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Flow Research Report No. 483

REMOTE TRACK TAPERING
FINAL REPORT

P.D. Bondurant
J. L. Doyle
J. C. Hake

August 1989

Prepared for
ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE BASE, TN 37389
Under Contract No. F40600-88-C0005

Distribution Unlimited;
Approved for Public Release

FLOW RESEARCH, INC.
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Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188

1a. REPORT SECURITY CLASSIFICATION
Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Distribution unlimited.
Approved for Public Release

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
Flow Research Report No. 483

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
Flow Research, Inc.

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
21414 - 68th Avenue South
Kent, WA 98032

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
U. S. Air Force

8b. OFFICE SYMBOL *(If applicable)*
AEDC/PKP

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
F40600-88-C0005

8c. ADDRESS *(City, State, and ZIP Code)*
Arnold AFB, TN 37389-5000

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.

11. TITLE *(Include Security Classification)*
REMOTE TRACK TAPERING (u)

12. PERSONAL AUTHOR(S)
P.D. Bondurant, J.L. Doyle, J.C. Hake

13a. TYPE OF REPORT
Final

13b. TIME COVERED
FROM 9/88 TO 5/89

14. DATE OF REPORT *(Year, Month, Day)*
August 1989

15. PAGE COUNT
22

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*
Remote, programmable, electro-mechanical actuator, Bitbus, inspection, cost-effective

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Projectile models are tested at Arnold Engineering Development Center's 880 foot-long G-Range test track, at speeds up to 20,000 feet per second. Under certain circumstances, it is desirable to taper portions of the track to compensate for wear on the models. By doing so, the models are prevented from "skipping" from side-to-side. Current track tapering methods require operators to manually adjust each track section, one rail at a time. This method is time-consuming and labor-intensive. A Phase I SBIR project was conducted to determinate the feasibility of developing a remotely-operable track tapering system to quickly and accurately adjust up to 80 separate rails. The study resulted in the design, fabrication and demonstration of a stable and repeatable prototype electro-mechanical actuator. A conceptual design has been developed that includes a control system and associated local area network. The system will be programmable to allow several possible taper angles over a distance of 200 feet. The successful completion of a Phase I feasibility study has laid the groundwork for a Phase II effort to develop a fully-functional track tapering system. A remotely-controllable track tapering system will significantly improve efficiency and reduce operating costs of G-Range.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL
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22c. OFFICE SYMBOL
AEDC/DOTR

DD Form 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

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INTRODUCTION

Projectile models are tested at Arnold Engineering Development Center's 880-foot-long G-Range hypervelocity test track at speeds up to 20,000 feet per second. The track is composed of four radially oriented rails which are housed in a cylindrical tube (Figure 1). Under certain circumstances it is desirable to taper portions of the track to compensate for wear on models. The tapering process prevents models from "skipping" from side to side. Currently, a significant level of effort is required to manually adjust each track section. Each individual rail must be shimmed to the prescribed position and then checked to assure that it has been properly aligned. This process is very time-consuming and costly.

A Phase I Small Business Innovative Research (SBIR) program was awarded to Flow Research to investigate the feasibility of remotely and quickly tapering the last 200 feet of the test track. The following report summarizes the work carried out during this program.

PHASE I OBJECTIVES

As outlined in the Phase I proposal, a system was envisaged that would allow operators to accurately control the adjustment of the track taper from a remote site, preferably the computer station that is currently being used to operate the Long Tube Inspection System (LTIS). To accomplish this, the program to develop such a system would require three principal activities: system control, rail positioning, and rail position verification.

The statement of work in the original SBIR solicitation indicated that certain unique considerations must be taken into account during a feasibility study:

- o Only the last 200 feet of track will be tapered during the first phase of the project. The system should, however, be expandable to allow tapering of the entire length of the track.
- o The track centerline must be maintained straight to within +/- 0.005 in./ft. No kinks or sharp edges between rails would be allowable.
- o The track can be swung into a side storage box at the side of the vacuum tank during free-flight tests.
- o The vacuum tank can be evacuated to 0.1 torr and pressurized to 1300 torr.
- o It is preferable to modify track sections versus replacement with new sections.

With these considerations in-mind, FLOW began the Phase I feasibility study to develop a remote track tapering system.

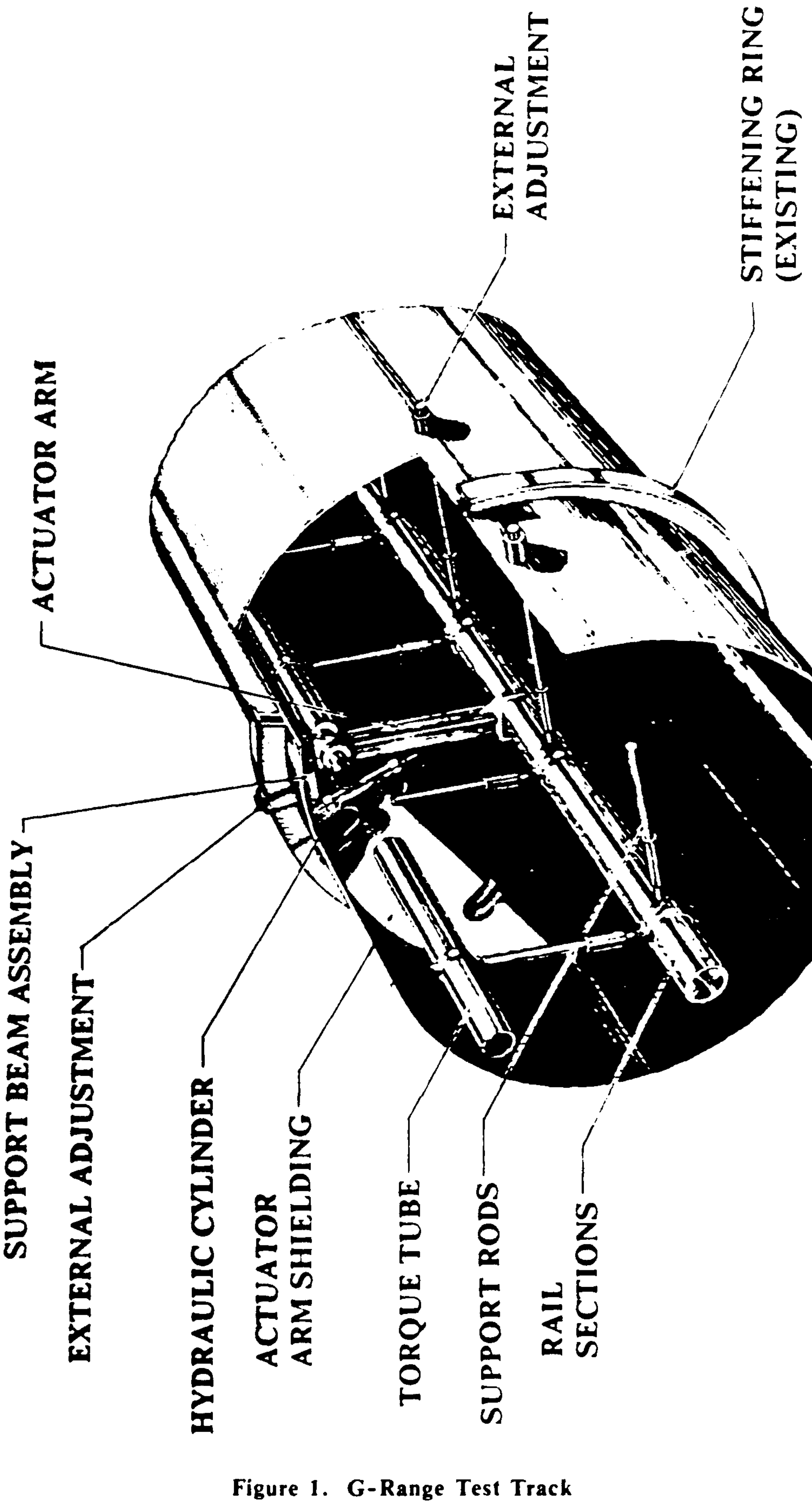


Figure 1. G-Range Test Track

PHASE I WORK

The project was broken into four subtasks:

