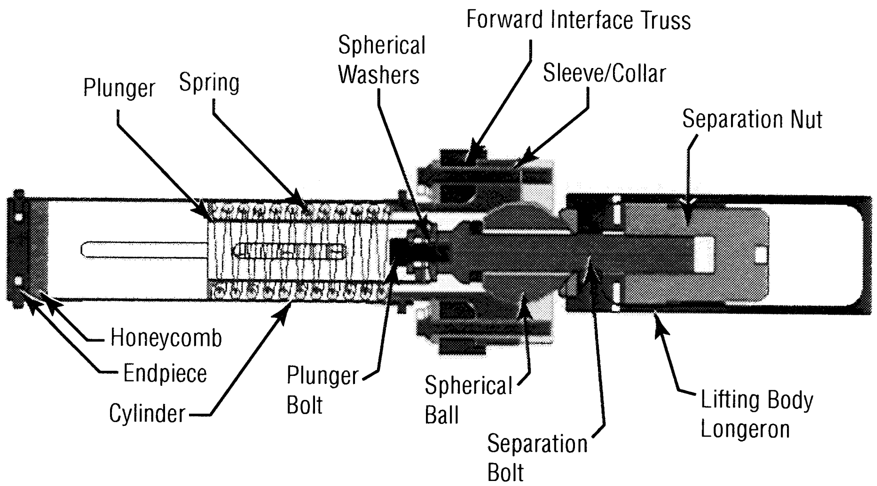


Figure 2. Section view of X–38 DPS joint and BRS design.

configuration in the Pyrotechnic Shock Facility (PSF), X–38 engineers decided to develop a bolt retractor subsystem (BRS) that would forcefully retract each separation bolt across the interface plane between the lifting body and the DPS. The objective of this system was to prevent snagging or pinching of the bolts as they crossed the interface plane during the separation events. Any snagging or pinching of the bolts might prevent proper separation of the two bodies and thus cause mission failure. A separation test was proposed to demonstrate this capability, but was canceled as the X–38 program and affiliated hardware were transferred from Marshall Space Flight Center (MSFC) to Johnson Space Center.

Before the BRS was shipped away, Flight Robotics Laboratory (FRL) personnel at MSFC requested the use of it to demonstrate that the laboratory could test pyrotechnic spacecraft separation. Additionally, the BRS design could be demonstrated to work as designed. Specifically, a bolt retraction time could be determined as well as the force impact to the spacecraft from the device. Initial spacecraft acceleration could also be determined. Neither time nor budget would allow a formal test, so a demonstration was planned. In this Technical Memorandum, "demonstration" is often used instead of "test" as a deliberate reminder that a rigorous test was not run; in particular, some of the data acquisition equipment planned for the original tests was not used. The use of "test" in the remaining paragraphs refers to the means used to validate the FRL as a pyrotechnic separation facility and not qualify the BRS as flight hardware.

The FRL will be described in detail later, but functionally the test facility is a flat concrete floor with an epoxy coating. It provides three dimensions (two translation directions and yaw) of almost frictionless movement for testing of a vehicle that floats on a cushion of air. For this demonstration, the Large Mobility Base (LMB) was used. The BRS described in section 2 was mounted on the LMB and a static stand. The LMB was maneuvered to the stand and the BRS bolt torqued to the required specifications. The nut separation pyrotechnics were fired and the vehicle movement was measured. However, before any pyrotechnic firing occurred in the FRL, the BRS was safely tested in the PSF.

## 2. X–38 DEORBIT PROPULSION STAGE BOLT RETRACTOR SUBSYSTEM DESIGN

The BRS design is a spring/plunger system. The plunger, attached to the head of the separation bolt, is loaded by a compression spring. Upon activation of the separation bolt, the compressed spring will drive the plunger and the attached separation bolt forcefully across the separation plane. Several factors influenced the design of this system:

- Structural margin of safety requirements
- Bolt retraction time as a function of DPS/lifting body postseparation dynamics
- Expected alignment and tolerances of the lifting body/DPS interface
- Ease of assembly and installation in the DPS
- Existing design of DPS and lifting body.

Some of these factors were not well defined during the design process. For instance, the required bolt retraction time was unknown because a full-separation analysis of the lifting body and DPS had not been performed. Due to the program schedule, an educated guess had to be made as to what an acceptable retraction time might be and then base the design on that.

The basic design parameters of the BRS were as follows:

- Structural safety factors of 1.5 on ultimate and 1 on yield
- Required bolt retraction time of 40 ms
- No interference during mating process of DPS and lifting body
- No interference with any DPS components during installation
- Interface with previously designed DPS and lifting body components, such as threads, longerons, etc.

The resulting design is shown in figure 2.

## 3. TESTING FACILITIES

### 3.1 Pyrotechnic Shock Facility

The PSF is used to perform pyrotechnic tests, shock tests, and pyrotechnic shock tests of both pyrotechnic and nonpyrotechnic systems and components. Personnel working in the facility are certified to handle pyrotechnic components. High-speed data acquisition is available to record up to 1 million samples per second per channel. A 21- by 31- by 18-ft reinforced-concrete explosives test chamber is used to test the systems and components.

For the PSF BRS demonstration, the BRS hardware and test fixtures were bolted on a reaction mass in the test chamber. The configuration of the BRS hardware is shown in figure 2 with the forward interface truss and lifting body longeron held in place by test fixtures. The demonstration setup is shown in figure 3. The test fixtures did not allow joint separation but the BRS was able to fully function by releasing the separation nut for full-separation bolt retraction. The PSF demonstrations did not simulate the X–38 vehicle/DPS separation event. A functional demonstration of the BRS was performed in the PSF to demonstrate that the BRS would function properly without damaging its components and causing a safety hazard in other test areas. The demonstrations also provided a good estimate of the bolt separation timing.

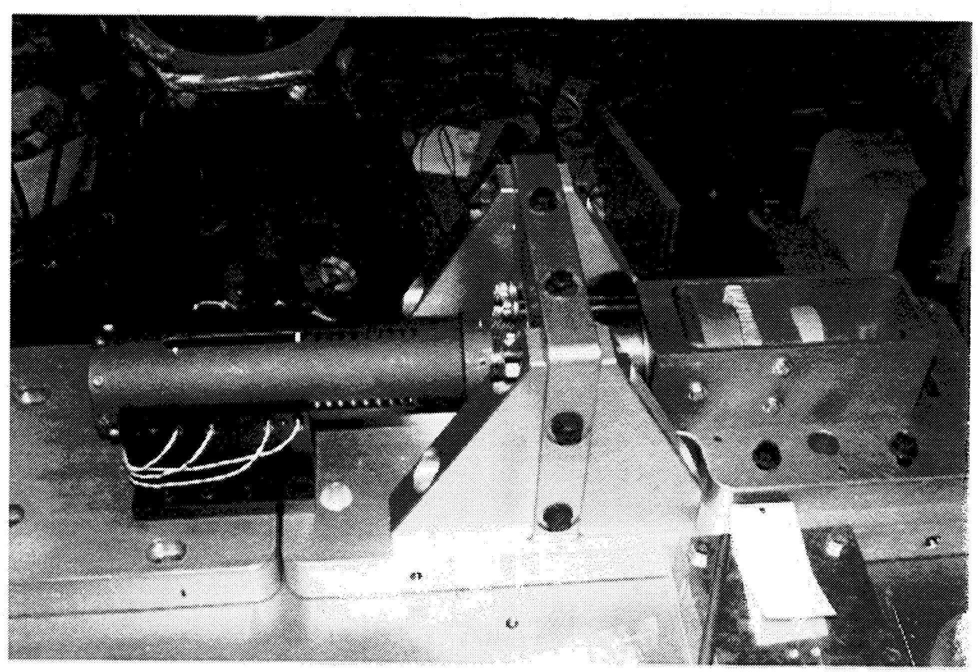

Figure 3. PSF BRS setup.

