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NEXT GENERATION MUNITIONS HANDLER – ADVANCED TELEROBOTICS TECHNOLOGIES DEMONSTRATOR (NGMH-ATTD): DEMONSTRATION AND EVALUATION REPORT

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EXECUTIVE SUMMARY

The long-term objective of the Next Generation Munitions Handler (NGMH) Program is to improve weapon-loading tasks. Overall loading improvement objectives were given by the U.S. Air Force (USAF) sponsor as follows:

- Reduced overall time (e.g., improved platform motion capability, improved arm positioning capability, and reduced jamming potential).
- Reduced crew size (e.g., enhanced human-machine interface, enhanced human-machine synergy, and enhanced functionality).
- Enhanced reachability, manipulability, and maneuverability, with better controls.
- Reduced soldier workload (e.g., reduced fatigue, reduced communication needs between crew, "near-weightless" operations, decreased jamming occurrences, and task space control).
- Reduced equipment footprint and weight.

These improvements in the loading process are thought to be feasible through the use of emerging telerobotics technologies. However, some of these technologies have never been implemented, either separately or in an integrated fashion, on systems with the size, payload, scale, and working environment that is expected for the NGMH. Additionally, no data exist on the feasibility of the implementation and/or the preferred configuration of these technologies for producing advanced weapon-loading systems. Therefore, the NGMH program managers decided that before initiating the development of a prototype, an Advanced Telerobotics Technologies Demonstrator (ATTD) should be developed.

Thus, the ATTD was developed, not as a prototype, but as a test-bed system to demonstrate the *feasibility* of integrating and using novel concepts and telerobotics technologies. The telerobotics technologies that were identified as candidates to meet the objectives of the ATTD system were as follows:

- Controls and actuation for high-precision positioning (submillimeter, sub-tenth-of-degree) and insertion tasks (force control) under high payload (2,500 lb).
- Omnidirectional platform motion.
- Hand-on-the-system telerobotics control.
- Human-machine synergistic interface with:
  - human-strength-amplification (with gravity compensation) for manipulation, and
  - come-along mode for the platform.
- System's joint motion coordination with real-time kinematic redundancy resolution.
- High-payload, high-impact-rated, high-resolution force/torque sensing.
- Active compliance control for operator aid in complex insertion tasks.

Performance measures for meeting the ATTD objectives with respect to these technologies were identified in an objective document provided by the USAF (shown in Fig. 1).

All these technologies were successfully developed, implemented, and demonstrated on the ATTD. The feasibility of integrating and using these technologies toward improving the weapons-loading process has been ascertained. All these telerobotics technologies, except one, are evaluated as ready for transition to a prototype development phase. The only exception is the high-payload, high-impact-rated, high-resolution force/torque sensing device that is essential for advanced force control methodologies and the novel "Human-Amplification Technology." An on-going task is addressing the design and development of a new sensing technology that should remedy the problems encountered on the ATTD.

All performance measures stated for the ATTD led to highly satisfactory results. The only exception being the overall ATTD system weight. Preliminary studies indicate that significant weight reductions are feasible at the prototype phase. The feasibility of several other technologies and/or features was demonstrated that were not initially planned in the scope of the ATTD. Among these are the new "operator lifts himself with the weapon" concept to achieve very high reach (e.g., for loading the bomber fleet); a new actuated missile end-effector with positive grasp and control of the weapon; a quick-connect concept to mount and use tines (e.g., for loading guns, for loading missiles directly out of containers, and for compatibility with U.S. Marine Corps (USMC) loading adapters and fuel tank loading adapters); a quick-connect adapter for rack loading in pylons and for pylon loading onto wings; and several adapter concepts for F-22 maintenance tasks.

The ATTD development also provided significant experience toward identifying the technological improvements that would be needed if the requirements for the future NGMH prototype(s) were to change significantly from those of the ATTD. Among the most likely of these is the need for an alternative omnidirectional wheel system if platform speeds in excess of walking pace or operations on "nonuniform" and nondeveloped surfaces were desired.

Of course, many other technologies that were not part of the ATTD scope (which focused on a particular set of emerging telerobotics technologies) will be necessary at the prototype phase. In particular, technologies specific to particular versions of the possible future NGMH prototypes (e.g., ship- or land-based versions) will need to be specifically developed, integrated, and tested. However, from the results of the ATTD phase, several activities can be identified that have generic and pervasive applicability to all future potential prototype(s) and that constitute high priority with respect to the overall NGMH Program. Some of these are discussed in detail in this report and are as follows:

- A high-payload, high-resolution, high-impact-rated force/torque sensing technology with outdoor weather resistance, in particular to large temperature ranges and temperature gradients.
- Weight mitigation studies to achieve even higher payload/weight ratios than the already excellent value of the ATTD.
- Related to the previous item are needs for detailed analyses of power requirements versus tasks to be performed, as any amount of "overkill" in the requirements may have a dramatic impact on other design areas. Additionally, depending on the sought performance levels in the future prototype(s), studies and experimental investigations related to alternative power supply and to power transmission modes and technologies are highly recommended because they could result in significant global savings for the ultimately deployed systems.
- A control/computational architecture that is better suited to large-quantity manufacturing than the development-oriented one used on the ATTD will be needed for the prototypes, which also allows ready implementation and maintenance of the novel human-amplification and related technologies.
- A related activity concerns the need for an innovative sensing bus architecture, which would allow simpler signal networking and wiring (and consequently enhanced reliability and maintainability), while assuring the controls and safety characteristics needed for the human-amplification and related technologies.
- Investigation and experimental comparisons of the Off-Centered Steerable Wheels design to achieve holonomic, omnidirectional, high-payload platform motion on nonuniform terrain or at high speeds should be performed to meet the expected USAF and USMC requirements for the land-based prototype.
- When the preceding studies, as well as those related to the other specific characteristics that will be desired in the future potential prototype(s) have been accomplished and the corresponding Engineering and Manufacturing Development (EMD) phase prototype(s) have been produced, formal system and component Reliability And Maintainability (RAM) studies should be undertaken.
- In a similar fashion, formal cost-mitigation studies based on conventional or innovative manufacturing methods should be performed during future EMD phases of prototype(s) development.
- Further human-machine interaction studies, focused primarily on the areas and results outlined in Sect. 4.5, should be conducted using the actual control components and systems that will be embodied in the future prototype(s) to respond to the probably different requirements of these systems. Therefore, our recommendation is to conduct these studies during the prototype development and/or EMD phases of the future program.

1. BACKGROUND

The ultimate objective of the Next Generation Munitions Handler (NGMH)* program is to design, develop, and field advanced systems to replace the current U.S. Air Force (USAF) and Navy munition-loading devices. The goals of the NGMH Program are to optimize personnel utilization, reduce operator workload, decrease weapon-loading times, improve safety of loading operations, and prevent jamming occurrences during munitions insertion. By improving the efficiency of the load crew, reducing weapon-loading times, and decreasing mobility footprint, the NGMH systems will make the overall loading process more cost effective.

The improvements sought in the loading process are thought to be feasible through the use of emerging telerobotics technologies. However, some of these technologies have never been implemented, either separately or in an integrated fashion, on systems with the size, payload, scale, and working environment that is expected for the NGMH. Additionally, no data exist on the feasibility of the implementation and/or the preferred configuration of these technologies for producing advanced weapon-loading systems. Therefore, the NGMH program managers decided that before initiating the development of a prototype, an Advanced Telerobotics Technologies Demonstrator (ATTD) should be developed. The purpose of the ATTD is to investigate the *feasibility* of using emerging telerobotics technologies to perform and/or improve aircraft munitions loading.

Through the development and evaluation of candidate telerobotics technologies on the ATTD, the set of the most advantageous telerobotics technologies and their preferred implementation mode for weapon-loading tasks will be established. These will in turn serve as the basis for defining the NGMH prototype(s) and for establishing the prototypes' design requirements. Thus, building on the results of the ATTD phase, the NGMH Program will enter a phase of prototype(s) development that will focus on achieving the specific requirements that will be outlined in the future Operational Requirements Documents (ORD) for the NGMH prototype(s).

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2. OBJECTIVES OF THE ATTD TELEROBOTICS TECHNOLOGIES FEASIBILITY DEMONSTRATIONS AND EVALUATIONS

Figure 1 shows the ATTD objectives that were provided by the USAF sponsor at the beginning of the ATTD phase. The telerobotics technologies that emerged during the ATTD design and development project as necessary to accomplish the goals of the NGMH-ATTD are as follows:

- Controls and actuation for high-precision positioning (submillimeter, sub-tenth-of-degree) and insertion tasks (force control) under high payload (2,500 lb).
- Omnidirectional platform motion.
- "Hand-on-the-system" telerobotics control.
- Human-machine synergistic interface with:
  - human-strength-amplification (with gravity compensation) for manipulation, and
  - come-along mode for the platform.
- System's joint motion coordination with real-time kinematic redundancy resolution.
- High-payload, high-impact-rated, high-resolution force/torque sensing.
- Active compliance control for operator aid in complex insertion tasks.

Thus the overall goal of the ATTD phase was to answer these two major questions:

– Can these telerobotics technologies be developed and implemented on a single system that meets the objectives stated in the document shown in Fig. 1?
– Is weapons loading feasible with these technologies, and if so to what performance level, as determined using the stated set of representative loading tasks?

Consequently, on the basis of the objective document for the ATTD project shown in Fig. 1, the objectives of the demonstrations and evaluations with the NGMH-ATTD are to (1) verify that aircraft weapons loading is feasible with the set of identified telerobotics technologies, through demonstrations involving the representative weapons and loading scenarios, and (2) evaluate the performance of the implemented technologies with respect to the stated performance measures, to determine the most suitable configuration and prime controls methodology candidates, with respect to these specific technologies, for the future NGMH prototype(s).