- Task 1 - System Requirements
- Task 2 - Conceptual Design
- Task 3 - Laboratory Mock-up Tests
- Task 4 - Reporting and Communication

The following is a summary of each activity.

Task 1 - System Requirements

The first phase of the project was devoted to obtaining a clear understanding of the problems inherent to the track tapering process. During a visit to G-Range, FLOW technical staff were able to examine the track and discuss the process with range operations personnel. The result was the development of the following set of technical goals.

Compatibility

The remote track tapering system must be compatible with the existing Long Tube Inspection System (Figure 2) and if necessary, the Track Straightness Measurement System (currently under development). As a result, the cost of the system will be reduced by taking advantage of the existing computer and other systems. For example, the control computer already in place for the LTIS can be used to control the remote track tapering system. In addition, the Remote Inspection Vehicle used by the LTIS contains four linear variable differential transducers (LVDTs). By modifying the analysis and display software, the LTIS could be used to verify the position of the rails after adjustment.

Modularity

The greatest advantage of making the system modular will be realized during system repair and maintenance. The track environment is extremely hostile. It would be impractical to harden the actuator modules against high-speed model fragments. Although the modules will be located on parts of the track that are fairly well protected, they will occasionally be damaged by flying debris. A design that allows quick and simple replacement, adjustment and calibration of system components will be most useful and cost-effective for range personnel.

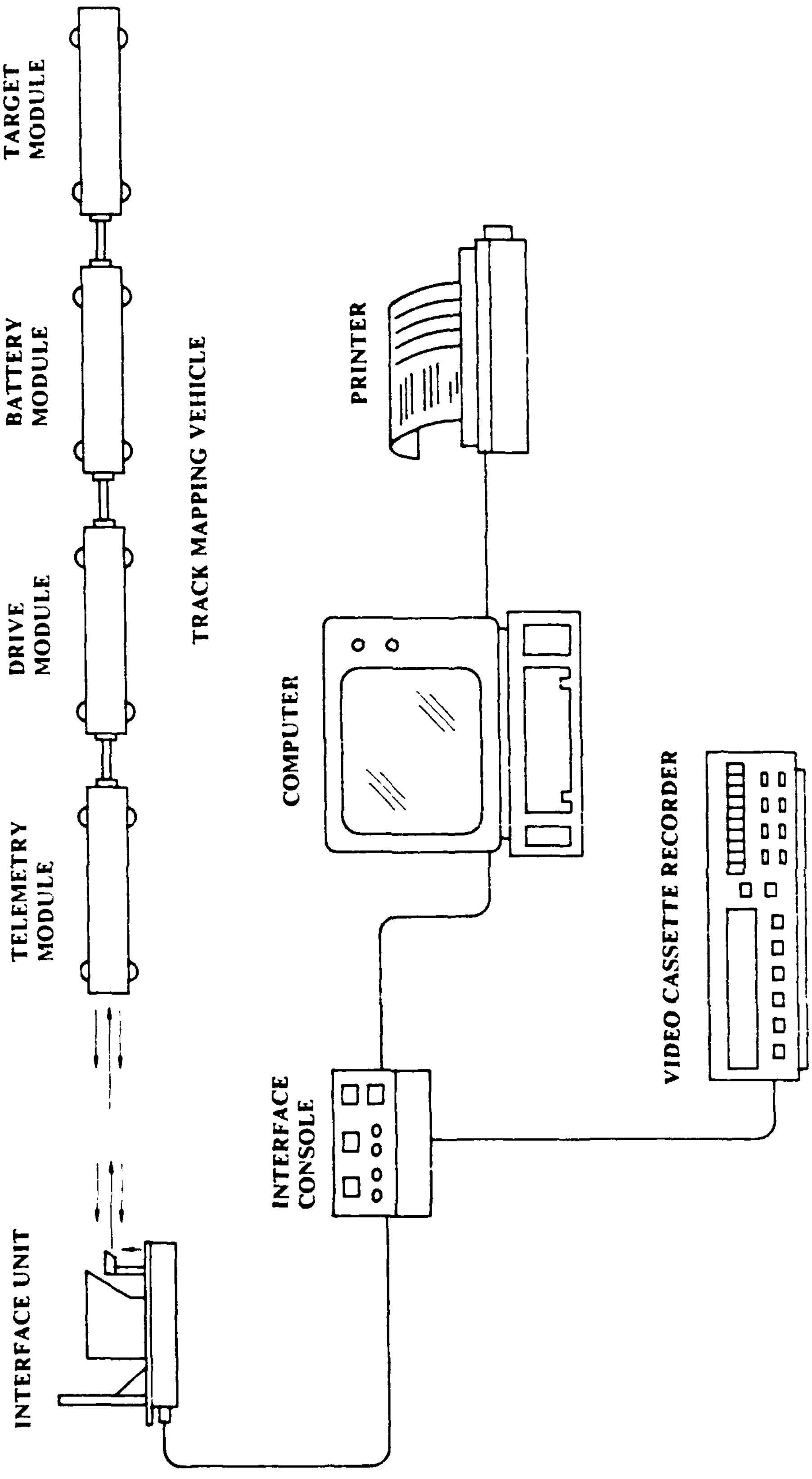


Figure 2. Long Tube Inspection System

Rugged and Stable

As stated above, the G-Range test track is a very hostile environment. All subsystems will be subject to shock, dust and large pressure variations. It is not known how much force the models impart to the rails as they pass. Although the components cannot be made "bomb-proof," they will be expected to provide dependable operation in this harsh environment. The system must be capable of solidly positioning the rails and maintaining stability as the model passes.

Accurate and Repeatable

Each rail actuator will be expected to operate over a distance of 0.100 inch and provide a taper of 0.005 inch over a distance of ten feet. If a down-range track section extends above its up-range counterpart, a model failure will occur. It is therefore important that the function of the actuator system be as accurate and repeatable as possible.

Cost-Effective

Developing a remote track tapering system will require the development of 160 individual electro-mechanical actuators and a network control system. The track sections will have to be removed and modified to accept the actuators. A serious consideration when evaluating potential designs will be the unit cost as well as the total cost impact on the project.

Another consideration that will impact the cost-effectiveness of the system will be the simplicity of operation. During every step of the process, FLOW must endeavor to minimize the complexity of the setup, calibration, and operation of the remote track tapering system.