## 3.2 Flat Floor Facility

A view of the FRL is shown in figure 4. The FRL contains integrated test and simulation capabilities built on developed technologies such as air-bearing floors, servo-drive overhead robotic simulators, precision targets, gimbals, air-bearing mobility units, and manipulator and visual system evaluation facilities. The facility is centered on a 43- by 86-ft precision air-bearing floor, the largest of its kind. Several mobility bases are used as spacecraft simulators on the air-bearing floor. A service area is located adjacent to the flat floor and is used for replenishing of pneumatic and electrical systems on the bases.

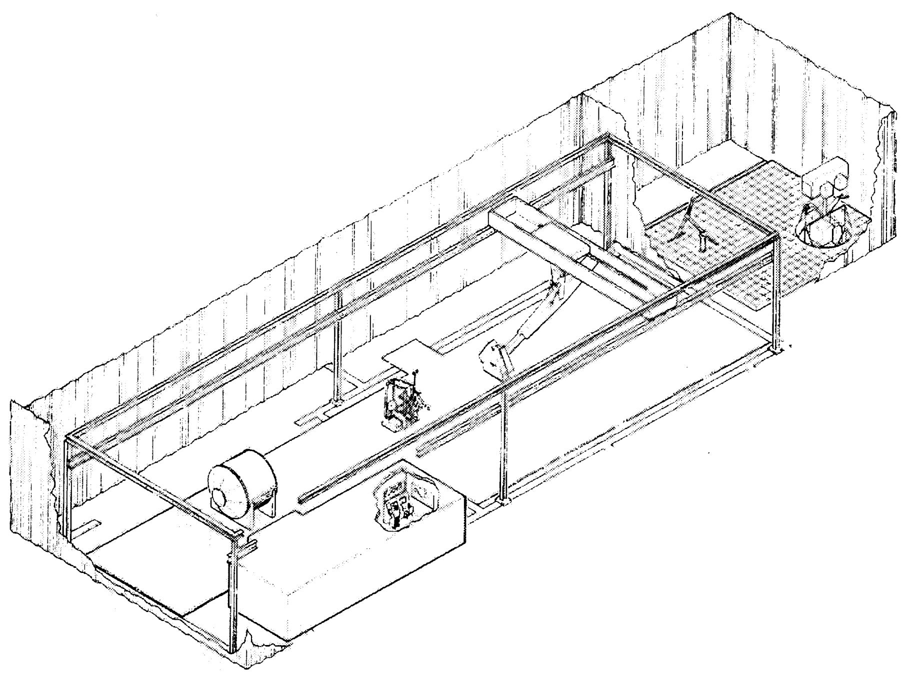

Figure 4. View of MSFC's Flight Robotics Laboratory (bldg. 4619).

## 4. MOBILITY BASES

### 4.1 Large Mobility Base

The function of the LMB is to provide a free-floating vehicle and interface for control system algorithm testing for NASA and its contractors. The large air-bearing mobility simulator acts as an air sled and is "flown" across the air-bearing floor, propelled by air jet thrusters. It has also been used to test docking sensors and mechanisms (fig. 5).

Three air bearings allow the vehicle to float across an epoxy resin floor. The LMB can run either a Windows or Linux operating system and is connected remotely to a local area network. A data acquisition card is used to communicate with all sensors and control the thrusters (fig. 6). Two accelerometers and a gyroscope are mounted in the center of mass to sense both the *X* and *Y* accelerations along with yaw rate. Three laser rangefinders (LRFs) (DME 3000s) are also mounted to provide *X* and *Y* locations along with the yaw of the vehicle.

There are 24 thrusters mounted for movement of the vehicle (fig. 7). This allows the vehicle to move in the $\pm X$, $Y$, and yaw directions. Six air tanks rated at 4,000 psi provide the air for floating and movement. Two banks of batteries each rated at 24 V provide power. One bank is used for dc power while the other is used to operate an ac converter. The ac converter provides 110 V ac power. For the BRS, two 4- by 4-in steel beams were mounted to give the vehicle some rigidity for attaching the BRS apparatus and for reacting to the separation forces.

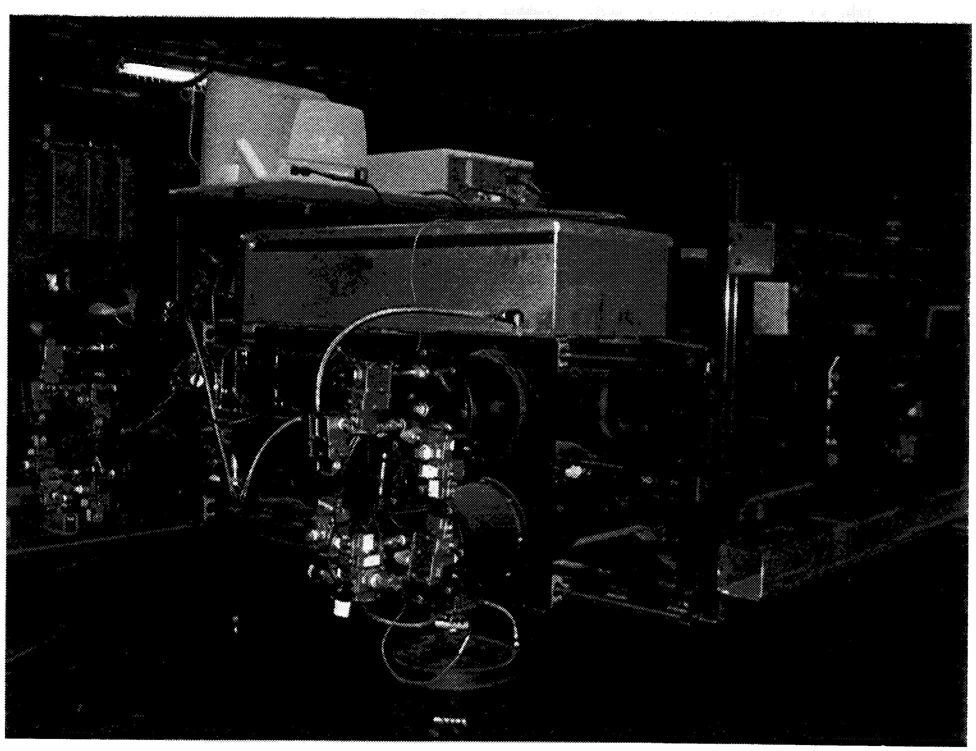

Figure 5. Large Mobility Base.

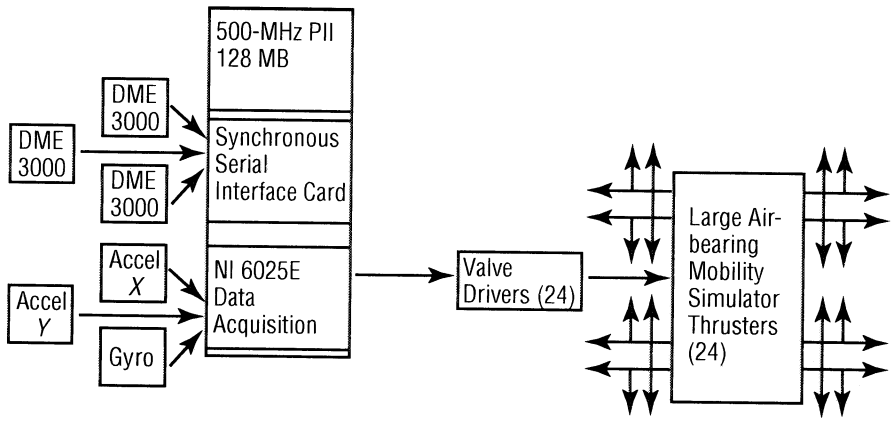


Figure 6. LMB interfaces.