Note that the ATTD has been developed with the objective of demonstrating the feasibility of the enabling technologies listed previously because their nonavailability would constitute a "show-stopper" for the overall NGMH Program. Obviously many other specific technologies or implementation features will be necessary for the future, production-focused version of the NGMH. These additional technologies and features will be investigated to respond to the complete set of requirements for the future prototype(s), and their detailed development and evaluation will be part of the prototype development and Engineering and Manufacturing Development (EMD) phases of the program. In other words, the ATTD is a feasibility test bed for a selected set of *telerobotics* technologies and the feasibility demonstrations and evaluations performed during the ATTD phase of the NGMH Program have focused primarily on these technologies.

Objective:

Evaluate the use of robotics technologies to increase manipulability and reduce operator workload during munitions handling operations while maintaining a high level of reliability and maintainability.

Subobjectives:

1. Design a Munition-Handling Platform

    1.1. Achieve omnidirectional emulation
    1.2. Reduce footprint and weight from present MJ-1 footprint and weight
    1.3. Design kinematics to accommodate all F-15E inboard pylon AIM-120/AIM-9 missile rail positions with worst-case configurations, F-15 inboard pylon with GBU-24, F-22 weapon bays, F-16 wing pylon TER with MK-82 and F-16 wing tip rail with AIM-120 or AIM-9 missile.

2. Develop a Munition-Handling Control System

    2.1. Sensing fidelity to handle AIM-9 to GBU-24
    2.2. Payload capacity up to GBU-24 (2,348 lb)
    2.3. Unified telerobotics architecture compliant
    2.4. Redundant trajectory generation

3. Determine Best User Interface

    3.1. Gravity compensation
    3.2. Multiple-user interface configurations

Performance Measures:

1. Platform positioning capability in confined 10- by 10-ft area
2. Manipulator/platform footprint
3. Manipulator/platform weight
4. Singularity avoidance
5. Positioning resolution
6. Maximum payload
7. System fidelity
8. Manipulability
9. Time to load
10. Degree of user feedback
11. User workload

Fig. 1. ATTD objectives and performance measures.

3. DEMONSTRATIONS AND EVALUATION METHOD

The demonstrations and evaluation activities of the ATTD telerobotics technologies feasibility were performed at Oak Ridge National Laboratory (ORNL). Many demonstrations and evaluation sessions were conducted, and for three multiday experimental sessions, actual load crews from the USAF and the U.S. Marine Corps (USMC) were available to execute loading tasks, perform user evaluations and provide user feedback. All load crew members who participated in the user evaluation had extensive experience in loading munitions using the "jammers" and consequently were particularly qualified to assess the effectiveness of the ATTD and to suggest improvements. Several engineers from the U.S. Navy also executed loading tasks with the ATTD during experimental sessions.

The ATTD is a self-propelled, diesel-engine-powered, hydraulically actuated weapons-lifting device. The system incorporates an 8-axis manipulator arm on an omnidirectional mobile platform. Control of the system is accomplished through human-machine interface (HMI) handles located on the platform and at the end-effector of the manipulator. Operator input on these handles is processed by a VMEbus-based computer system, which drives the motion of the system. Attachments can be secured to the end-effector for handling various weapon systems up to 2,500 lb. An isometric representation of the system is shown in Fig. 2.

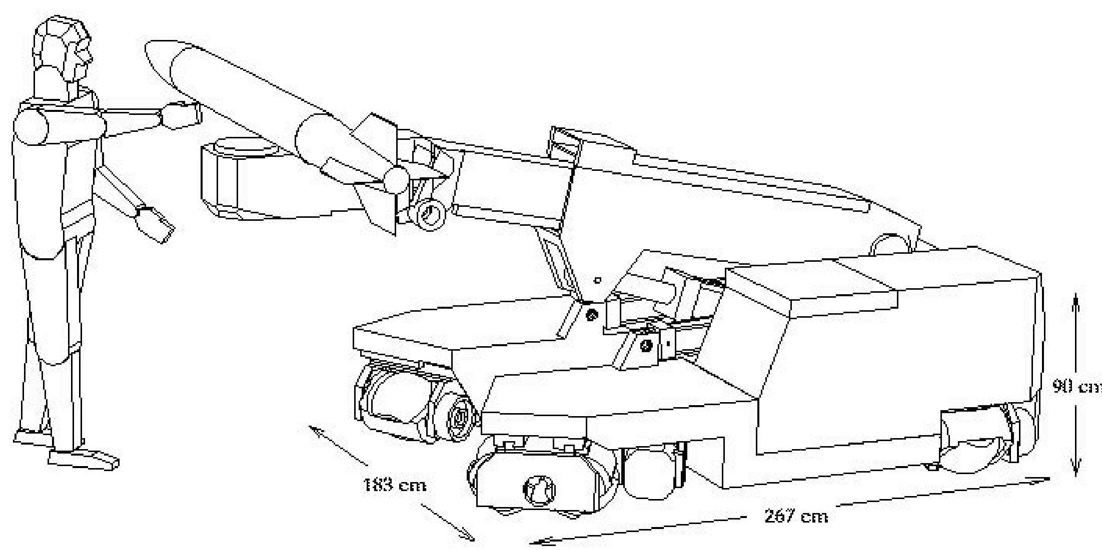


Fig. 2. Isometric view of the ATTD.

For objectives that are represented by quantitative values, the ATTD telerobotics technologies performances were evaluated by measuring data related to the performance measures identified in the ATTD objectives statement of Fig. 1. The results of these quantitative evaluations are presented in Sect. 4. The data were acquired during performance of representative loading scenarios. For those objectives and performance measures in Fig. 1 that are more qualitative in nature, such as the degree of user feedback and the user workload, evaluation data were obtained through "structured user feedback reports" from the actual load crews that performed representative loading tasks. Summaries of these analyses are included in Sect. 4.

The omnidirectional and positioning capabilities of the mobile platform were demonstrated and tested by maneuvering the ATTD through "obstacle courses" and/or very densely occupied areas during motions between the weapons trailer and the loading pylon and by positioning it at preselected locations.

The telerobotics technologies related to the manipulator arm were evaluated by loading various weapons on pylons. The initial set of representative tasks specified by the USAF sponsor in the initial document shown in Fig. 1 was subsequently augmented with some tasks involving Navy-specific weapons, racks, and rack positions. This extension of the evaluation program was done to cater to Navy interests after the Navy/USMC joined the USAF-led NGMH Program. The resulting set of representative weapons/rack configurations used in the loading task scenarios is as follows:

1. MK-82 bomb on a MAU-12 rack
2. MK-82 bomb on a BRU-32 rack
3. MK-84 bomb on a MAU-12 rack
4. MK-82 bomb on a rack positioned 36 in. from the ground (assumed F-22 clearance)
5. AIM-120 missile on an inboard pylon launcher simulating front approach and a worst-case configuration with fuel tanks
6. AIM-9 missile on a launcher simulating a side approach to a wingtip launcher
7. AIM-7 missile on a LAU-116 launcher simulating fuselage height and loading configuration

Many photos taken during the various sessions with the load crew are included in Sect. 6 as illustrations of the experimental setup and loading tasks.

4. RESULTS

4.1 SAFETY-RELATED RESULTS

Weapons-loading systems currently in use in the military forces are typically passive, mechanical systems. Consequently, the safety and error recovery systems they employ are typically passive, mechanical devices. Robotics and mechatronics systems, on the other hand, are active systems driven by electronics and software. Consequently, they require both active and passive safety systems implemented as multiple and redundant active and passive devices. The safety issue is even amplified in the NGMH case by the following fact: conventional robots have typically been of two types, teleoperated or autonomous, both essentially separating the human from the robot workspace. This is not the case with the hand-on-the-system telerobotics and the "Human-Amplification Technology" (HAT) developed for the NGMH and implemented on the ATTD. In fact, these technologies imply a sharing of the robot workspace by the human. Because these technologies have never been used, experimented with, or implemented in any system, particularly with the payload capacity (and consequently power) of the NGMH, new concepts for safety systems were required for the ATTD.

The redundant mechanical-electrical-software safety systems implemented and demonstrated on the ATTD are as follows:

- Enable switch on all HMIs that functions as a deadman switch to disable all systems except the engine when released by the operator.
- Hardware kill switches to disable all systems, including the engine.
- Electronic hardware watchdog, also called "heartbeat detector," that shuts down and disables the system if not periodically reset by the Central Processing Unit (CPU). This interlock shuts down and locks up the system in the event of a computer failure, accidental computer shutdown, or any software problem that results in the computer control loop failing to execute.
- Software watchdog that shuts down and locks the system in the event of a resolver failure. Other sensor problems are detected and remedied through the following item.
- Forward total system modeling and forecasting for loop-rate behavior assessment of all power/active components. This will detect problems with sensors and actuators whose behavior falls outside the system norm. This method provides some assurance that unforeseen failure modes can be detected and that the system can shut down safely. For example, servovalve malfunction or failures are inferred through this system.
- Relief valves to prevent overpressure in the hydraulic system.
- Check valves and isolation valves on all hydraulic cylinders that prevent motion in the event of any hydraulic or electrical failure.

Major results summary. Demonstrations of the feasibility of advanced safety systems for human-amplification robotic systems, and in particular of the previous features, were performed during several team meetings and experimental sessions, including actual disconnecting of the sensors, servovalves, and computer.