Task 2 - Conceptual Design

The following is a review of the conceptual design that was developed during this program. It is broken into three primary categories, Control System, Electro-Mechanical Actuators, and Track Taper Verification.

Control System

Fundamental to the design of a semi-automated track tapering system is determining a method to reliably command as many as 160 individual actuators spread over a distance of 200 feet. If, eventually, the entire test track is to be controlled (as referenced in the original SBIR solicitation), the system must be expandable to as many as 704 actuators spread over 880 feet. These actuators must be controlled from a central location convenient to the track operations personnel. The method of communication between the control point and the actuators must be reliable and self checking. The desired positions of the actuators must be accurately communicated. If not, any actuator that is not in the correct location when a test shot is fired may cause model failure.

Networking

The most practical and cost-effective way to control a large number of independent actuators is through the use of a local area network (LAN). Three LAN options were investigated during this program. The following is a brief description of each.

PC-Based LAN - This approach would use one of the popular local area network topologies, such as Ethernet or IBM Token Ring, used to connect personal computers (PCs). This approach would require a small PC-compatible computer at each network node.

Bitbus LAN - Bitbus is a standard LAN that was developed specifically for communication between a central control point and a number of remote locations. It is a master/slave-type LAN. The central control point initiates all communications and there is no communication between slave nodes in the network. The nodes do not speak unless spoken to by the central controller. The maximum number of nodes on a bitbus network are determined by the bit rate used on the network. The table below summarizes the information.

Speed	Total Length	Nodes	Repeaters
2.4 Mbits/sec	100 ft	28	0
375.0 Kbits/sec	3,000 ft	84	2
62.5 Kbits/sec	8 miles	250	10

Flow-Designed LAN - This approach would employ a custom-designed LAN that would be developed specifically for G-Range. It would, however, most likely not be cost-effective unless there were several hundred network nodes. It is a formidable task to design the handshaking communication protocols required for error-free bi-directional communications necessary for this project.

Of the three methods that were evaluated, the bitbus approach is considered most appropriate for this application. It is the least expensive network to implement and is technically well suited to the system requirements. The data are transmitted using the RS-485 standard for differential data transmission, which provides a high degree of noise immunity from outside noise sources as well as lower-radiated electromagnetic interference (EMI) from the network. Optically-isolated repeaters can be used to reduce or eliminate ground loop couplings, due to ground potential differences from one portion of the network to another. Data integrity is assured by the bitbus protocol and message-passing standards built into the bitbus hardware and firmware. The datalink protocol uses a subset of IBM's Synchronous Data Link Control (SDLC).

Topology

Three network topologies were considered. They are outlined below.

- One network node per track section: each node would control eight actuators.
- Two network nodes per track section: one on each end, controlling four actuators.
- Eight network nodes per track section: one per actuator.

Investigations indicated that as many as eight actuators could be controlled from a single bitbus node. This would require one network node per track section. The system would use one bitbus network operating at a rate of 62.5 Kbit/sec. The central controller could be located anywhere in the test facility, and it is presumed that the controller would use the LTIS computer. Discussions with G-Range operations personnel indicated that it would be preferable to locate nodes at track joints, rather than mid-sections. As shown in Figure 3, these nodes would control a total of eight actuators. By routing the cabling along the top of the tank, and "dropping" cable to each track joint location, we could avoid strapping any cable to the already congested track sections. With one node per track joint, a maximum of 21 nodes would be required. Figure 4 depicts the detailed layout of one network node controlling eight actuators.

Motion Control

This task was broken into two subtasks, the consideration of indirect position feedback (i.e. measure motor drive shaft turns), and direct position feedback of the rail movements. The following discussion considers the merits and disadvantages of each approach.

Indirect Position Measurement - Two position-encoding methods were considered most practical. Both approaches employ a motor and track position sensor in a closed loop feedback system. The principal difference is the type of track position sensor used.

The first method uses a 10 or 20 turn potentiometer to feed back rail position. It would be mounted to the motor shaft, and would report the number of drive shaft turns. The potentiometer is used as a variable voltage divider with the output voltage proportional to the location of the track. The main advantage of this approach is that the position of the track can be read at any time. A disadvantage in using this approach is that it is an entirely analog control loop, which is inherently susceptible to noise problems and drift with temperature and time. The second and overriding disadvantage is that the number of motor turns would be limited to 10 or 20 turns. To use this approach would require a separate gear train for the potentiometer.

The second approach that was considered uses an incremental optical encoder as the position sensor. Since this has digital outputs, the complete motor control feedback loop can be digital and designed with zero drift over time and temperature. An HCTL-1000 digital motion control integrated circuit (IC) is considered the best choice. To be cost effective, one HCTL-1000 would be used to control up to 8 actuators (one per node). Each node controller would move each actuator separately. The power would be applied to the first actuator and moved to a home position to establish a reference, the motion control IC would then be commanded to move to the required location, and then the power removed and the same sequence applied to the next actuator. This sequence would happen very quickly, 10 to 20 seconds for all eight actuators.

Direct Position Measurement - This approach employs a sensor that measures the absolute movement of the rail, relative to some reference point. A sensor such as a LVDT could be mounted inside of the actuator housing. It would measure the movement of the wedge or rail, relative to a reference surface. When the system was instructed to move, the motion controller would move the actuator between two known reference locations. This would automatically calibrate the position sensor's gain and offset relative to the reference locations. The controller