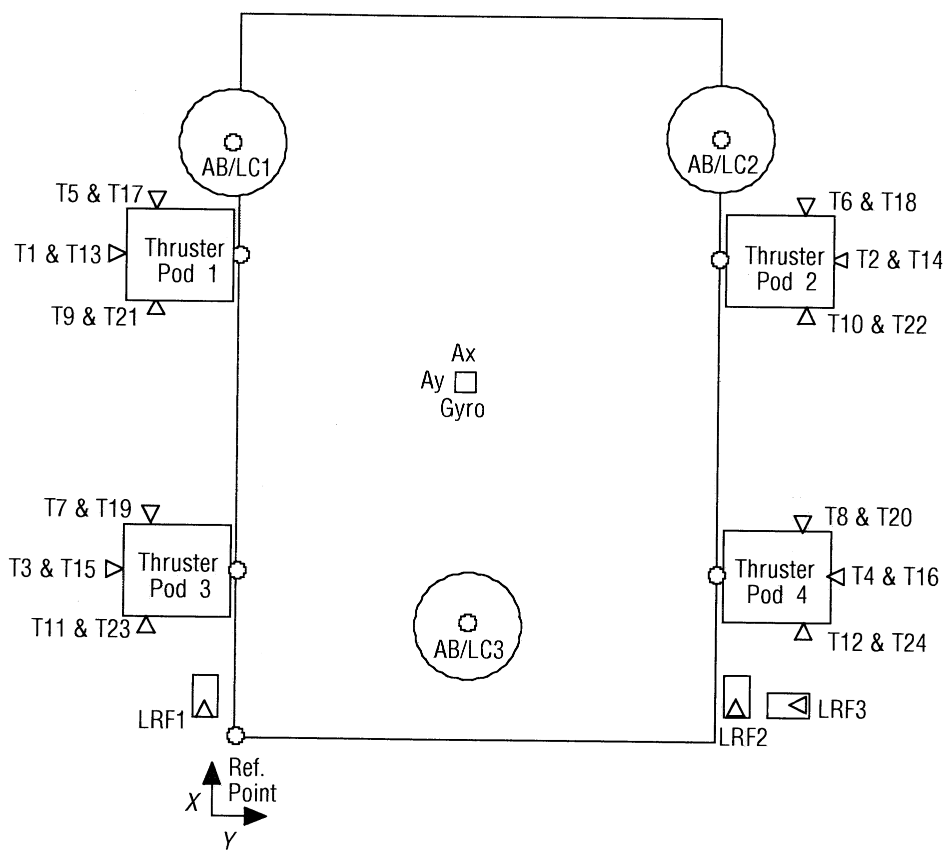


Figure 7. LMB schematic. T is thruster, AB is air bearing, LC is load cell, LRF is laser rangefinder, and Ax and Ay are accelerometers in the $X$ and $-Y$ directions.

### 4.2 Small Mobility Base

The Small Mobility Base (SMB) is similar to the LMB but the shape is triangular and, as the name implies, is smaller than the LMB. The SMB also has one bank of batteries and fewer thrusters than the LMB. The SMB could be used with the LMB for a two-body docking/separation test.

## 5. INTERFACE HARDWARE

### 5.1 Standoffs

LMB misalignment relative to the stationary base could impact proper assembly or performance of the BRS. In addition, misalignment could cause a moment about the center vertical axis of the LMB. Therefore, two threaded rods with crush nuts were used to control the distance between the LMB and stationary base and make them parallel (fig. 8).

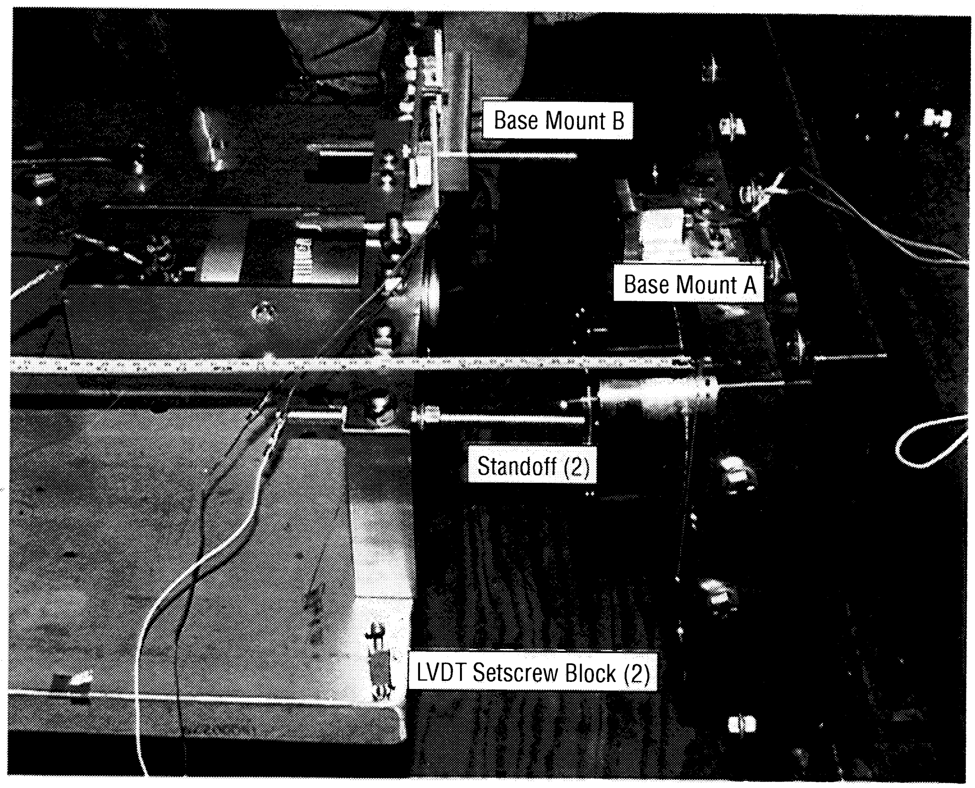


Figure 8. Interface hardware.

### 5.2 Large Mobility Base Balancing

The center of mass of the LMB needed to be centered on the vehicle as well as the long axis of the BRS so as to not cause a moment about the center vertical axis of the LMB. The LMB is equipped with a mass scale above each air bearing, allowing accurate centering of mass by placing lead weights at different points along the substructure.

### 5.3 Pyrotechnic Initiation/Pin-Pull Mount

Proper recording of the precise moment the bolt separation device activated was needed for subsequent data analysis. Since the data acquisition system was on the LMB and the pyrotechnic device was stationary, a method was needed for the firing signal to cross the interface without impacting the LMB's ability to free-float. The solution was to use a light-emitting diode (LED) and phototransistor as described in section 10. The LMB mount contained the phototransistor while the LED was in the base (figs. 8–10). The LED was contained in a two-piece mounting bracket that was created when base mounts A and B were connected with fasteners and compressed on the base bracket. Alignment pins were used in a set of match-drilled holes, providing positive alignment for the light beam.

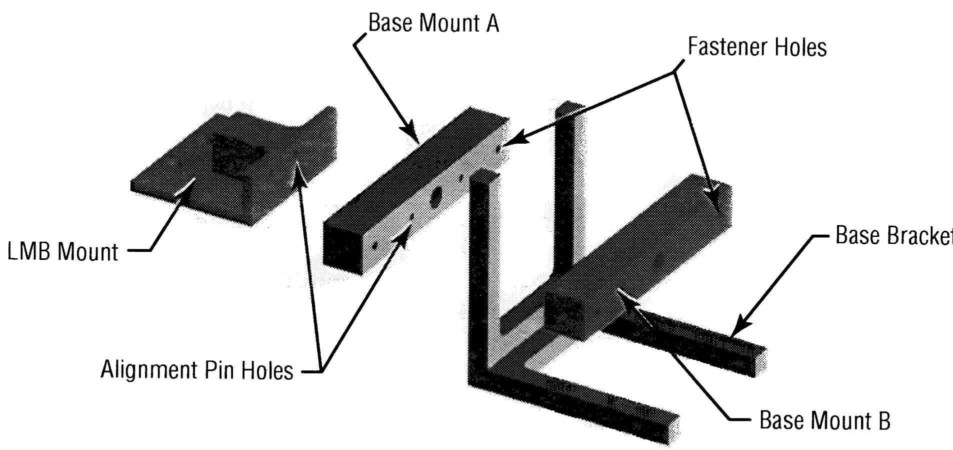


Figure 9. Mounts and alignment holes.