During the entire development and experimental life of the ATTD, only three "excursions" of the system were observed. All three occurred during control software (not safety software) development phases, and all were traced to programming errors that once corrected never led to similar improper system behavior. Since implementation of the safety features described previously, some events have triggered some of the safety features and have resulted in the system freezing in place, however and no "excursion" has been recorded. An example of this triggering actually occurred during one of the system demonstration meetings. During the entire wheel control software development, the threshold of overpressure in the wheel motor line had been set to a very low value. That value had not been changed for the demonstration. When attempting to demonstrate the ATTD capability for climbing over obstacles (in that case, a 2- by 4-in. wood beam), the resulting power need led to pressure in a wheel motor line that exceeded this threshold. After adjusting the threshold value in the software to allow climbing over small obstacles, the demonstration was continued and successfully performed.

A very important result achieved with the ATTD is the 0.2-second and fault detection for all the safety features. This pushes the envelope of what is feasible with the current generation of processor that was selected (in 1996) for the ATTD. In fact, several problems, intrinsic to the processor themselves, have been encountered because of this "pushing of the envelope" and have been relayed to the manufacturer. It is highly recommended that a task be conducted at the initiation of the NGMH prototype(s) phase, dedicated to simplifying the system's overall computational architecture and bus hardware to achieve a "production-oriented" configuration that will be more suitable for prototype(s) development, while maintaining the novel human-amplification safety concepts described previously.

4.2 SYSTEM GEOMETRY AND OVERALL CHARACTERISTICS

4.2.1 Footprint

The measured footprint of the ATTD in its transport/storage configuration is 4.88 m^2 (52.5 ft^2).

Major result summary. This footprint is comparable with, or smaller than, that of the smallest "jammers" of the MJ-1 family and is consequently smaller than that of the MJ-40 and MHU-43 systems. Thus, the feasibility to achieve this criterion on the prototype is ascertained, of course, under the assumption that the prototype will have payload, reach, and power-related requirements similar to those stated for the ATTD.

4.2.2 Weight

The total weight of the ATTD in its normal loading configuration is approximately 4,420 kg (9,750 lb).

Major result summary. Although this weight is well in excess of the current jammers, achieving such a weight value in the ATTD is very promising for meeting much lower values on the prototypes. It is important to realize that the ATTD was designed to include redundant features for testing, some of which considerably add to the ATTD weight and will not be included in the prototype as the result of the ATTD investigations, and that no special weight optimization has been performed for the ATTD. Current estimates are that at least 3,000 lb could be removed from the current system through optimizations of material, kinematics, configuration, and manufacturing process; and that at least 50% weight reduction could be achieved at the prototype phase using conventional weight-reduction technologies.

4.2.3 Reach

The kinematics implemented in the ATTD allowed all load stations of the representative set of tasks to be reached easily, including the very difficult F-15E inboard pylons, using the kinematic redundancy capability of the manipulator.

Major result summary. All stations simulating wing and fuselage locations were reached easily, including those requiring motion of the end-effector very near the ground, for example, in situations simulating operations under fuselages, including the F-22. The height of stations that can be reached with the ATTD is approximately 3.4 m (134 in.), which is considerably greater than all station heights that were considered.

One of the only exceptions to the feasibility of easily reaching all stations that are foreseen for the future prototype(s) is the very obstacle-dense station of the Navy F-18 fuselage shoulder (located behind the landing gear wheel), for which very limited space is available for the weapon-holding end-effector itself. This particular Navy aircraft station was not included by the sponsor in the set of representative tasks for the ATTD, and no detailed data were provided for it. However, it is our recommendation that this particular station be studied in careful detail if it is to be considered for loading by the future prototype(s).

With the achieved success in the height-reaching criterion, the question arose near the end of the ATTD development phase of loading significantly higher stations such as those of the bomber fleet (top station at a 192-in. height). A concept was developed for this purpose, calling for an operator to lift the weapon and himself or herself using the HAT. Now riding on a footstep attached to the end-effector, the operator's eyes remain in constant proximity of the weapon, while the end-effector-mounted HMI allows operation of the entire system by a single operator. Hardware was designed and developed to provide a feasibility proof-of-principle of this additional concept and feature, and a feasibility demonstration was successfully accomplished, as shown in Fig. 3.

Fig. 3. The "operator lifts himself with the weapon" concept allows for reaching high stations while maintaining single-operator capability for full control of the entire system and visual proximity to the weapon.

The major result in this area is that, using the novel "operator lifts himself with the weapon" concept and simple attachments or easily removed support devices, the feasibility of reaching all weapons stations of both the fighter and the bomber fleet has been demonstrated. Additionally, these concepts can be further extended to provide reach capabilities for a wide variety of maintenance tasks such as those dealing with gun emplacement, seat and canopy replacement, pylon and rack emplacement, surface inspection, vertical and horizontal maintenance and replacement, and fuel tank handling.

4.2.4 Maximum System Height

The ATTD was maneuvered under a 90-cm (36-in.) line. This demonstration was performed with an AIM-120 missile on the end-effector to simulate operations under an F-22.

Major result summary. These demonstrations were fully successful, showing that the feasibility to achieve this criterion at the prototype phase has been ascertained.

4.2.5 Payload

The initial goal for the maximum desired payload of the ATTD was 2,400 lb. However, during the course of the project, this goal was changed to take into account the typical weapon-handling safety factors of "build at three, test at two," while still maintaining a desired weapon payload of 2,400 lb. The ATTD was tested for full operation under a variety of payloads up to 4,800 lb. The photo in Fig. 4. was taken during one of these test series, with a payload of two bomb bodies totaling nearly 4,500 lb.

Fig. 4. One of the overload safety tests using two large bomb bodies as a payload totaling near 4,500 lb.

Major result summary. These results have ascertained the feasibility of achieving the high-precision control required by loading tasks with payloads of up to 5,000 lb. Based on the safety factors that will be imposed on the prototype(s), the feasibility of handling weapons of at least 2,500 lb seems ascertained. Requirements for handling weapons of much larger weight that 2,500 lb, while imposing safety factors of 2 and 3 as discussed earlier, and while maintaining the loading-related precision controls, will need to be carefully considered at the prototype development phase, as they may significantly impact all other performance criteria initially stated as NGMH objectives.

4.2.6 Other Developments

Other developments that were not included in the initial ATTD phase objectives list were added during the course of the project. In particular, the USAF reported several instances of missiles having been dropped from the missile adapter currently in use by load crews. A request for an improved missile end-effector with a complete, positive grasp of the missile was added to the NGMH program, with a design effort initiated during the ATTD phase. Consequently, a novel missile end-effector was designed, fabricated, and successfully tested as part of the ATTD project. Figure 5 shows this hydraulically actuated design, which includes adjustable grippers for missile diameters between 12.5 cm (5 in.) and 20 cm (8 in.). The performance of this design was judged sufficiently robust so that transfer of the technology was initiated to private-sector companies toward EMD-type activities for both implementation on the future NGMH and investigations for retrofitting the design to the current family of jammers.

Other hardware components that were not initially in the ATTD plans and that were added to the project scope during the development period included a quick-connect adapter to allow rapid loading of a bomb rack in pylons and attachment of pylons to wings. A quick-connect system of tines to demonstrate the feasibility of adapting and using tines in various loading processes was also added.

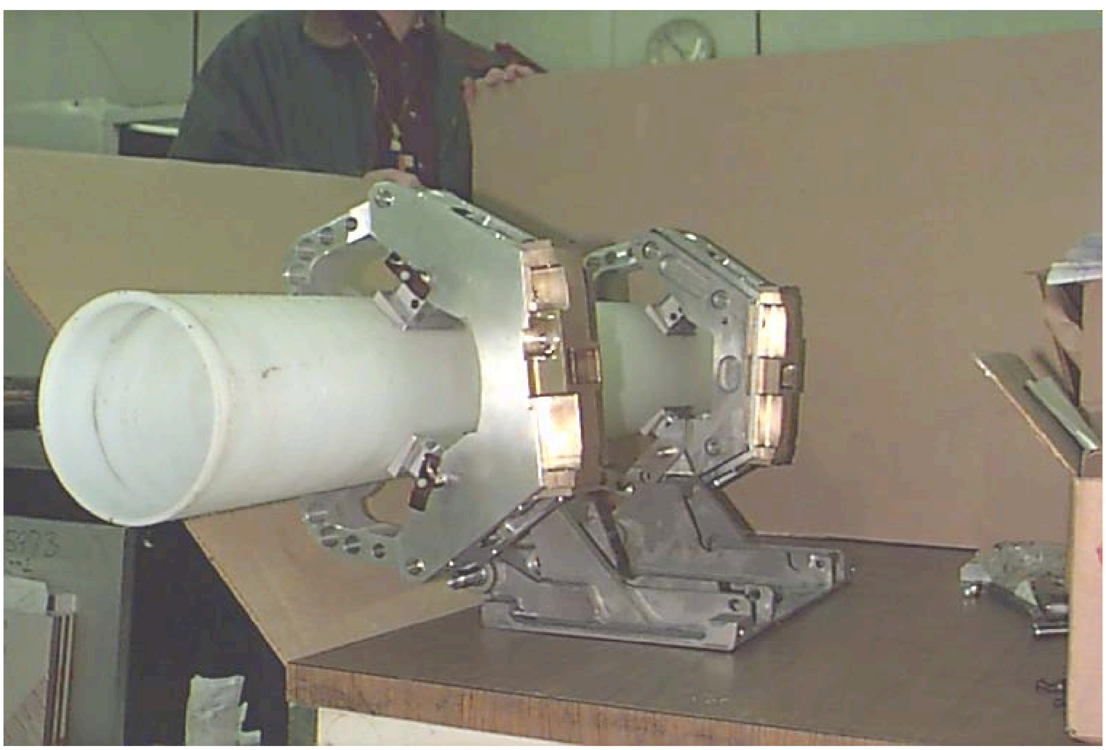


Fig. 5. Novel hydraulically actuated missile end-effector including adjustable grippers for missile diameters between 12.5 cm (5 in.) and 20 cm (8 in.).