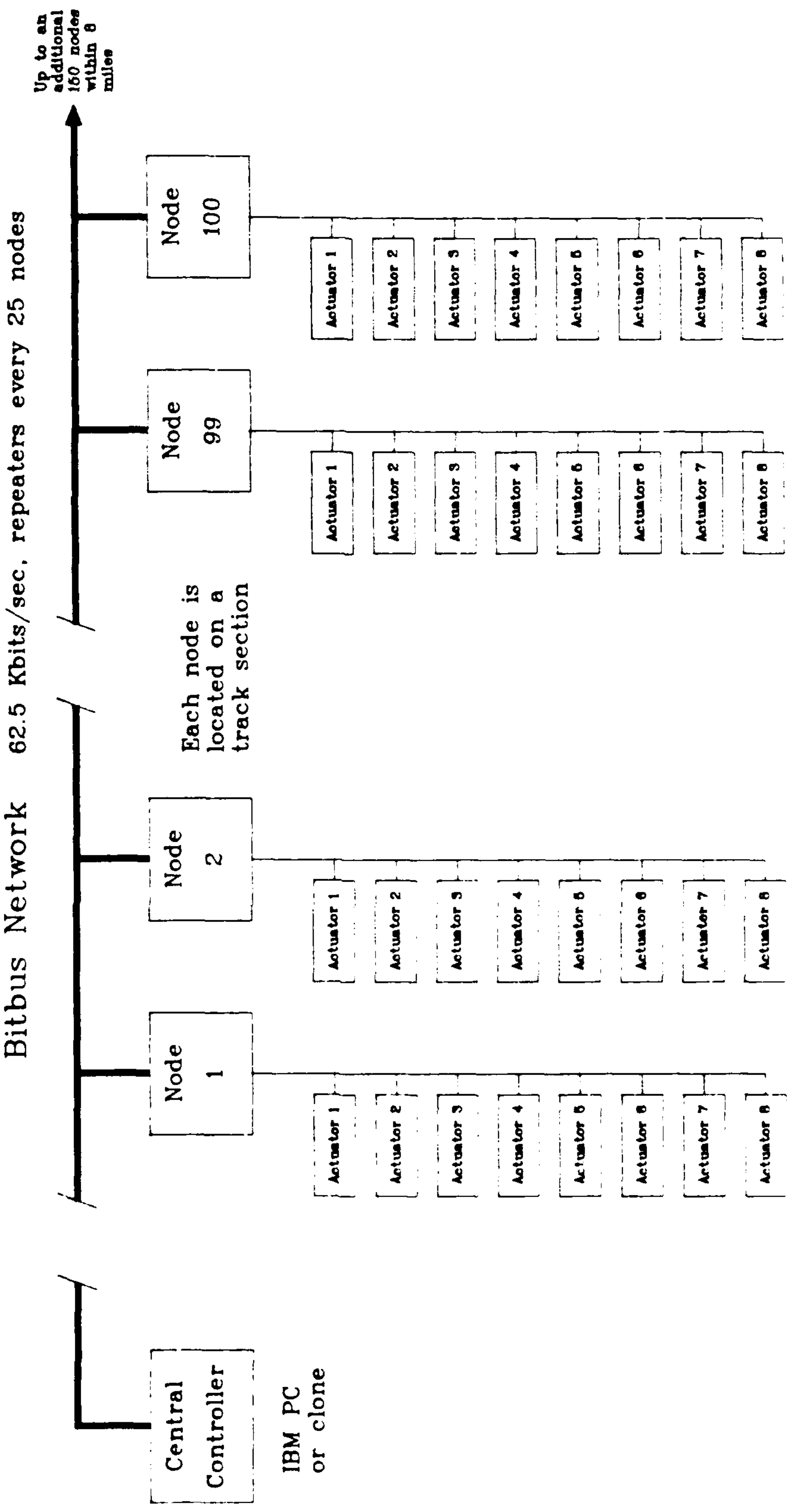
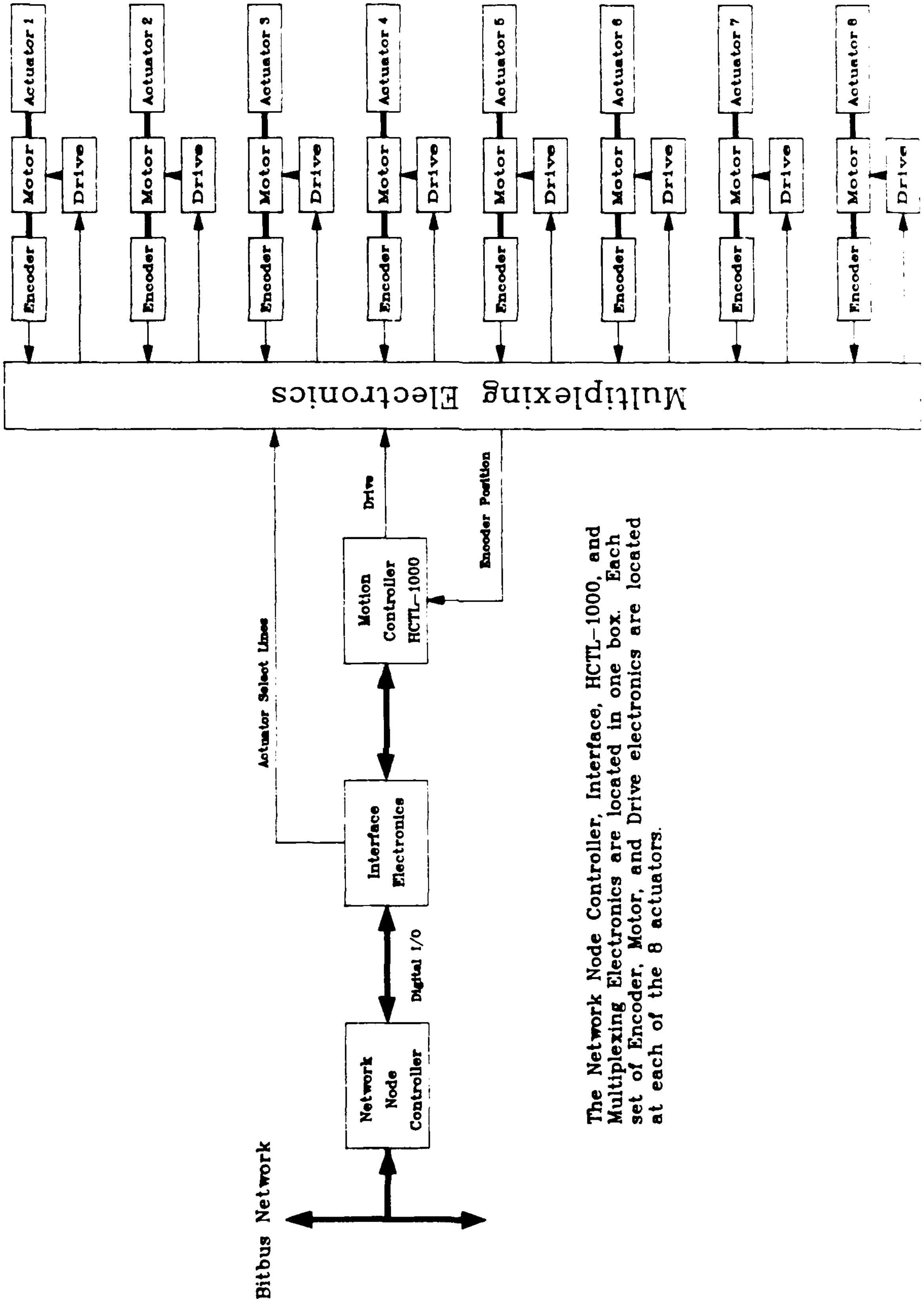


Figure 3. Nodes at Joints



The Network Node Controller, Interface, HCTL-1000, and Multiplexing Electronics are located in one box. Each set of Encoder, Motor, and Drive electronics are located at each of the 8 actuators.

Figure 4. Network Layout

could then move the rail to the launch location. This procedure would allow the computer to perform a thorough check of the integrity of each actuator, every time the track was adjusted. If a problem were detected during this self-check, the central controller would be notified. The operator would be told, via the computer, which actuator had a problem.

Although the position sensors (referenced as indirect measuring devices) are very accurate, they cannot compensate for wear. Discussions with AEDC G-Range operations personnel indicated a preference for direct rail measurement as opposed to indirect methods. We concur with this approach.

Controller

The central controller is the operator's interface with the system. It is anticipated that the existing Long Tube Inspection System computer will be used as the central controller. A single PC board will be plugged into the computer to interface with the bitbus network. The operator's normal interaction with the system will be very simple. Upon system power-up, the system will perform a series of self-checks and will prompt the operator to respond to a series of simple questions, such as desired track diameter at the Recovery Tube interface. The computer will automatically calculate the individual actuator positions and position each actuator without operator intervention. If any actuators malfunction, the problem and location of the actuator will be reported to the operator. A maintenance mode will be available as well. This will allow manual control of individual actuators for testing purposes.