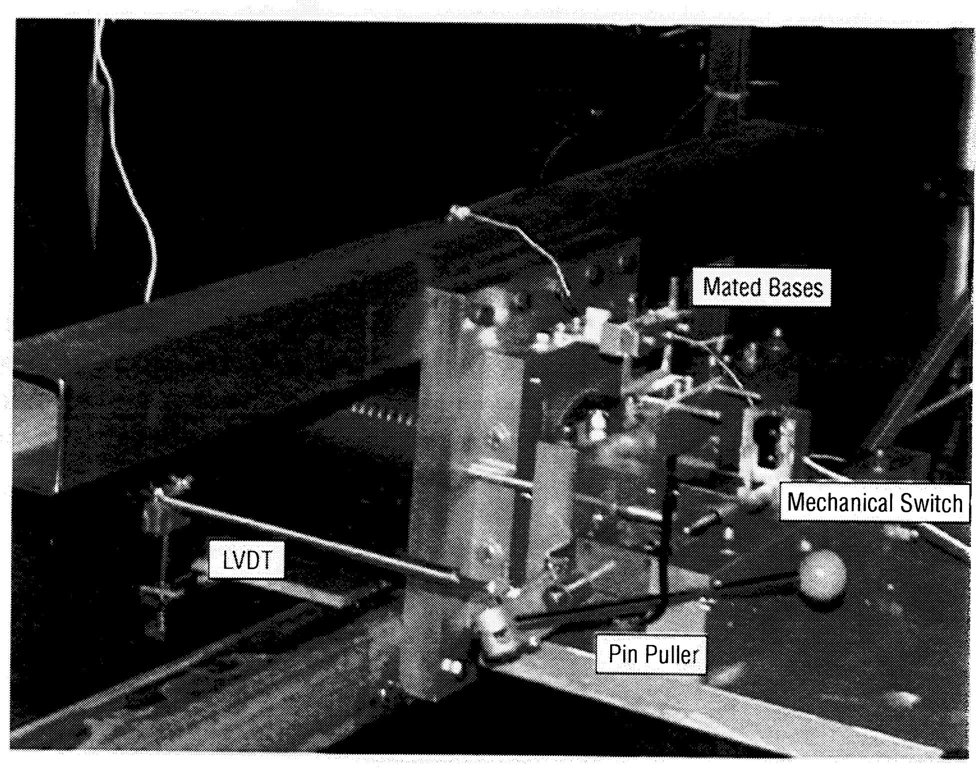


Figure 10. Interface hardware (pin-pull setup).

## 5.4 Linear Variable Displacement Transformer Mounts

Two linear variable displacement transformers (LVDTs) were to be used for measuring the distance the LMB moved from the stationary base. Being faster and more accurate, they would have served as the primary system and the LRFs would have been a backup system. The LVDTs consisted of a large cylinder into which a smaller cylinder was inserted. As the LMB moved after firing, the smaller cylinder would slide from the larger cylinder and generate a proportional electrical signal. Mounting was achieved using a V-block and setscrew block. Both blocks were placed on a smooth cylinder that screwed into a baseplate. This allowed smooth rotation of the blocks if needed during vehicle movement (fig. 11). A data logger failure prevented using the LVDTs.

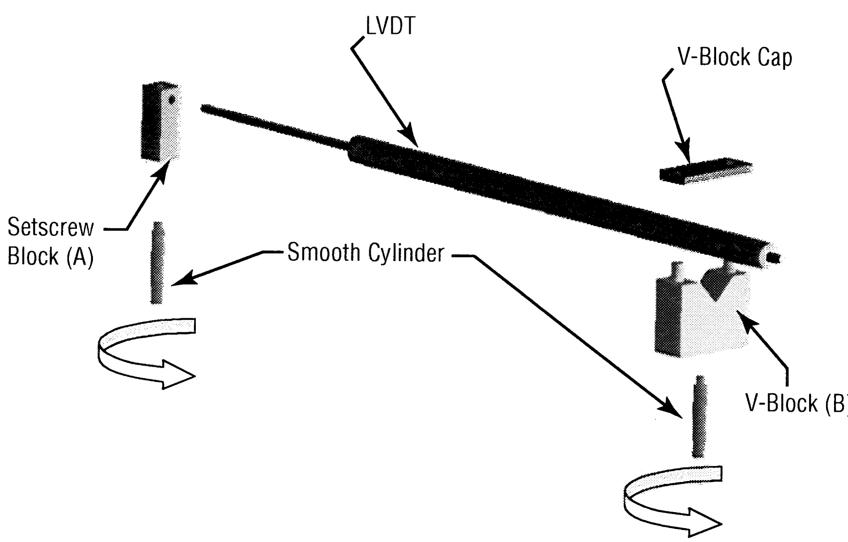


Figure 11. Blocks and LVDT.

## 5.5 Pin-Puller

A pin-pull test was used to verify the ability of the LMB and flat floor facility to run the pyrotechnic demonstration. The pin-pull system used the identical BRS interface except for a hole in the BRS bolt perpendicular to its main axis that allowed a pin to lock the bolt in place for preloading. Once the BRS was installed, the pin was pulled from the hole, allowing the bolt to release (fig. 10).

## 6. PHOTOGRAPHIC TEST DATA

### 6.1 High-Speed Film Cameras

Two high-speed film cameras recorded the separation event in the PSF with a rate of 400 frames per second (fps). The first camera recorded the plunger/separation bolt retraction as viewed through the slots in the cylinder of the BRS. A painted white stripe on the plunger gave contrast between components. The second camera recorded the movement of the separation nut. One 400-fps camera recorded the separation event in the FRL. The camera recorded the plunger/separation bolt retraction as viewed through the slots in the cylinder of the BRS and showed the separation of the LMB.

The camera viewing the plunger showed that the retraction time from separation to interface crossing was ≈20 ms for the separations in the PSF and FRL. Figure 12 shows the plunger at rest in the FRL, one frame before plunger movement. Figure 13 shows the plunger at the white mark that represents the end of the bolt clearing the joint interface. In figure 14, the cylinder and surrounding fixtures are shown as they moved through the camera's field of view. The second camera in the PSF showed little movement in the separation nut upon separation.

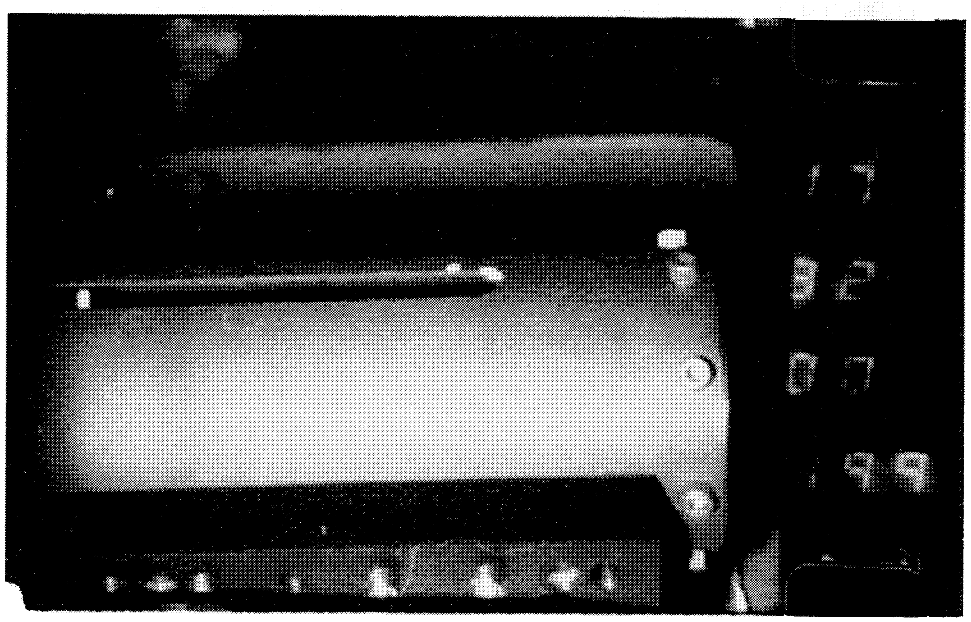

Figure 12. Pyrotechnic fired: time = 99 ms.