4.3 PLATFORM-RELATED RESULTS

4.3.1 Omnidirectionality

The platform was successfully maneuvered in all translational directions, including forward, backward, laterally, diagonally, in turning, and in rotational motion in both open and densely occupied environments using (1) the joystick located on the ATTD platform and (2) the joysticks located on the end-effector.

Major result summary. The results of the demonstrations clearly show that complete, holonomic, omnidirectional platform motion is achieved with the Orthogonal Wheel (OW) design with total weight on the wheel system in excess of 6 tons (13,200 lb). Also demonstrated were a wheel pod extension mechanism to increase overall stability during some loading tasks, as well as the ability of the OW to negotiate small obstacles such as chains, cables, hangar door sliding rails, or 2- by 4-in. type objects.

Note that these results, as well as the successful demonstration of smooth motion control of the OW on a hydraulically actuated platform with more than 6 tons of total weight capacity, refer to motions at walking-type speed over relatively smooth terrain. The initial goals stated for the NGMH-ATTD considered loading operations in hangars or airport parking ramps performed by crews operating the system mostly from the end-effector-mounted HMI and therefore at their walking speed. For these conditions, the ATTD demonstrated the applicability and appropriateness of using the OW design.

An important result of the ATTD investigations, however, is that OW designs, just like Ilonator Wheels (IW) designs (also called Swedish rollers), encounter significant drawback for operations at high speed (e.g., > 10 km/h) on rough, bumpy, or undeveloped road surfaces. The underlying cause, common and intrinsic to both OW and IW designs for operations under these conditions, is the instantaneous displacement of the contact point with the ground that occurs at the change of contact from one roller to another in the basic wheel assembly. On the basis of available data to date about these designs, we believe that attempts at remedying the resulting “shocks” that arise from the spatial discontinuity in contact points through the use of suspension systems would add significant additional complexity to the platform mechanisms without actually resolving the root-cause effect that is intrinsic in these designs for operations at high speed or on nonuniform type surfaces.

Therefore, one of the major outcomes of the ATTD project is that both OW and IW are suitable for loading tasks involving low-speed (walking-speed) motions on relatively even terrain (e.g., runways, airport parking and ramps areas, and ship decks). However, if any operations involving speeds faster than walking speeds or if nondeveloped surfaces are included in the requirements of the future NGMH prototype(s), then OW and IW are not suitable under their current implementation. In such a case, the third design [Off-Centered Steerable Wheels (OCSW)] for achieving omnidirectional platform motion (recommended as essential for end-effector HMI-controlled operations in environments with tight clearances or that are densely packed) should be considered. Based on the preliminary indications of their desired requirements for the future NGMH prototype(s) from both the USAF and the USMC, initiating experimental investigations (using the ATTD system) of the feasibility of using the OCSW to meet the future NGMH requirements is highly recommended, before initiation of the prototype design. This, in our opinion, is one of the most significant risk mitigation tasks identified for the continuation of the overall NGMH Program.

4.3.2 Positioning Capability in Confined Areas and 10- By 10-Ft Restricted Areas

The key parameter for the platform positioning technology is the relative positioning capability (i.e., the creep motion capability). This capability is essential for rapid operations under the F-22, for example, operations using the hand-on-the-system control concept and all tasks involving maneuvering in densely occupied environments. This creep motion positioning capability was demonstrated by having the operator move the ATTD platform to weapon acquisition positions at the trailer and weapon-loading positions during full loading task scenarios, as well as through "obstacle course" maneuvering around the 10- by 10-ft frame supporting the test pylon and racks. It was evaluated through experimental measurements of the distance between the platform and an object after the operator had driven the platform toward and as close to an object as the controls would allow, from various directions. These experiments showed a positioning accuracy for the ATTD platform between 1 cm (0.4 in.) and 2.5 cm (1 in.), depending on the set of control gains used and the approach direction to the object.

Major result summary. The platform positioning accuracy achieved with the ATTD is extremely good for a 6-ton (platform plus payload) wheeled platform and ascertains the feasibility of achieving the very precise platform positioning that will be necessary for the loading tasks envisioned for the future NGMH prototype(s).

Another important result of these investigations is that with the novel high-precision hydraulic control methodologies used for the ATTD, the platform positioning accuracy becomes almost directly (inversely) dependant on the power demand of the vehicle. Reductions in vehicle power requirements, if desired, at the prototype(s) development phase, could result from two areas: the first is obviously a careful carving of the requirements for the prototype(s), to ensure essential motion capability needs (e.g., reasonable platform speeds while holding maximum payload, ramp angles, and obstacle sizes) without generating "overkill" conditions in platform power demand. The second area, which is highly recommended for investigation before or during the prototype phase, involves detailed and experimental evaluation of the tradeoffs between hydrostatic approaches and high-pressure and servovalve approaches for the various precision-versus-payload tasks implied by the NGMH weapon-loading functions.

4.4 MANIPULATOR-RELATED RESULTS

4.4.1 Singularity Avoidance

The ATTD kinematics includes no singularity, in the sense that no particular set of configuration and desired displacement in the end-effector working envelope leads to a large (or infinite) joint displacement requirement. Consequently, singularity avoidance has been achieved in the ATTD through its design. This was accomplished while allowing the working envelop of the manipulator to reach all loading stations with a clear approach path, that is, with the obstacle avoidance capability (e.g., F-15 inboard pylon station with pylon tank) provided by the kinematic redundancy of the ATTD manipulator design and the corresponding redundancy resolution algorithm.

Major result summary. A similar approach to preventing singularity can be used in the design of the future NGMH prototype(s). The advantage of achieving singularity avoidance through design, rather than counting on numerical techniques to remedy a design shortcoming, is of course large gains in the control algorithm and the resulting control loop rate, as well as smooth and uniform system response to the operator's commands throughout the entire working envelope. Attention to ensuring this criterion will be required in the design of the future NGMH prototype(s), particularly if the prototype(s) requirements were to lead to significantly different set of kinematics (e.g., less than 6 joints or no kinematic redundancy).

4.4.2 Positioning Resolution

During the munition-loading process, there are two precision positioning tasks: (1) acquiring a weapon from a trailer and (2) loading the weapon onto a rack or launcher. Both were regularly accomplished by all operators with no limitation in positioning resolution. Through the loading of all weapons considered (several bombs and missiles, with weights varying from near 200 lb to near

2,400 lb), the feasibility of smooth control for submillimeter relative positioning resolution of very high payloads was ascertained, as well as smooth sub-tenth-of-degree relative orientation resolution (needed to align the missiles' three lugs into the launcher rails' cavities).

Major result summary. Achieving high-precision positioning under high payloads and payload ranges is the result of the novel control algorithms implemented on the ATTD. To our knowledge, such control performances have never been achieved on any previous system with payload weight of the type involved here. In addition, unique force/torque-based control performances were also demonstrated on the ATTD. This included active compliance controls to provide both (1) automatic alignment of the weapon lugs during insertion tasks to serve as an operator-aiding mechanism and to speed up loading tasks and (2) highly constrained position/orientation surface following to allow sliding of the missiles onto their launcher rails. Furthermore, these latter force/torque-based control technologies were implemented in conjunction with the HAT, which provided a feasibility demonstration of novel human-machine synergy concepts (i.e., hand-on-the-system force feedback to the operator) that were conjectured to be the most appropriate for the NGMH Program (although they did not exist at program initiation).

These major results, which for the first time demonstrated feasible achievement of the difficult precision-payload goals of large-weapon loading, were the essence of the ATTD phase of the program, and the success of the various demonstrations definitely ascertains the feasibility of achieving such goals in future prototype(s). Of course, these feasibility results hold only as long as the requirements on the prototype do not significantly differ from the performance goals stated (and achieved) for the ATTD.

4.4.3 Sensing System Fidelity

All precision, impact rating and force/torque-control objectives that were attempted for the ATTD were successfully achieved with weapon payloads varying from near 200 lb to near 2,400 lb. These objectives were met, however, despite a major shortcoming in the end-effector-mounted, six-axis force/torque sensor. At the project onset, one of the objectives of the ATTD system design was to use commercial equipment as much as was practical. No sensing device meeting the ATTD requirements was available commercially. Therefore, development of a novel product was contracted to a leading force/torque sensor manufacturer (JR3). The resulting sensor achieved all load, resolution, and overload stated requirements; however, this sensor has a large thermal drift coefficient. This drift problem results in large variations in relatively small amounts of time (typically less than a minute) of the sensor bias and threshold values (e.g., see Fig. 6), which substantially limits the operation time under "nominal" parameter settings and essentially prevented reaching the theoretically predicted performance range in the ATTD controls.

Major result summary. Although the feasibility of achieving the sensing fidelity with respect to load, overload, impact rating, and resolution necessary to handle the wide payload ranges and tasks of the loading functions has been ascertained, the feasibility of achieving these goals while allowing operations in environments with large temperature variations (e.g., -40 to 120°F) has not been ascertained. One of our highest priority recommendations based on the ATTD results has been to initiate the design of a refined force/torque sensing device, specific to the NGMH loading function, that could meet the stated objectives. As of this writing, this task has been initiated and is expected to continue during FY 1999.