Electro-Mechanical Actuators

The mechanical actuators for the tapering system must serve a dual purpose in positioning the rails. During a tapering operation, the actuators need to reliably move the rails to a commanded position. Just as important, however, is the need to stabilize and support the rails between tapering operations, when the range is actively testing models. The primary objective for this design task was to add the ability to independently reposition each rail, without sacrificing the rigidity and stability of the current system.

The existing rails get their primary structural support from the track tube sections. Each rail is bolted to a tube at 6-inch intervals, which provides stabilization for the rail in both the radial and lateral (side to side) directions. Without the support of the tube sections, the rail itself is relatively flexible. For example, with only simple supports at each end, the middle of a rail would sag approximately 0.012 inch due to it's own weight.

Modifying the existing support system to include a set of rail actuators is complicated by several factors. The first is a lack of understanding of the forces exerted on the rail by a test shot. Although it is believed that the existing system is overdesigned, it is not known what the actual factor of safety is. Furthermore, each bolt cannot simply be replaced by an actuator because of the high cost and complexity of the associated communications and control system.

Another consideration is that the actuator system must not have any backlash or clearances that would allow the position of the rail to change after a tapering operation. This is particularly important for actuators near the end of the rail, where a smooth transition to the next rail is extremely important.

The concept developed for the tapering system (Figure 5) is to use an actuator at each end of the rail, and intermediate stabilizers located between the actuators. The actuators will be commanded from the network to move each end of the rail to predetermined setpoints, and the stabilizers will be manually locked to prevent unwanted track motion during a test shot.

Actuator Design

The actuator design (Figure 6) uses a wedge drive system to move the rail with respect to the support tube. The rail is attached to the secondary wedge by a 3/8-inch bolt and sleeve assembly, and is guided by a set of bushings in the actuator housing. The secondary wedge is driven by the primary wedge, which moves in the axial direction. The wedge drive offers several advantages: high stiffness; a 10:1 mechanical advantage; and zero backlash. In addition, the wedge system cannot be back-driven by the rail.

In this design, the radial forces from the rail are transmitted directly from the secondary wedge to the primary wedge, through the primary wedge to the actuator housing, and then to the support tube. The secondary wedge and actuator housing are steel, and the primary wedge is bronze. The broad contact areas between these parts provides a very stiff support for the rail. A spring is used to apply 195 pounds of force to the wedges (radially outward) against the actuator housing. The springs are used strictly to preload the system, not to counter any of the forces generated during a test shot.

The primary wedge is driven by an ACME lead screw. This provides additional mechanical advantage, which increases the resolution of the system and decreases the drive torque requirements. The ACME nut is fixed with respect to the primary wedge, and the lead screw is rotated by the motor. The pitch of the screw is 0.05-inch per turn, which requires 36 degrees of motor motion to move the rail (through the wedges) by 0.0005 inch. The linear backlash between the nut and lead screw is 0.005 inch, or less. This translates into 0.0005 inch radial backlash at the rail. The thrust bearings for the lead screw are preloaded to zero backlash.

Actuator Drive System

The lead screw is driven by a motor and gearhead combination. In laboratory tests, the prototype actuator required 9 in-lbs of torque to translate the rail. This was higher than our initial design estimates, which were based on the coefficients of friction for the various materials. However, a wealth of low cost motors are available in this torque range.The choice of motor technology is likely to be influenced more by the cost of the controls and communications than by the cost of the motor itself. Given the low angular resolution, modest torque requirements, and the simplified control interface, a stepper motor is very well suited to this application. We chose to operate the prototype system using a stepper motor and a 3:1 gearhead. The gear reduction was necessary because the stepper motor and controller are a general purpose (laboratory) demonstration system, and were not sized for this particular application. Commercial stepper motors are commonly available in either 90 or 180 steps per revolution, which is more than adequate for this application.