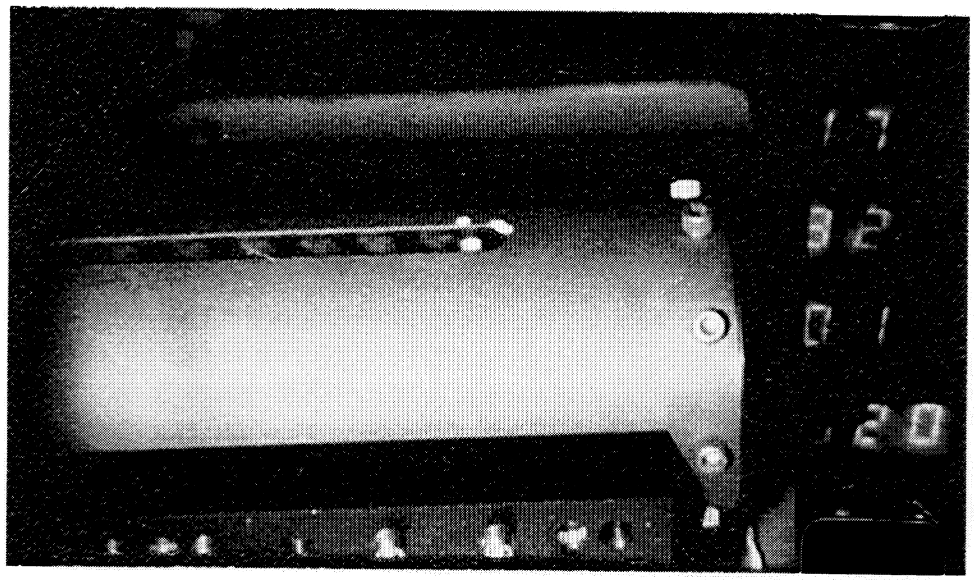

Figure 13.  Bolt has cleared: time = 120 ms.

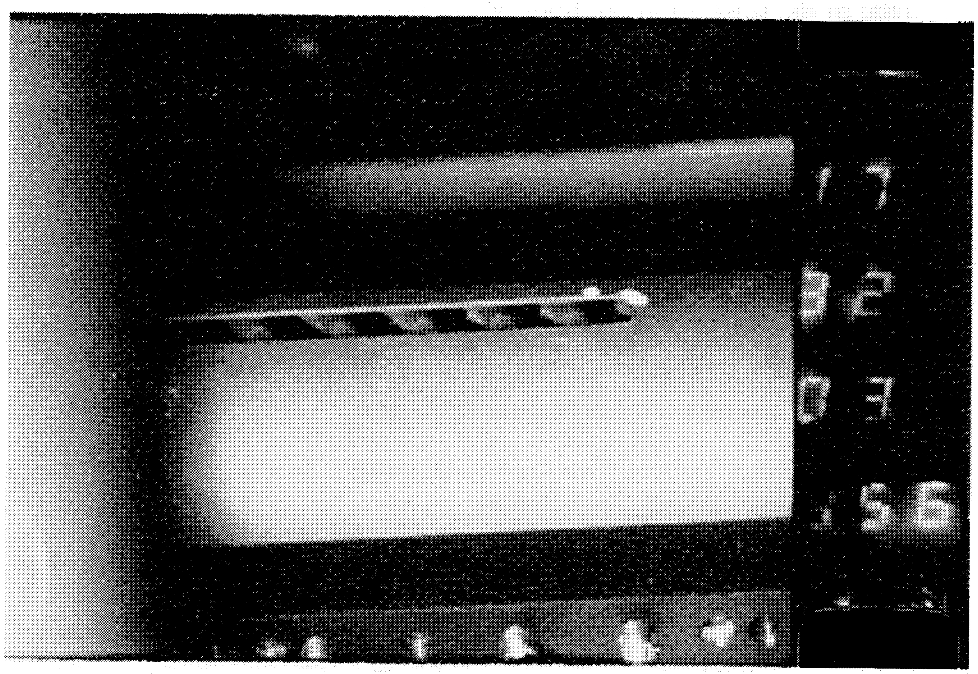

Figure 14.  Shows movement of cylinder and LMB: time = 3 s, 156 ms.

### 6.2 High-Speed Digital Camera

One high-speed digital camera recorded the separation event in the PSF and FRL with a frame rate of 500 fps. The camera recorded the plunger/separation bolt retraction, as viewed through the slots in the BRS cylinder. This camera also showed that the retraction time was ≈20 ms in the PSF and FRL demonstrations. Figure 15 shows the FRL demonstration one frame before plunger movement. Figure 16 displays the plunger at the white mark that represents the end of the bolt clearing the joint interface, 10 frames after figure 15. In figure 17, the cylinder and surrounding fixtures are shown as they moved through the camera's field of view, 400 frames after figure 15.

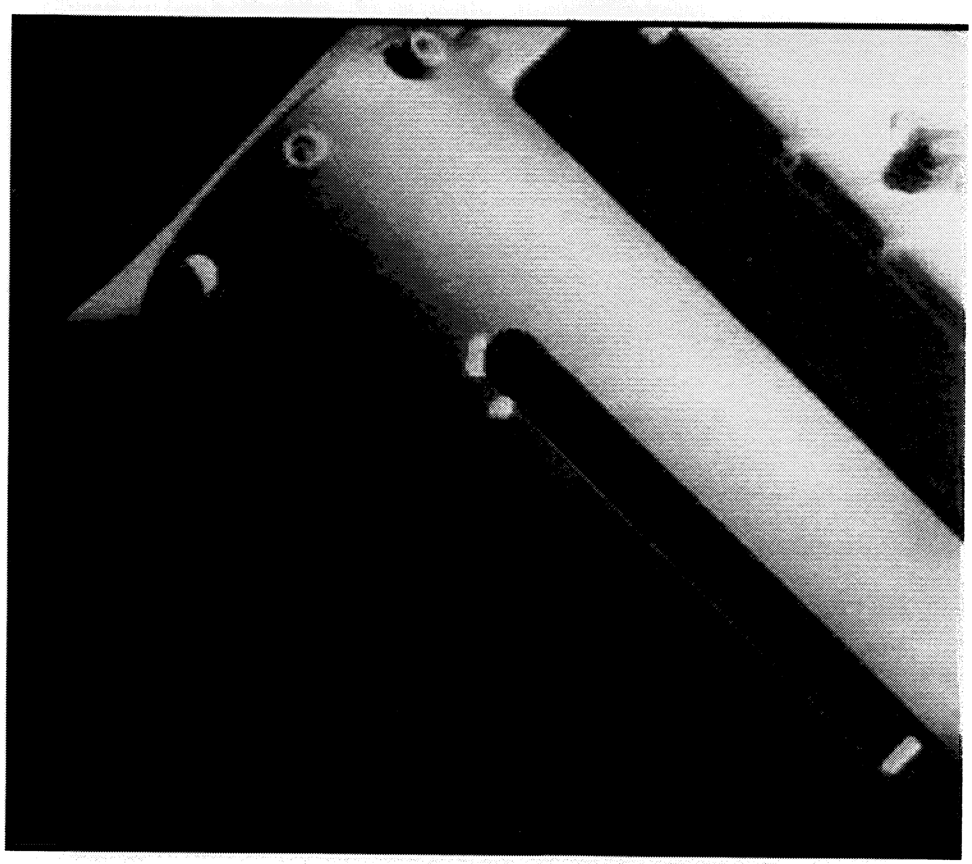

Figure 15. Test start.