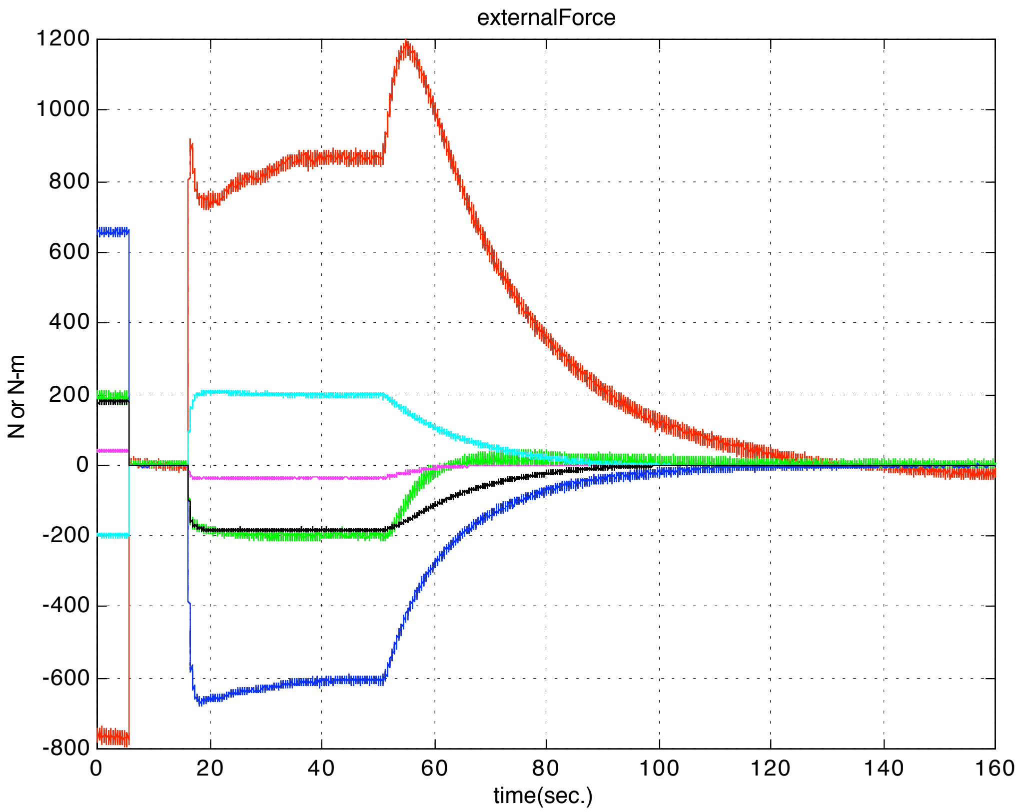


Fig. 6. Data log showing the thermal drift behavior and the sensitivity to pressure variation at startup and shutdown of the six-axis of force/torque of the JR3 sensor.

4.4.4 Manipulability

In the Robotics field, this performance measure relates to a particular index (the norm of the trace of the determinant of the robot's Jacobian matrix) expressing the "ease" with which the system can achieve motion in its workspace. As mentioned in Sect. 4.4.1, the ATTD system includes no singularity and therefore exhibits a particularly good manipulability index. From a more human-factors point of view, manipulability for the novel hand-on-the-system concept embodied in the ATTD is taken as an indication of the ease with which operators can hand-drive the motion direction of the system through its workspace from any configuration. From the crew reports, the ATTD exhibits very good characteristics with respect to manipulability and the operator's position during loading tasks (e.g., see Fig. 7), as was expected from a kinematically highly redundant mobile manipulator system. One situation, however, that occurs during the weapon acquisition task at the trailer needs attention. When motion of the platform is used to insert the end-effector in the trailer space below the weapon, it is possible for an operator to be squeezed between the platform frontal surface and the trailer. This can be easily remedied, procedurally, by making as much use as possible of (1) the manipulator rather than the platform to insert the end-effector into the trailer spacing and (2) the platform motion to withdraw from the spacing once the weapon has been acquired.

Major result summary. The experiments show that achieving high manipulability in the prototype(s) design should not present any particular difficulties, assuming that the requirements do not impose arbitrarily low numbers of joints for the system. The hand-on-the-system concept proved very effective in allowing the operator to guide and easily position the overall system for all tasks considered. This concept, integral to the HAT, is highly recommended for use in the future NGMH prototype(s).

Fig. 7. A typical operator's position with respect to the machine during a bomb-loading task.

4.4.5 Time to Load

The experimental apparatus used in the demonstrations of the ATTD included an F-15 pylon and several racks, as indicated in Sect. 3, mounted on a 10- by 10-ft frame. This configuration is not fully representative of actual loading conditions; therefore, detailed quantitative loading time studies and comparisons with the MJ-1 jammer available at ORNL were not attempted to this date. Furthermore, as discussed in Sect. 4.4.3, the current force/torque sensor used on the ATTD exhibits significant temperature-change-induced drift, which results in large variations of the control settings over periods on the order of a minute. For tasks such as missile loading, which requires the finest control over times on the order of minutes, the current sensor drift represents a possible hazardous condition when used by nonexperts (in the ATTD computational and controls methodologies). For these reasons, complete timing experiments over all of the selected representative loading tasks have not been performed with the crew members. This may occur at a later date, based on program guidance and completion of the planned task on design of a novel sensor for the ATTD, recommended in Sect. 4.4.3 as one of the highest priority items for the overall NGMH Program.

Nevertheless, some loading task timing data were acquired during the experiment program with the crew members. These data are presented in Sect. 4.5. In addition, some "subjective data points" are worth noting: qualitative comparisons of loading times for loading tasks witnessed by ORNL personnel while at USAF and USMC facilities and performed at ORNL with the ATTD, indicated, in all instances, better or shorter loading times using the ATTD. This qualitative evaluation may be sufficiently important in itself considering that these shorter or equal loading times were obtained with a single operator in control of the ATTD versus 2, 3, 4, and in some instances 6, operators at the field facilities. The potential for total person-time (i.e., total workload) savings using the ATTD concept indeed is very large, possibly as much as 50% to 80%, depending on the actual tasks and procedures implemented in the future prototype(s).

Another example of qualitative total workload was provided by two of the Navy team engineers, John Arneo and Rob Cimler, who reported times on the order of 20 minutes to load an AIM-7 Sparrow on the shoulder station of an F-18 using a SASS loader (of the “jammer” family type). Although the actual complex and difficult geometry of that station could not be fully duplicated on the test frame at ORNL, the loading of an AIM-7 on a LAU-116/A rack was achieved in less than 6 minutes by a single operator using the ATTD and the new missile end-effector, despite slight malfunctioning of the LAU-116/A rack provided by the Navy. Thus, recognizing the differences in station setup, but also the similarity in loading experience of the operators, this qualitative “experiment” indicates a ratio of about 6 in total workload or person-time (1 person × 6 minutes versus 2 persons × 20 minutes).

Major result summary. Although no complete, comparative and quantitative experiments have been performed with respect to load time, the initial qualitative and preliminary evaluations seem to indicate a potential for better or equal load time, and more importantly, a potential for significant workload or person-time saving using the telerobotics technologies embodied in the ATTD. In addition, similar qualitative and preliminary evaluations seem to indicate a potential for significant reduction of jamming occurrences through the active force control, human-amplification, and insertion-aid technologies.

4.4.6 End-Effector Speed

Although not in the list of performance measures considered for the ATTD, end-effector speed has been the subject of many questions, particularly since the value that will be used as a requirement for the future prototype(s) will have a significant impact on the power and dynamics requirements for the manipulator, and consequently on the size, power, and weight of components such as the structure, actuators, and the engine. This requirement, if inappropriately set (e.g., “overkill”), therefore has the potential to significantly affect what would otherwise be feasible with respect to total system weight size, footprint, etc., as well as the overall operational safety.

Motion data were gathered during the later parts of the experimental sessions with the crew, after they had a chance to practice with the system and after the control parameters had been adjusted to respond to their feedback. Plots showing the recorded magnitude of the end-effector velocity vector are shown as examples in Figs. 8 and 9. The plots in Fig. 8 were recorded during loading experiments with a 225-kg (500-lb) bomb, while those in Fig. 9 are for a 1,000-kg (2,200-lb) bomb.

Major result summary. The data logged with the ATTD indicates that the maximum speed used by any of the operators in loaded conditions (with any of the representative weapons) is about 4 in./s. However, as explained in detail in Sect. 4.5, “Human-ATTD Interactions,” it is important to note that two very different human factor modes seem to dominate the loaded and the unloaded operations. In unloaded operations, the emphasis seems to be on speed, whereas force input and HMI handle topics become important only in the sense that they should not restrict motion. In loaded operations users are more sensitive to responsiveness and less concerned with speed and HMI topics.