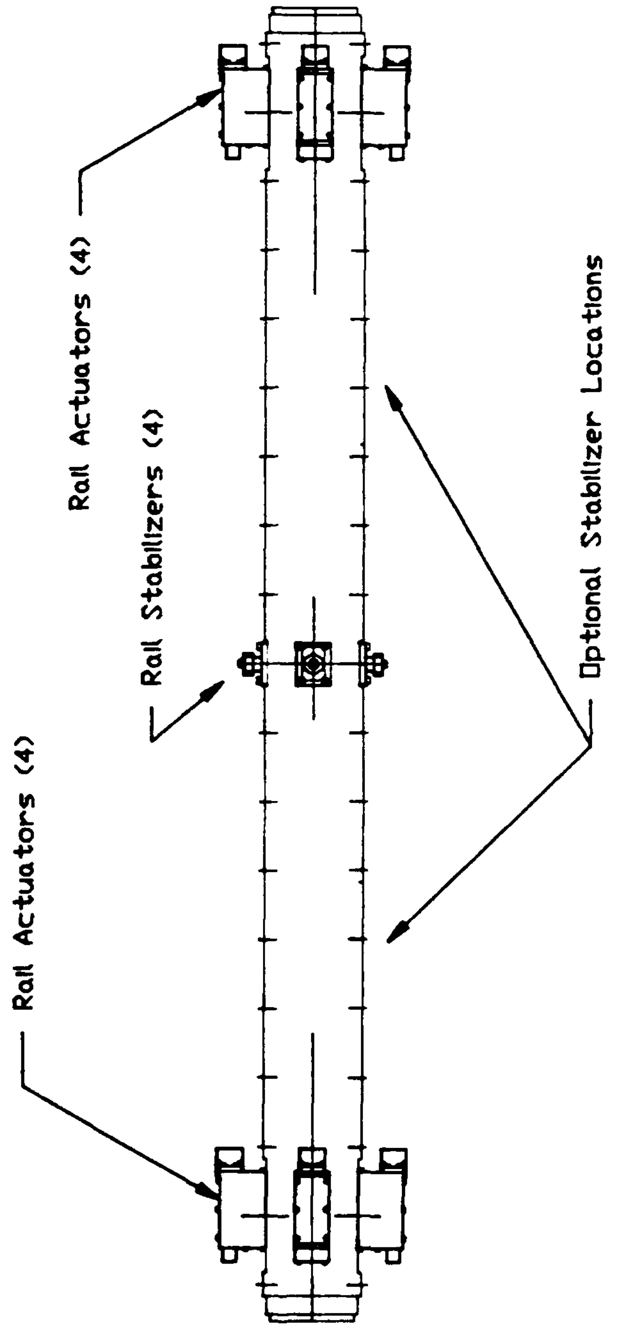


Figure 5. Tube with Actuator

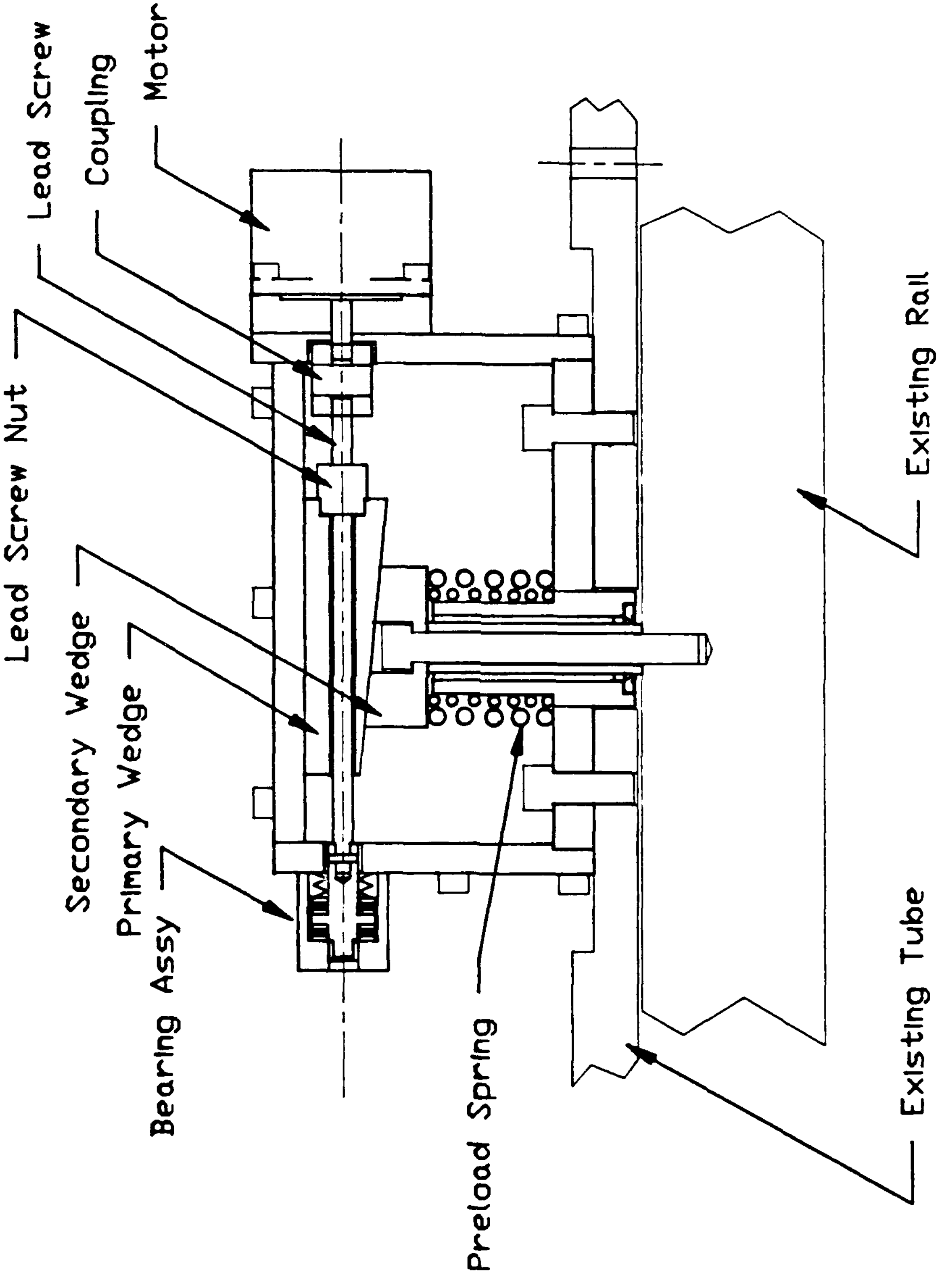


Figure 6. Actuator Detail

Stabilizer Design

The intermediate stabilizers (Figure 7), provide support for the rail at intermediate points between the rail actuators. During a tapering operation the stabilizers are released, allowing the actuators to move the rail to the desired position. When the tapering process is completed, the stabilizers will be manually locked, providing rigid support in the radial, longitudinal, and axial directions.

Tests will be conducted during Phase II to verify the stability of the above-described stabilizer configuration. In the event that additional support is required, stabilizers will be provided at three equidistant locations between actuators.

Taper/Center Verification

As discussed in the Phase I proposal, it is critical to have a high level of confidence that the rails are in the proper position prior to firing a test shot. Two levels of verification were considered and are discussed below.

Remote Inspection System Approach

This concept is the most conservative approach considered. It relies on a module that would be developed exclusively for track taper verification, which would interface with the pre-existing Long Tube Inspection System. Under this concept, the track would be remotely tapered and then the inspection vehicle would be installed and driven through the length of the track. A map of the track rail positions would be generated which could be evaluated and archived.

To implement this approach, a module would be designed and developed which would replace the Sensor Module on the Remote Inspection Vehicle (RIV). In addition, software would be developed to analyze and display the results.

Local Sensor Values

This approach is based upon the premise that the actuator system will employ highly accurate and reliable position encoders. These encoders must be independent of wear and backlash, and must directly measure the movement of the rail. This would alleviate the need for shaft-mounted encoders on the drive motors.

Of the two concepts, the local sensor approach is considered the most cost-effective. To confirm this, a series of tests will be conducted during the Phase II preliminary design effort.