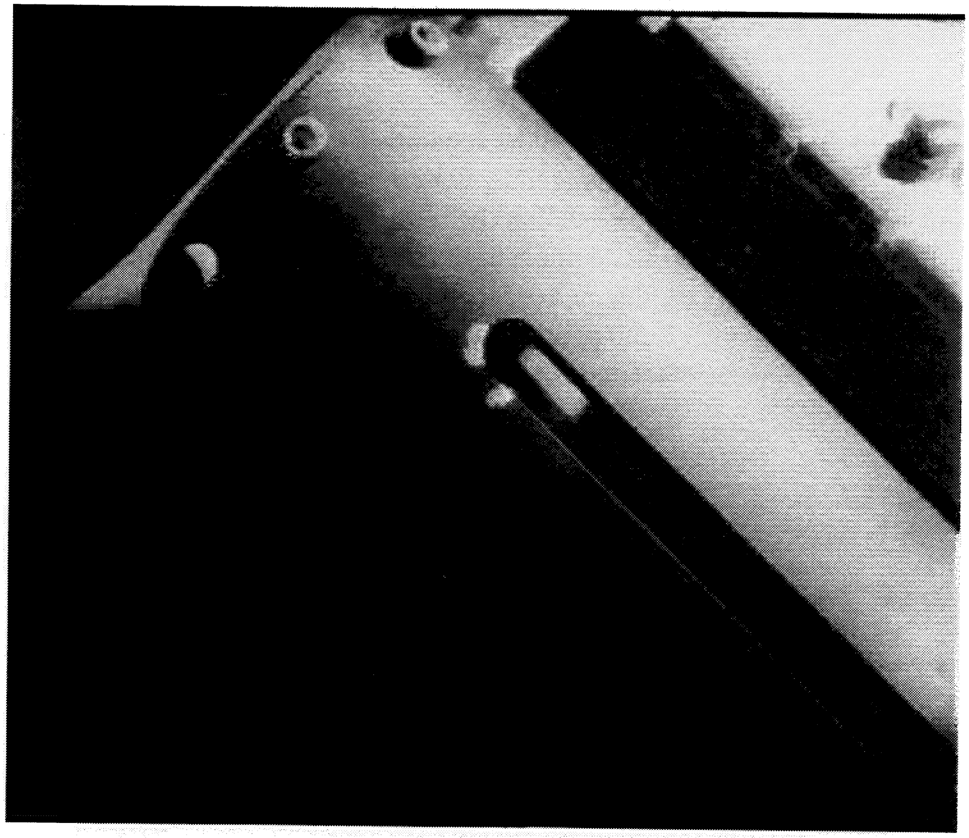

Figure 16. Bolt crossing interface plane.

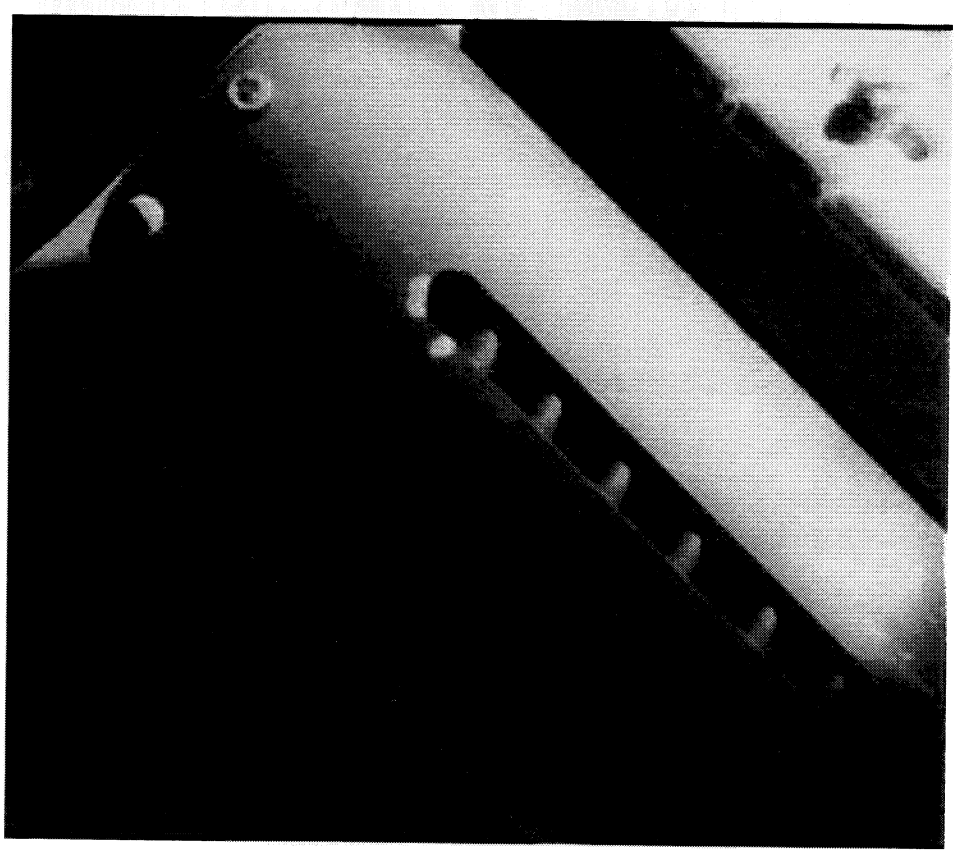

Figure 17. Cylinder movement.

## 7. BOLT TIMING SYSTEM

A timing system was designed and built to measure the timing of the plunger in the BRS without physical contact. The system uses four infrared LED light sources and sensors mounted in an aluminum frame. The frame held the LED and sensor firmly in place, with the distance from the first to the last sensor being the same as from the installed end of the bolt to the interface plane. The LED output is reduced through a small hole in the frame to reduce crosstalk to the next sensor. The input to the sensor also passed through a small hole to improve accuracy and to reduce crosstalk. The LED and sensor types were a cost-efficient, quick solution that also met thermal vacuum environment requirements. A possible improvement to this system is suggested in section 10.

The timing system is mounted under the BRS cylinder and the LED light passes through two slots in the cylinder and in front of the plunger. The frame is adjusted so that the output is slightly reduced at the first sensor output. This is done so that the first initial movement can be detected. Upon separation, the first sensor output triggers a data acquisition system that records the output of the four sensors. Time constraints and a recorder failure limited the use of the uncalibrated timing system to the PSF. The timing system results show the same separation time of ≈20 ms that the camera results show. Figure 18 shows the data obtained during the pin-pull demonstration in the PSF.

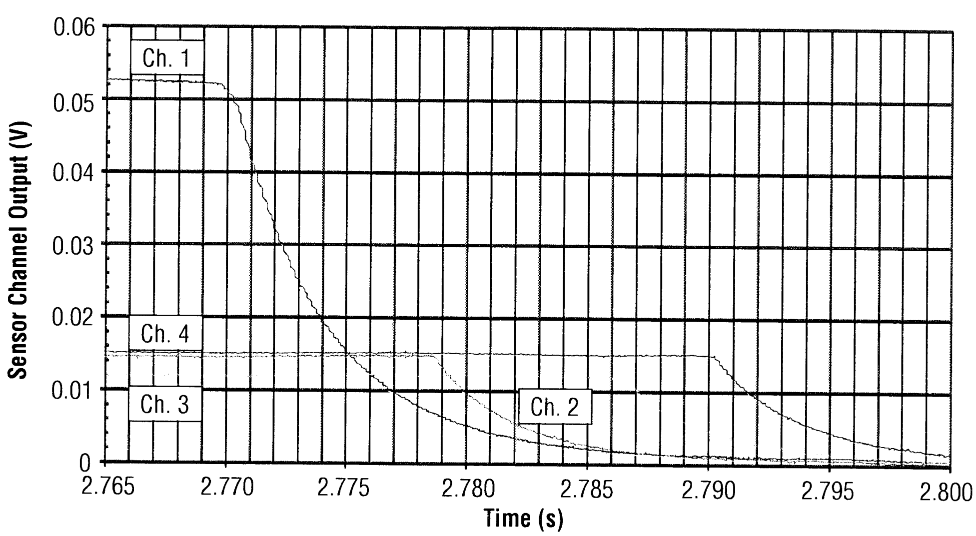


Figure 18. X–38 pin-pull demo in PSF on 10/2/01.

## 8. LASER RANGEFINDERS

The LMB is equipped with three LRFs: two in the *X* direction and one in the *Y* direction. The LRFs reflect from a special tape on the border of the flat floor. No movement was observed in the *Y* direction or yaw. Figure 19 shows the X2 LRF data. The plot shows a start point and movement away, gradually slowing (decelerating). A detonation circuit sensed the pyrotechnic fire command. This circuit was used to help determine the start time (point 606 in the data or 27,860.4 ms).