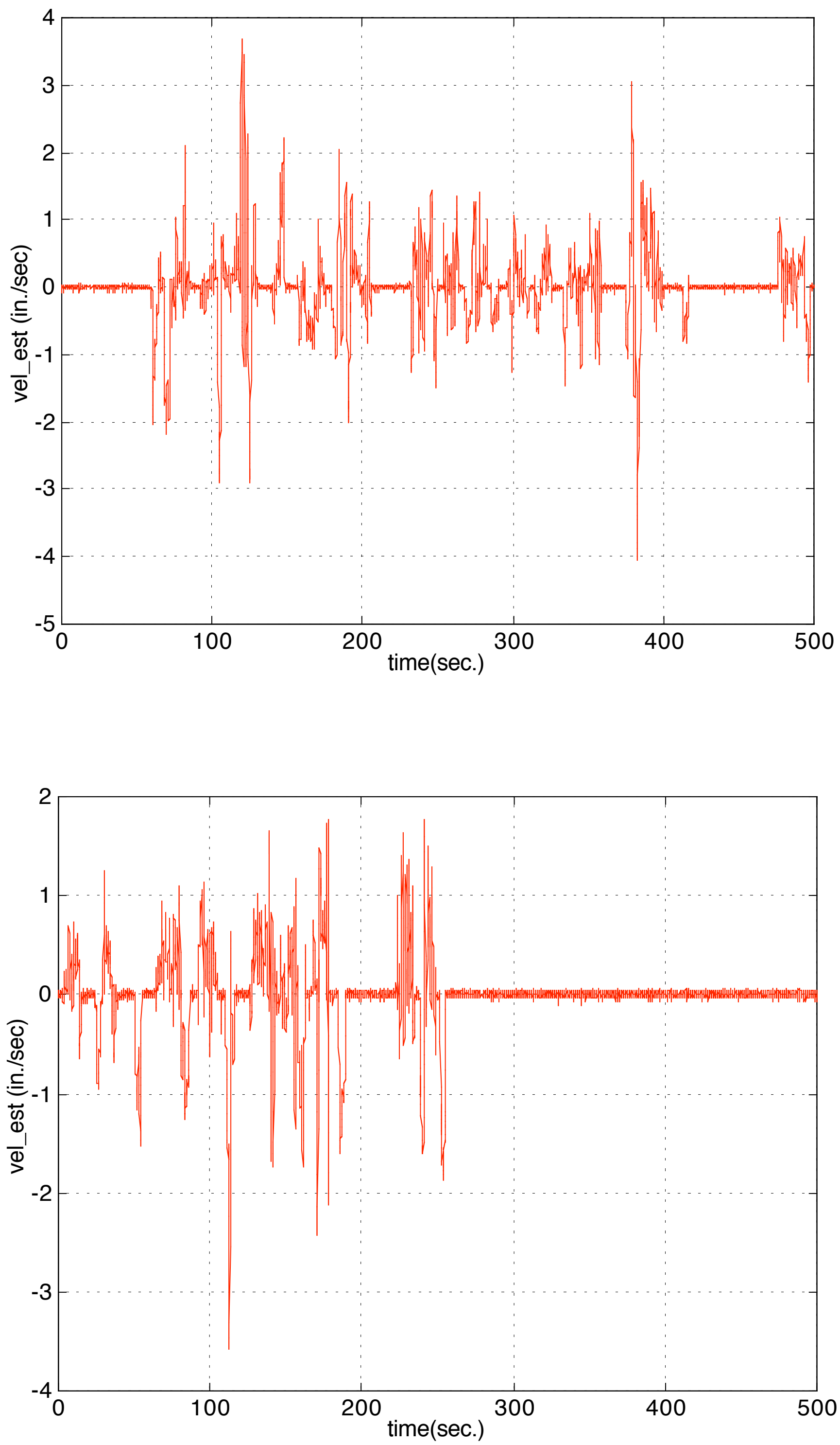
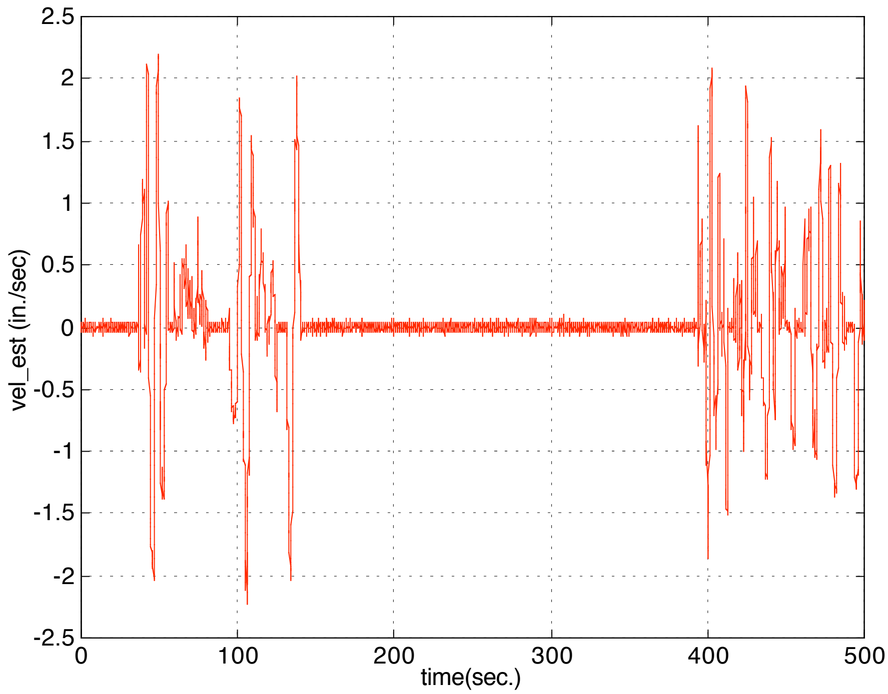


Fig. 8. Sample end-effector speed magnitude profiles during loading experiments with a 225-kg (500-lb) bomb.



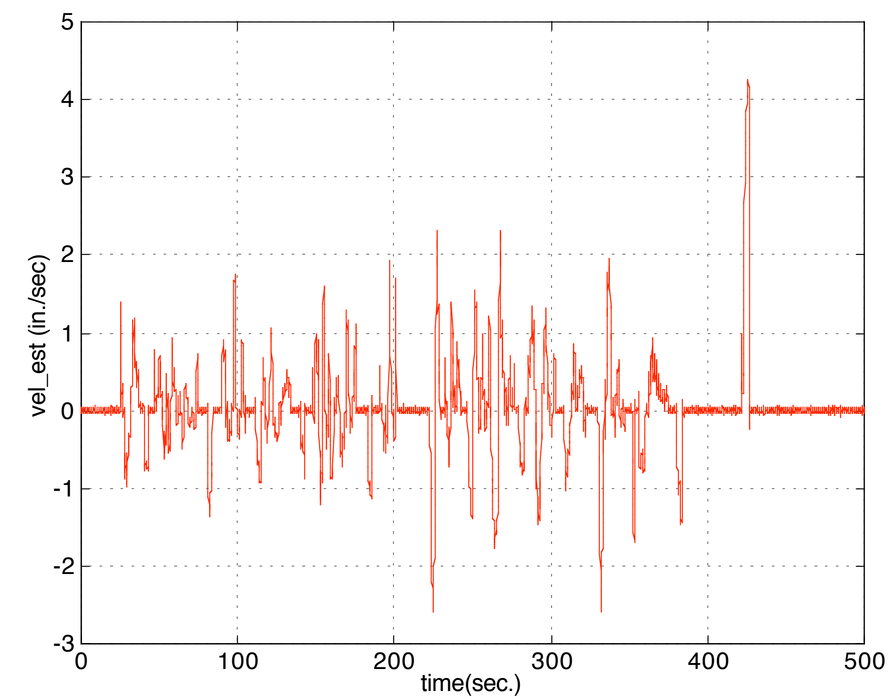


Fig. 8. Continued.

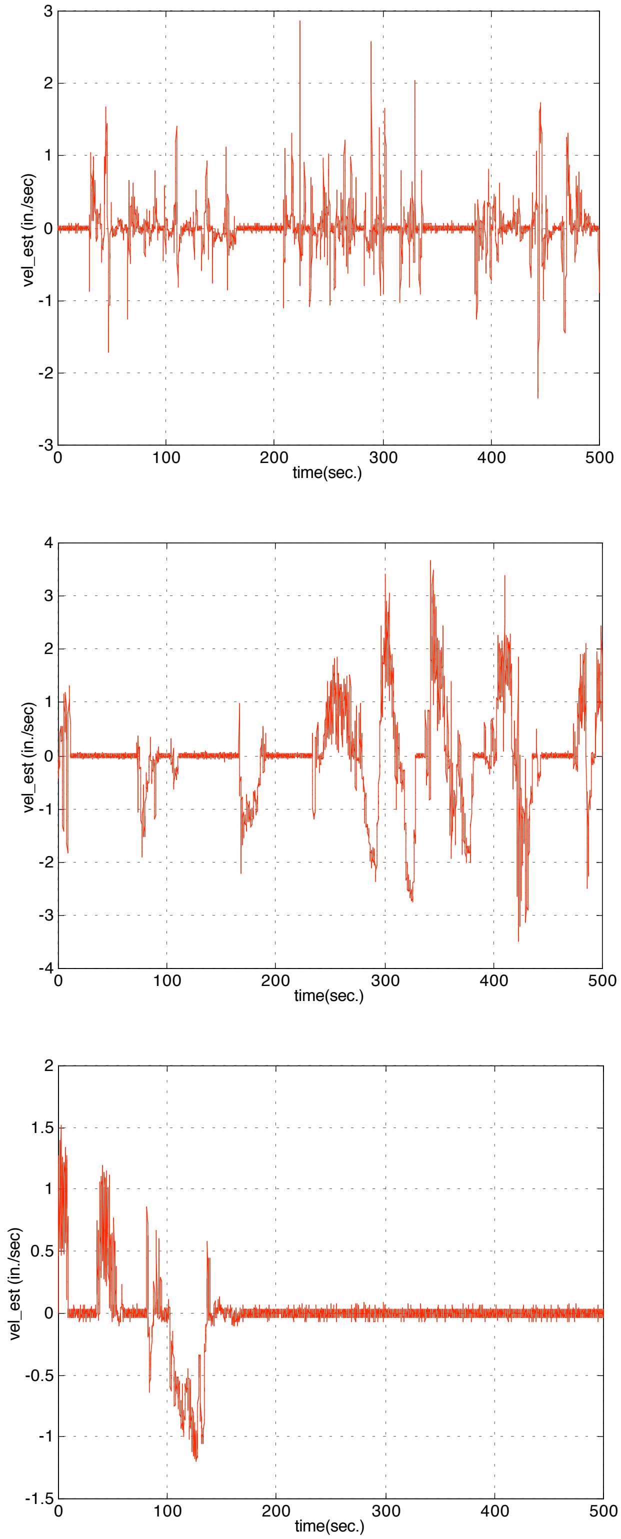


Fig. 9. Sample end-effector speed magnitude profiles during loading experiments with a 1,000-kg (2,200-lb) bomb.