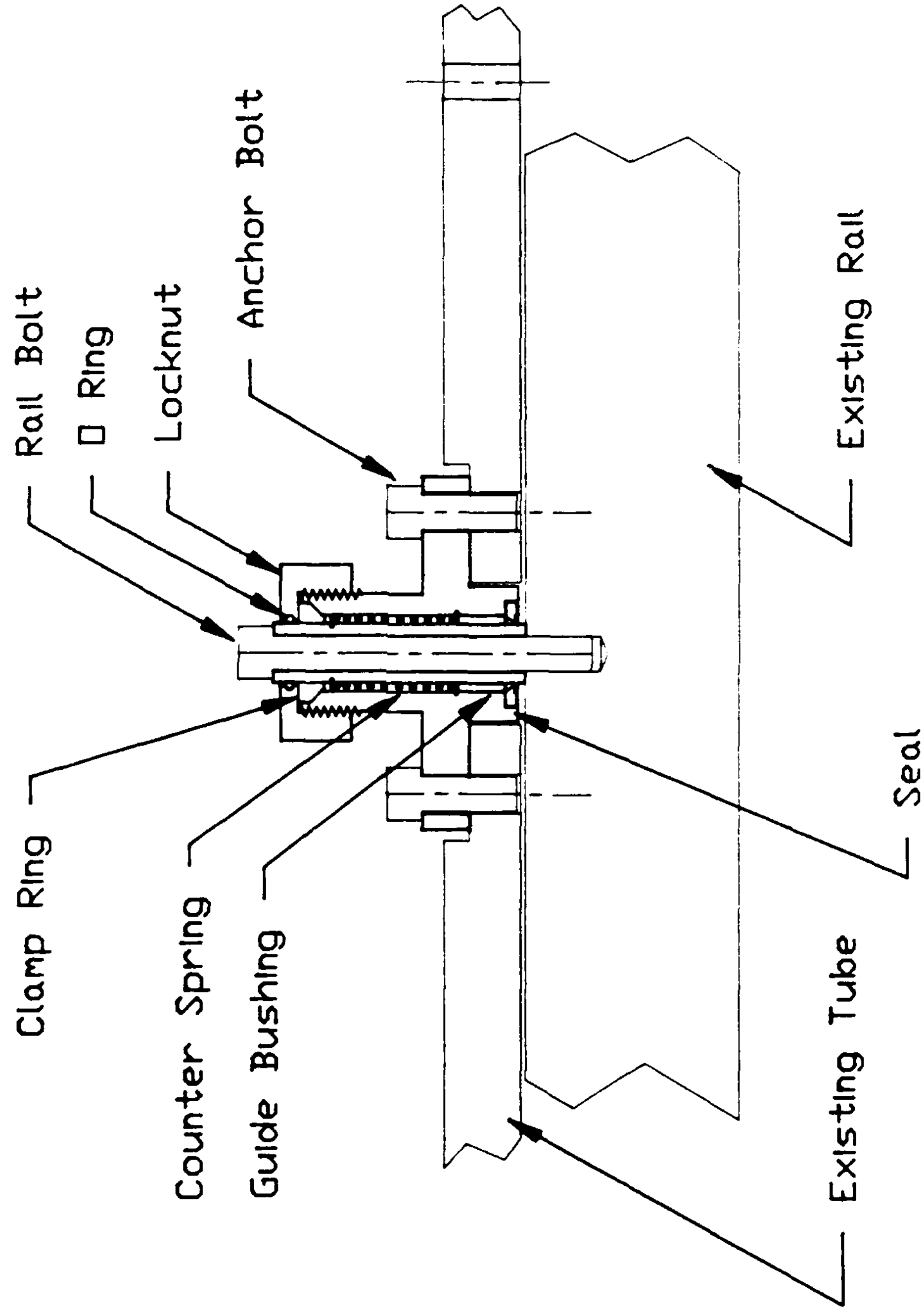


Figure 7. Stabilizers

Task 3 - Laboratory Mock-up Tests

The prototype rail actuator was set up in FLOW's laboratory (Figure 8). A 4-foot section of track rail was modified to interface with the actuator assembly. As shown in Figure 9, the rail pivoted at one end, and was attached to the actuator at the other. A stepper motor and gearhead were attached to the actuator and controlled by a Compumotor™ controller unit. This system allows programmed control of the stepper motor speed, direction of travel, and distance. A linear variable differential transformer (LVDT, Figure 10) was used to monitor the position of the rail. It's analog output was routed to a digital oscilloscope, which could provide hard-copy output of results. A dial indicator was used to calibrate the LVDT displacement sensor.

The following is a summary of the tests that were conducted.

General Function

Upon assembly, the actuator was operated through it's range of motion. The first series of tests were conducted without the rail being attached. The 300-lb. preload did not hinder the linkage shaft from moving through its full range of motion. The actuator was monitored through several hundred cycles.

The next step was to attach the rail and repeat the tests. When the system was actuated again, the motor would stall at certain points along the range of travel. Close observation indicated that the motor stalls were due to two factors, 1) misalignments in the rail and actuator assembly, and 2) too much preload from the spring assembly. To overcome this problem, the system was carefully aligned and one of the preload springs was removed. This reduced the preload to 135 pounds.

After the adjustments, the system was run through its full range of motion without difficulty. The LVDT was attached and the controller was programmed to run the system through approximately 10,000 cycles.

Hysteresis

A repeatability test was conducted to determine the ability of the system to return to a predetermined location. During this test the motor was instructed to repeatedly move through a set of goal locations, and the resulting position of rail was measured. The system was allowed to cycle through this test many times (approximately 20,000 motion cycles) over a period of several days, which is many times the number of cycles required during the life of the installed system.

During the repeatability test, an LVDT was used to record the motion of the rail with respect to the actuator housing, and display it on the digital oscilloscope. Figure 11 shows an example trace of rail position versus time. The system is very repeatable when approaching a point from the same direction, on the order of a few tenths of a thousandth of an inch. When

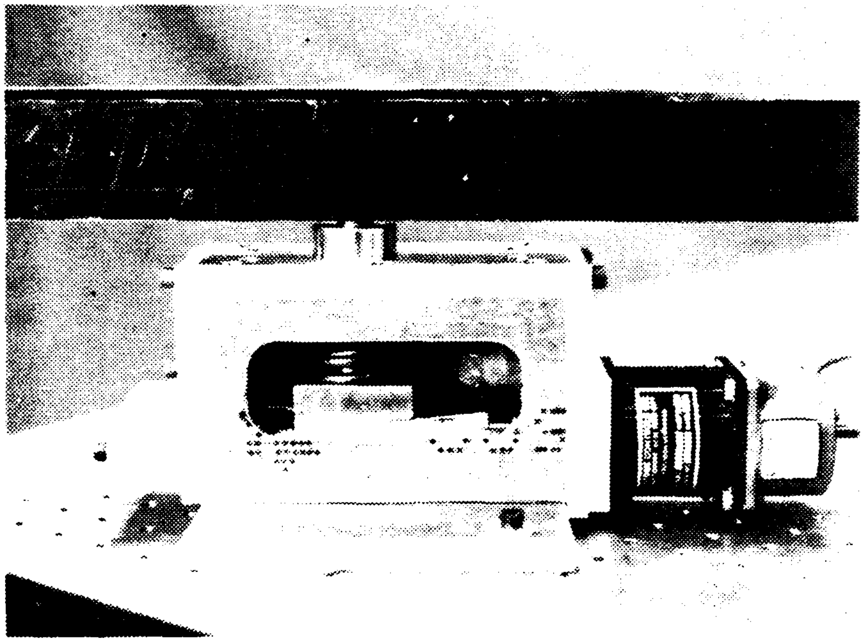


Figure 8. Actuator Assembly

Figure 9. Actuator Laboratory Test Setup

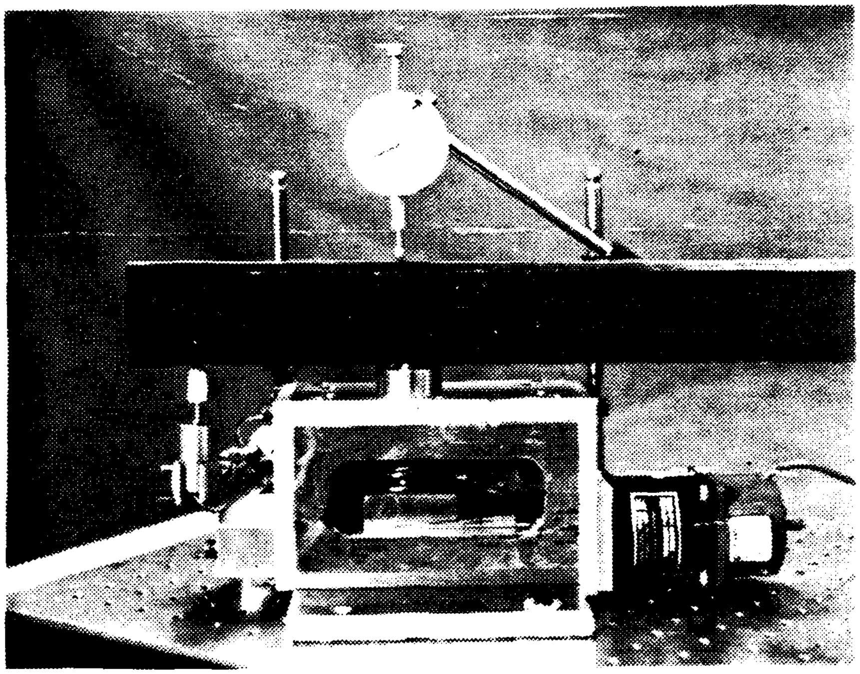


Figure 10. Instrumented Actuator Assembly

approaching the reference point from the opposite direction, the hysteresis was observed on the order of 0.0015 inch.