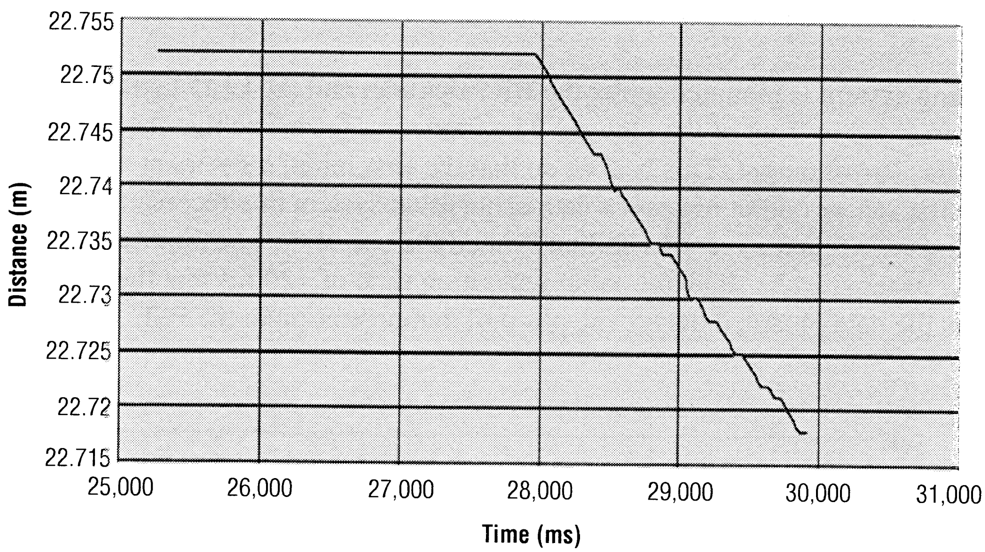


Figure 19. X2 laser rangefinder.

## 9. ACCELEROMETERS

The accelerometer data (fig. 20) were run through a digital Butterworth filter using National Instruments Corporation's LabVIEW™ in order to separate the rigid body acceleration from the pyrotechnic shock and airflow vibration. Using this low-pass filter with a 0.25-Hz cutoff, the peak solid body acceleration seen was 0.015 Gs (fig. 21). Differentiating the position data twice gave an acceleration of 0.0094 Gs (fig. 22). Therefore, using an average of 0.01 Gs, the spacecraft saw a peak acceleration of ≈0.1 m/s$^2$. (Please note the sign of the peak is different because of sensor orientation, as shown in fig. 7.) Peak velocity derived from position data was 0.02 m/s. Drag from the atmosphere and floor as well as air-bearing thrust contributed to the deceleration.

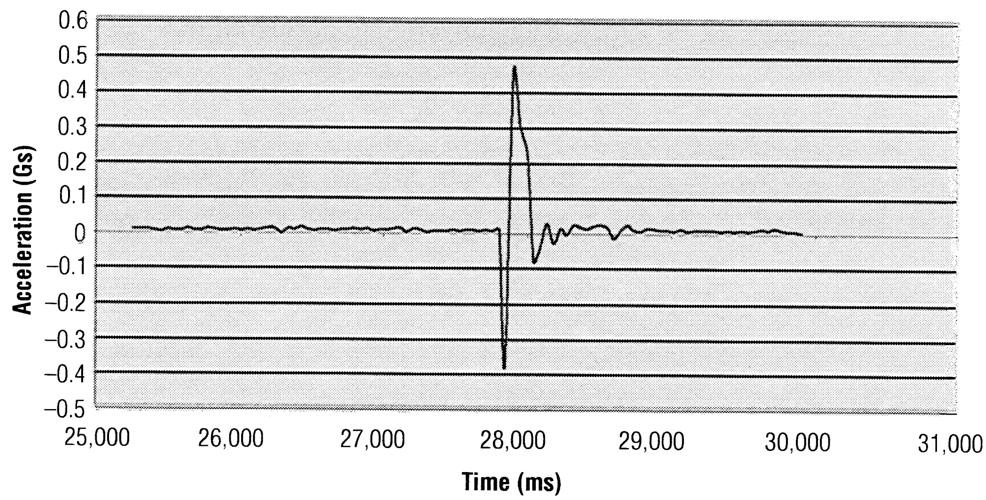


Figure 20. Accelerometer $X$.

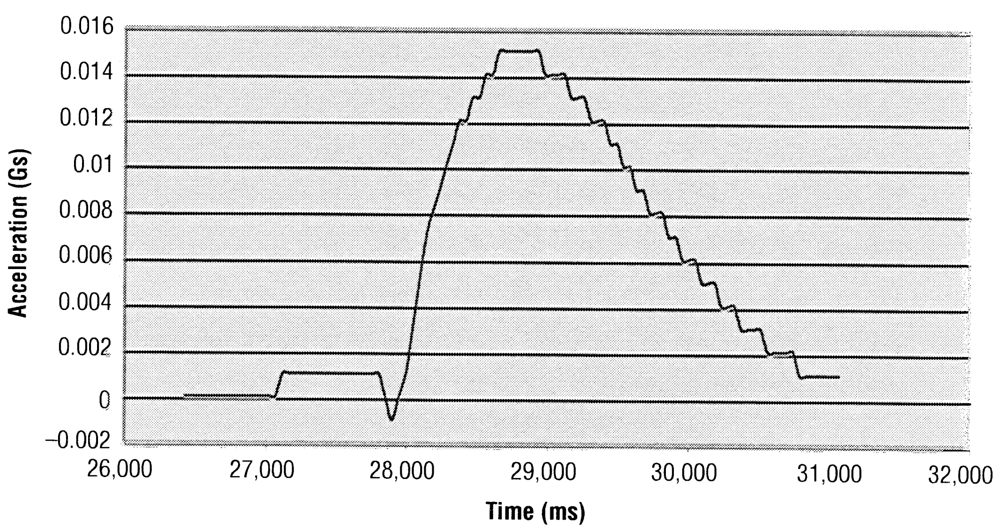


Figure 21. Butterworth filter (0.25-Hz cutoff).

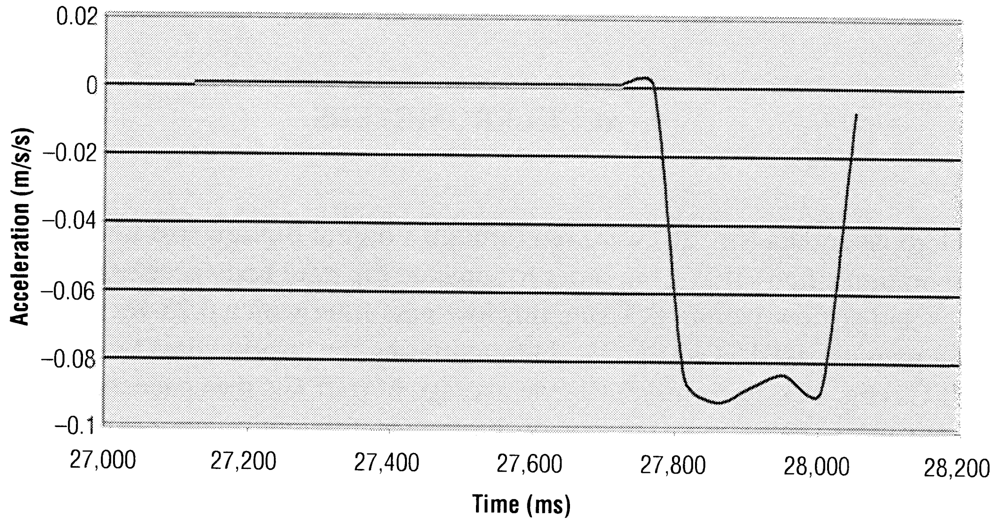


Figure 22. Position data converted to acceleration.

## 10. PYROTECHNIC INITIATION TIMING SYSTEM

One important part of the BRS data acquisition was to time-stamp the actual firing of the pyrotechnic and the pulling of the pin during the pin-pull test. This was done using an infrared-emitting diode and a phototransistor (fig. 23). In the pyrotechnic firing, the emitting diode was connected to the pyrotechnic switchbox in parallel with the pyrotechnics. Once the pyrotechnic is fired, the emitting diode is turned on and is detected by the phototransistor. The phototransistor, located on the LMB, is sensed using the onboard data acquisition card and time-stamped.