4.5 HUMAN-ATTD INTERACTIONS

This section describes preliminary testing to garner feedback about the ATTD from experienced fighter load crews. The purpose of the testing was to provide preliminary information about control system parameters and to gather feedback from users about functionality. To that end, the USAF and USMC load crew interacted with the ATTD during testing sessions and provided feedback about the performance of the system. Certain control system parameters were changed during the course of the testing and feedback from the participants was used to make a rough estimate of "good" initial operating parameters. Section 6 contains photos taken during the various sessions with the load crew that illustrate the experimental setup and loading tasks.

4.5.1 Experimental Series 1: Heavy Lift Dexterous Manipulator Only

4.5.1.1 Experimental setup

The participants in the testing program were expert munitions loaders provided by the USAF. All of the participants were senior noncommissioned officers with many years of experience loading munitions, supervising loading, and training load crews. None of the crewmen had seen or operated the NGMH before participating in the testing program, but all had been informally briefed about the project before arriving at ORNL.

The principal apparatus for the experiment was the heavy-lift dexterous manipulator (HDM) component of the NGMH. At the start of testing, the HDM was positioned in front of a rack with a USAF weapons rack. Two types of (inert) conventional bombs were positioned near the rack for loading tasks. The two types were a 225-kg (500-lb) bomb fitted with a "ballute" retarder and fins and a 1,000-kg (2,200-lb) bomb fitted with standard fins.

Operational safety was an important concern during this testing program because of the nature of the HDM and its payloads and because of the relative inexperience of the load crews with the NGMH Program. For that reason, the first half-day of the testing program was devoted to a formal briefing on the NGMH project.

Testing itself was conducted using an informal format that encouraged the participants to interact with the HDM in a manner that allowed them to become familiar with its capabilities. At the end of each exercise with the NGMH, participants were briefly questioned about their experience with the machine. Any evaluative comments made by users were recorded, as were suggestions for improvement. The observer also noted important events or noteworthy differences in operating style during the task and then briefly questioned participants about problems with the system and reactions to the control system setup for that task.

Participants interacted with the system unloaded, moving the HDM through space with no set task and with no load on the end-effector. Having completed a series of sessions unloaded, they then acquired a 225-kg bomb (reaching out with the manipulator and placing it on the end-effector) and loaded it onto the rack. These two types of operations define the "unloaded" and "loaded" conditions.

Two extremes of human-amplification controls were tested: one termed "viscous" mode and the other termed "acceleration" mode. The viscous mode provided resistance to the operation motion much like a damper (e.g., the dampers used on household screen doors). Acceleration mode is comparable to moving an object in space with some external forces being cancelled.

Parameter modification during testing changed linear velocity, orientation velocity, linear force amplification, or moment force amplification gains. In viscous mode, linear velocity gain (labeled "Vel" in succeeding tables) determined the velocity of the system movement along the three spatial dimensions in response to a given joystick force input. Also in viscous mode, orientation velocity gain ("OrVel") determined the system rotational velocity around the three spatial axes in response to a given joystick moment input. In acceleration mode, linear force amplification gain ("Linear") determined the relationship between forces at the joystick and forces exerted by the manipulator about a remote center of compliance. Also in acceleration mode, moment force gain ("Moment") determined the relationship between moments at the joystick and moments exerted by the manipulator about a remote center of compliance.

4.5.1.2 Variables and data analysis

Initially, the terms "lag," "speed," "responsiveness," and "force input" were defined in vernacular terms for the participants in an attempt to regularize user feedback. However, after the first day of testing it appeared that the participants were able to provide richer feedback by reporting comments about the system using their own (sometimes colorful) terms. Therefore, the former scheme was abandoned in favor of the more free-flowing narrative interaction between testers and participants. This provided the best opportunity for a qualitative evaluation of the machine by the participants, and many good comments and important suggestions were recorded.

To provide a more structured analysis of user opinions, data about the context of the comment were also recorded with each comment. The context data included the testing date and session; the task, whether free-space motion or operations with a 225-kg (500-lb) bomb; and an identifying tag for the source of the comment (participant or observer). Each comment was then interpreted in two ways: first, the object of the comment was identified, and second, a valence was assigned to the comment. Comment objects included:

- General – comments referring to the general functioning of the HDM.
- Lag – comments referring specifically to the time between control input and system response.
- Speed – comments about manipulator end-effector speed.
- Responsiveness – comments about how well the manipulator followed the user's intended trajectory.
- Force input – comments about the amount of physical effort required to control the manipulator.
- Handle – comments about the human-machine interface at the end-effector.
- Suggestion – comments that were suggestions that might enhance the system.

Comment valences included (1) positive – comments that expressed approval of the machine, (2) neutral – comments that were not evaluative or that were not clearly positive or negative, and (3) negative – comments that expressed disapproval of the machine. All suggestions were coded as neutral. The latter procedure allows a more easily interpretable analysis of user reactions to the HDM than the raw comments themselves, but one should be cautious about generalizing from this procedure. First, categorization of comments depends upon the interpreter; this procedure is prone to reliability and bias problems. Second, comparison of operating modes and parameters carries with it the assumption either that comment frequency was randomly distributed across modes and parameters or that frequency was related to opinion strength. If these assumptions are not met, the validity of conclusions drawn from these data is questionable. As there was no attempt to randomize the administration order for modes and parameters, the threat to experimental validity from order effects (e.g., practice and fatigue) seems particularly potent. However, bearing these caveats in mind, use of the valence data does provide a clearer picture of user reactions to HDM operations.

Qualitative analysis of user comments was conducted by combing the experimental log for important user and observer comments. Comments were perused for trends in reactions to the HDM, for particularly illuminating reactions, and for suggestions for improving the machine. Each of these is discussed in the results section. Analysis of the valence data was by cross-tabulation of the percentage of comments in each valence category.

4.5.1.3 Results

The results of this informal testing program are necessarily qualitative, given the informal nature of the testing program and of the observations made during testing. However, this is appropriate to the purposes of the testing program. What follows is an analysis of the responses made by users.

On several occasions, participants referred to "fighting it" and reported an improvement in ease of use when speeds were increased. This is probably caused by users pushing harder on the handle when the HDM is moving more slowly than they would like it to move. The resulting higher forces, with the accompanying higher levels of muscle activation, were then interpreted (or at least reported) as "fighting" the HDM. This is similar to movement problems associated with teleoperators characterized by poor responsiveness. This can be ameliorated by increasing the velocity capability of the machine, but this must be done with appropriate consideration of the safety implications of higher speeds. Ease of use is not necessarily the most important criterion.

Examples of responses regarding the acceleration mode are "too sensitive at first" or "I liked it when I got used to it." Such comments may indicate a need for greater training with the acceleration mode than with viscous mode. During formal testing, it will be important to be sure that users have reached asymptotic performance levels with both modes to be sure that inexperience with one or the other does not skew the results of that testing. These comments may also indicate the need for relatively lower sensitivity to control inputs during certain phases of acquisition and loading. It is a well-established fact that any goal-directed movement occurs in two stages: a slewing phase, in which the target is approximately reached, and a fine-adjusting phase, in which final target acquisition occurs. The former is characterized by high-amplitude, low-frequency inputs and the latter by low-amplitude, high-frequency inputs during teleoperation. It seems likely that the problems users reported with acceleration mode are related to this control phenomenon. During fine-adjusting, high-frequency inputs may interact with system inertia to make the system less controllable with some system gains.

These reports may be related to fundamental human movement phenomena. A relationship exists between the amount of force produced by humans, whether to maintain impedance or accelerate a limb, and the variability in the force exerted. Human movements and forces during contact are, of course, produced by muscle contractions. These seem to be regulated by a motor unit (a unit comprising muscle fibers and their activating motor-neuron) recruitment scheme. Forces are generated by recruiting motor units to participate in the force impulse; each motor unit has a characteristic force waveform that varies from others in amplitude, duration, onset ramp, and offset ramp.

The variability in force impulses in amplitude and duration is determined by the sum of the variability of participating motor units. One effect of this is that the accuracy of human arm position at the end of a movement (or force variability during contact) is governed by the amount of force used to execute the movement (or the amount of force exerted during contact). The greater the force, the greater the number of participating motor units and the greater the variability of the force impulse and, therefore, the greater the position (or force) variability. Under some gain settings in acceleration mode, the force required to accelerate and decelerate the end-effector may require forces that produce variability greater than the final target positioning tolerance. Reports of improper sensitivity could be related to this effect.

Table 1 presents percentages of comments in each valence category, summed across modes, parameter settings, and tasks in the first row, and excluding the initial parameter setting for each mode and task in the second row. As the table shows, the majority of comments about the HDM were favorable (59%). When we exclude the initial parameter settings, which were always set in what was anticipated to be the low-performance ranges, the percentage of favorable comments was much higher (78%). In addition, the percentage of negative comments was nearly halved (from 27 to 14%). This indicates a highly favorable reaction to the HDM in general terms.

Table 1. Comment valences averaged across all modes, settings, and tasks (%)

	Negative	Neutral	Positive
All modes/settings	27	14	59
Excluding initial settings	14	7	78

User acceptance of the two control modes (viscous and acceleration) differed. Table 2 presents the percentages for each valence within each mode. A high percentage of comments about the viscous mode were positive (68%), and a low percentage were negative (17%). Just under half of the comments about the acceleration mode were positive (49%), and a relatively high percentage (though still a minority) of comments were negative (39%). More than twice the percentage of comments about the acceleration mode were negative than for the viscous mode.