The hysteresis was very repeatable, and is considered to be due primarily to clearance between the guide bushings and the rail sleeve. Although a substantial amount of this clearance could be eliminated, this would not be necessary if direct rail encoding were used.

Stiffness/Impact Resistance

To simulate the impact loading which occurs during test shots, the rail was struck with a hammer while running the repeatability motion. Once again, the LVDT was used to record the position of the rail with respect to the actuator housing. Figure 12 shows the rail position versus time when a hammer blow was delivered while the system was at one extreme of the repeatability motion. Although the blow removed the hystersis, no other detrimental effects were apparent.

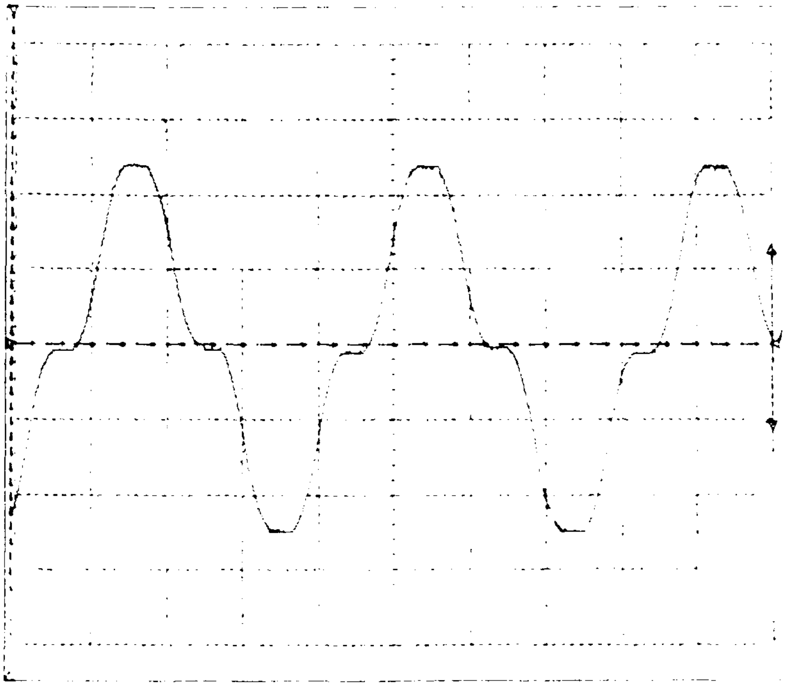


Figure 11. Oscilloscope Trace
Vertical Scale: 0.02 Inches/Division

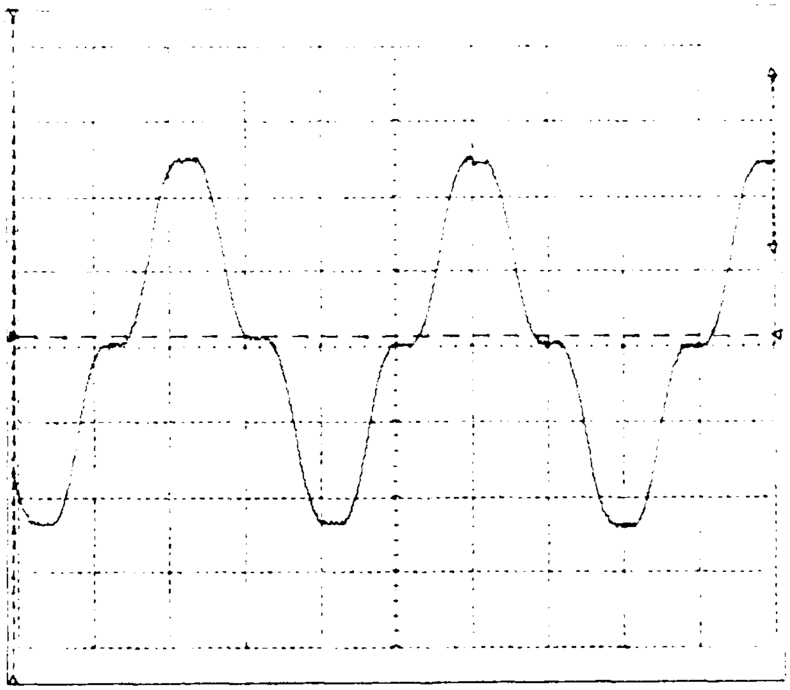


Figure 12. Oscilloscope Hammer Blow
Vertical Scale: 0.02 Inches/Division

Task 4 - Reporting and Communication

In addition to the monthly progress reports, a full technical program review was held at FLOW headquarters in Kent, Washington on June 15, 1989. During this meeting, the results of the 6-month feasibility study were reviewed. In addition, the prototype electro-mechanical actuator system was demonstrated. After the program review was completed, discussions were held to

obtain feedback from both operations and management perspectives at AEDC. The following is a summary of the feedback and observations that resulted from the discussions:

Control System

- When designing the operator interface for the network control system, keep it as simple as possible. Avoid complex setup and control operations.
- Power to the network should be provided via a manual breaker located downrange. This will minimize the amount of cable that must be run throughout the range.
- When considering routing the network cabling, it may be most appropriate to string it along the top of the tank and "drop" it to each node cluster. Running cable along the track sections should be avoided.
- A manual rail locking device is preferable to a solenoid-activated device (which was originally proposed). This will require less wiring and will not adversely effect the time required to complete a tapering process.
- Because of the time required to manually calibrate each actuator, frequency of calibrations must be kept to a minimum. Preferably, this would not be more than once a year.
- Because the actuator system will be exposed to low atmospheric pressures, consideration must be given to the potential adverse effect on electronic components. This may require the node modules to be located outside of the track.

Actuator System

- It was agreed that all actuators would be provided with a local manual override mechanism. This would allow track tapering even if one or two actuators were not controllable by the network system.
- Currently, some rails are supported at distances up to 40 inches without apparent negative effects.
- Care must be taken to prevent the ingress of dust. Actuator assemblies must be provided with filtered vent holes to allow operation under vacuum.
- Solvent-based greases should be avoided. A copper-based grease (C5A) has been used with good results in the range environment.

- The lateral forces that are imparted into the rails from passing models are not well known by range operations personnel. Therefore, it was recommended that an instrumented test section should be mounted in G-Range for 30 to 60 days, to measure these forces. This will allow the design group to determine the minimum number of rail stabilizers required for each track section.

- Preference was given to direct measurement of rail movements, rather than indirect measurement. This will eliminate the possibility of errors due to part wear.

Verification

- Of the two options that were considered, the local encoder method is considered the most potentially cost-effective. It would not require the development of any new equipment and, if properly designed, would be very reliable. We will therefore propose a local sensor-based rail verification method in the Phase II proposal.

SUMMARY

The Phase I feasibility study has resulted in the confirmation that a cost-effective and reliable remote track tapering system can be developed for G-Range at Arnold Center. A prototype electro-mechanical actuator has been designed, built and tested that, with minor improvements, will serve as the foundation of the system.

A Phase II proposal will be submitted that details the full remote track tapering system.