Timing for the pin-pull test is similar to the pyrotechnic firing. Instead of using a switchbox, a mechanical switch is placed behind the bolt (fig. 10). Once the pin is pulled, the switch turns on as the bolt retracts. The emitting diode and the circuit works in the same manner as the pyrotechnic firing.

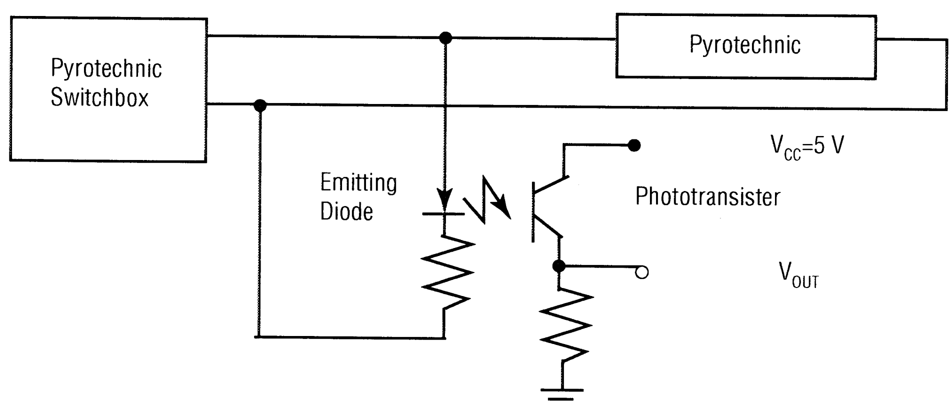


Figure 23. LMB data synchronizer.

## 11. ANALYSIS OF FORCE IMPACT

Since these demonstrations were performed quickly due to program cost and schedule constraints, the force distribution between the joint components could not be precisely determined. However, visual inspection of video taken during the demonstrations showed that motion occurred several picture frames after the plunger/bolt mass impacted the honeycomb at the end of the bolt retractor cylinder. In other words, the authors felt stored spring energy was the largest contributor to the motion experienced by the mobility base and not joint energy.

## 12. ANALYSIS OF SPRING DYNAMICS AND BOLT RETRACTION TIME

The bolt retractor spring was designed to retract the separation bolt across the lifting body/DPS interface plane in a time of 0.020 s after activation of the pyrotechnic release nut. The spring, with a nominal diameter of 3.355 in, was designed at MSFC and built by Leeco Spring International, Houston, TX.

Neglecting friction, the idealized equation for a spring-mass system, such as that used in the BRS, is

$$m\frac{d^2x}{dt^2}+kx=0 \ , \tag{1}$$

where $m$ is the mass of the bolt/plunger/washer assembly, $k$ is the spring stiffness, and $x$ is the displacement of the bolt/plunger/washer assembly from the spring's free length. The solution of this differential equation is well known and is

$$x = x_0 \cos \omega t$$

$$\omega = \sqrt{\frac{k}{m}} \ , \tag{2}$$

where $t$ is time and $\omega$ is the natural frequency. Since $x$ is defined from the free length position of the spring and the spring is initially compressed before bolt retractor activation, the initial displacement is $x_0$. In the BRS that was demonstrated, $x_0$ was 5 in.

The distance that the bolt/plunger/washer assembly needed to travel to clear the interface plane was 4.189 in. This means that

$$x_{ic} = x_0 - 4.189 = 0.811 \text{ in} \ , \tag{3}$$

where $x_{ic}$ is the displacement of the spring from its free length at the point of interface crossing. The time of interface crossing, $\tau_{ic}$, is calculated by substituting $x_{ic}$ for $x$ in equation (2):

$$x_{ic} = x_0 \cos \omega \tau_{ic} \tag{4}$$

The equation for calculating $\tau_{ic}$ thus becomes

$$\tau_{ic} = \frac{1}{\omega}\cos^{-1}\left(\frac{x_{ic}}{x_0}\right) . \tag{5}$$

The BRS spring had the following values: $k$ = 85.05 lbf/in and $m$ = 5.152 lbf/386.4 in/s$^2$. Substituting these values into equations (2) and (5), the time to cross the interface becomes $\tau_{ic}$ = 0.018 s.

## 13. BOLT RETRACTOR SUBSYSTEM RESULTS

The X–38 BRS demonstrations tentatively proved that the BRS design was viable for its intended use as part of the X–38 separation system. The design goal bolt retraction time of 40 ms was exceeded by a factor of 2 (average of 20 ms) for all the demonstrations. Project engineers were concerned that friction, tolerances, and other factors unaccounted for in the analysis would add considerably to the theoretical retraction time. As it turned out, the retraction times were within 2 ms of the theoretical values. This significantly increased confidence that the design would perform as intended in the space environment.

It must be emphasized once again that these demonstrations did not qualify the BRS hardware for flight. To do so would require more stringent data acquisition and data collection than occurred during the demonstration.

## 14. FLIGHT ROBOTICS LABORATORY RESULTS

The X–38 BRS demonstration proves the FRL is suitable for doing these kinds of tests. Possibly a second air-bearing vehicle, such as the SMB currently used in the FRL, could be used instead of a static stand; then, an actual two-body separation could be tested. Either the SMB or the LMB can be weighted differently to simulate actual weight differences in the spacecraft.

Any separation mechanism needs to be safe for the FRL personnel and facilities. The BRS, both pyrotechnic and pin-puller, was tested in the PSF. Once a device has been proven safe, the FRL can be used.

## 15. CONCLUSIONS

The demonstration was a success and the BRS worked as anticipated. The FRL showed its capability to perform vehicle separation testing. A summary of the pyrotechnic firing results is shown in table 1. Obviously the time and budget limitations did not allow a complete set of data to be acquired. A data logger failure prevented the use of LVDTs. In an actual test, using them may have shown a slight displacement from initial release of joint energy that could not be seen with the cameras and a different speed for each of the displacements (joint versus the bolt impact). In a rigorous test schedule, multiple runs with different bolt tensions would have been recorded and compared. Some of the lessons learned include the following: (1) Soft-mounting the accelerometers would have filtered out the higher frequency vibrations from both pyrotechnic shock and tank air flow and reduced the posttest data processing; and (2) while the bolt timing system provided the bolt retraction time, a fiber optic laser/sensor arrangement would have provided more accurate and reliable timing data; i.e., a sharper rolloff may have been visible in figure 18.

Table 1. FRL pyrotechnic firing results.

| | |
|---|---|
| Time for bolt to clear | 20 ms |
| Bolt torque | 1,100 ft-lb |
| Honeycomb crush depth | 0.52 in |
| LMB weight | 3,795 lb |
| LMB peak acceleration | 0.1 m/s$^2$ |
| LMB peak velocity | 0.02 m/s |
| Primary force contributor | Stored spring energy |

## APPENDIX—AUTHOR BIOGRAPHIES

A.S. (Nick) Johnston works on the Orbital Simulation Team at NASA Marshall Space Flight Center, Huntsville, AL. He has a B.E.E. from Auburn University and an M.S. in physics from The University of Alabama at Huntsville. His current interests are control algorithms for the LMB and verification testing of the Advanced Video Guidance Sensor using the Sensor Optical Calibration Robot.

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**13. ABSTRACT** *(Maximum 200 words)*

The Flight Robotics Laboratory (FRL) successfully demonstrated the X–38 bolt retractor subsystem (BRS). The BRS design was proven safe by testing in the Pyrotechnic Shock Facility (PSF) before being demonstrated in the FRL. This Technical Memorandum describes the BRS, FRL, PSF, and interface hardware. Bolt retraction time, spacecraft simulator acceleration, and a force analysis are also presented. The purpose of the demonstration was to show the FRL capability for spacecraft separation testing using pyrotechnics. Although a formal test was not performed due to schedule and budget constraints, the data will show that the BRS is a successful design concept and the FRL is suitable for future separation tests.

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