Table 2. Comment valences for control modes across parameter settings (%)

Control mode	Negative	Neutral	Positive
Viscous	17	15	68
Acceleration	39	12	49

However, there was considerable change in the percentage of positive and negative responses across control mode and parameter setting combinations. Table 3 presents these percentages.

Some of the differences in Table 3 are worth noting. First, acceleration mode seemed sensitive to gain manipulations. In the unloaded condition, the initial gain settings received a majority of negative comments, and when the linear gain was halved, all of the comments were negative. However, when the linear gain was doubled (from the initial setting), all of the comments were favorable. The only cases in which all of the user comments were positive occurred in acceleration mode, as did the only case in which all of the comments were negative.

Table 3. Comment valences for all modes, settings, and tasks (%)

Load	Mode	Setting	Negative	Neutral	Positive
Unloaded	Viscous	Initial	33	24	43
Unloaded	Viscous	Vel[a] X 3	20	7	73
Unloaded	Viscous	OrVel[b] X 3	0	7	93
Unloaded	Acceleration	Initial	62	23	15
Unloaded	Acceleration	Linear[c] X .5	100	0	0
Unloaded	Acceleration	Linear[d] X 2	0	0	100
Unloaded	Acceleration	Moment X 2	0	0	100
Loaded	Viscous	Initial	14	29	57
Loaded	Viscous	OrVel X .5	0	14	86
Loaded	Acceleration	Initial	57	14	29
Loaded	Acceleration	Linear X .25	0	17	83
Loaded	Acceleration	Linear X .5	33	11	56

[a] Linear velocity gain.
[b] Orientation velocity gain.
[c] Linear force amplification gain.
[d] Moment force gain.

Second, there seemed to be an interaction of load and parameter settings in both modes. High gain settings led to higher percentages of positive comments when unloaded. However, when manipulating the 225-kg (500-lb) bomb, low gain settings led to higher percentages of positive comments.

The user comments also allow an evaluation of the components of the system in terms of valence. Table 4 presents the percentage of each valence within comment topics. From Table 4, it appears that general comments were mostly favorable (69%). Force input comments were mostly negative (50%), which probably reflects the importance of this parameter for ease of use. Handle comments were also mostly negative (58%). Handle placement, orientation, size, and so on, are very important for ease of use. The high percentage of negative comments indicates that there is still work to be done to arrive at an optimal handle configuration and placement. Comments related to control system performance (lag, responsiveness, and speed) were mostly favorable.

Table 4. Comment valences for specific topics (%)

Topic	Negative	Neutral	Positive
General	22	8	69
Force input	50	6	44
Handle	58	33	8
Lag	0	20	80
Responsiveness	26	15	59
Speed	26	11	63
Suggestion	0	100	0

Table 5 presents the percentage of the total comments recorded, sorted by topic and valence. Table 5 also presents the percentage of total comments for each topic, which is an indicator of the salience of each topic for the users during the testing. No single topic produced a majority of comments. The highest percentage of comments (37%) were general comments, directed at overall system functioning. The next most frequent comment topic was responsiveness (20%), followed by speed (14%), force input (13%), and the handle (9%). The ranking of topics on percentage of total comments may be evidence of the relative importance of each of these topics for user acceptance. However, because of the informal nature of the testing some caution should be taken in using this interpretation.

Table 5. Comment valences for specific topics as a percentage of all comments (%)

Topic	Negative	Neutral	Positive	Total
General	8	3	25	37
Force input	7	1	6	13
Handle	5	3	1	9
Lag	0	1	3	4
Responsiveness	5	3	12	20
Speed	4	1	9	14
Suggestion	0	3	0	3

Table 6 presents comments sorted by exercise and topic. This table provides some further insights into how the users interacted with the HDM, particularly when comparing comments across load conditions. The number of general comments and the percentages in each valence category were about the same for the two conditions. However, no force input comments were recorded during the loaded condition, while 13% of the total were recorded for force input in the unloaded condition. More handle comments were made in the unloaded condition (8%) than in the loaded condition, and in the latter, all of the comments made were neutral. In both conditions, 10% of the total comments recorded were about responsiveness; however, in the unloaded condition 77% of comments were positive, while in the loaded condition comments were equally distributed between positive and negative (43%). In the unloaded condition, 13% of the comments were about speed, and 61% of these were negative; in the loaded condition only 1% of the comments were about speed, and all of these were positive. Taken together, these figures seem to indicate a different approach to unloaded and loaded operations. In unloaded operations, the emphasis seems to be on speed, and force input and handle topics become important in that they restrict motion. In loaded operations, speed, force input, and handle topics are less important and users are more sensitive to responsiveness. Many of the negative comments about responsiveness during loaded exercises referred to responsiveness being too high, particularly when close to the rack (fine-adjusting phase).

Table 6. Comment valences for specific topics within tasks, as a percentage of all comments within each task (%)

Exercise	Topic	Negative	Neutral	Positive	Total
Unloaded	General	21	8	71	18
Unloaded	Force input	50	6	44	13
Unloaded	Handle	64	27	9	8
Unloaded	Lag	0	20	80	4
Unloaded	Responsiveness	8	15	77	10
Unloaded	Speed	28	11	61	13
Unloaded	Suggestion	0	100	0	1
Loaded	General	24	8	68	19
Loaded	Handle	0	100	0	1
Loaded	Responsiveness	43	14	43	10
Loaded	Speed	0	0	100	1
Loaded	Suggestion	0	100	0	1

4.5.2 Experimental Series 2: USAF and USMC Loaders – Arm and Vehicle

4.5.2.1 Experimental setup

The participants in the testing program included the same expert munitions loaders provided by the USAF for the first experiment. Participants also included expert munitions loaders provided for the program by the USMC. All of the participants were senior noncommissioned officers with many years of experience loading munitions, supervising loading, and training load crews. None of the crew had seen or operated the NGMH before to participating in the testing program, but all had been informally briefed about the project before arriving at ORNL.

The principal apparatus for the experiment was the fully functional NGMH, including the HDM and the omnidirectional platform. Inert bombs and missiles were placed on a standard-issue bomb trailer for loading exercises. A standard F-15 weapons rack was mounted at the typical height (from the floor) on a rack approximately 15 ft from the trailer.

Operational safety was again an important concern during this experiment because of the nature of the HDM and its payloads and because of the relative inexperience of the load crews with the NGMH. For that reason, the first half-day of the testing program was devoted to a formal briefing on the NGMH project.

Testing itself was conducted using an informal format that encouraged the participants to interact with the HDM in a manner that allowed them to become familiar with its capabilities. At the end of each exercise with the NGMH, participants were briefly questioned about their experience with the machine. Any evaluative comments made by users were recorded, as were suggestions for improvement. The observer also noted important events or noteworthy differences in operating style during the task and then briefly questioned participants about problems with the system and reactions to the control system setup for that task.

Participants interacted with the system unloaded, moving the HDM through space with no set task and with no load on the end-effector. Having completed a series of sessions unloaded, they then acquired a 225-kg bomb (reaching out with the manipulator and placing it on the end-effector) and loaded it onto the rack. These two types of operations define the unloaded and loaded conditions.

Manipulator parameters were set at levels judged best at the conclusion of the first experiment.

4.5.2.2 Variables and data analysis

As was true of the first set of participants, members of the second set were able to provide comments about the system using their own terms. Therefore, the free-flowing narrative interaction between testers and participants was used to gather information during the second experiment. This provided the best opportunity for a qualitative evaluation of the machine by the participants, and many good comments and important suggestions were recorded.

Task-timing data were collected for both the USAF participants and for ORNL testing personnel. These data were collected informally by an observer while load crews operated the NGMH. During testing, emphasis was on familiarizing users with the system rather than on a formal task protocol. Therefore, users often repeated a subtask (e.g., attaching the weapon to the rack or acquiring the weapon at the trailer) until they were confident in their ability to complete the task. Therefore, task-timing data were not part of a rigorous task analysis, but rather observations taken in the course of informal exercises. This means that, although the data have some value for understanding how well load crews perform tasks with the NGMH, they lack sufficient exactitude to be representative of performance.

Qualitative analysis of user comments was conducted by combing the experimental log for important user and observer comments. Comments were perused for trends in reactions to the HDM, for particularly illuminating reactions, and for suggestions for improving the machine. Each of these is discussed in the results section. Analysis of the valence data was by cross-tabulation of the percentage of comments in each valence category.

Task and subtask completion times were taken informally while USAF loaders and ORNL users were operating the NGMH. These data are reported as indications of the times that may be possible with the NGMH, but not enough of these data were collected to reliably represent typical performance.

4.5.2.3 Results

The loaders made fewer comments during the second testing week. During the first test, 167 loader comments were recorded, but only 33 were recorded during the second test. The latter comments were, for the most part, more specific and more directed at NGMH characteristics that could be improved. Table 7 shows the numbers and percentages of comments by valence.

Table 7. Comments and valences during the second test

	Total	Positive	Neutral	Negative
Sum	33	5	12	16
Percentage (%)		15	36	48

Most of the comments (55%) during the second test were general questions or suggestions about NGMH functioning. Of the total, 24% of the general comments were negative. Many of the negative comments (30% of the total) were expressed by the USMC loaders and appeared to be reactions to their introduction to the NGMH. The USAF loaders had the benefit of previous exposure to the system, which the USMC loaders lacked. In addition, concerns about a hurricane heading for their hometown the day of the testing and their resulting eagerness to return home early, is thought to have significantly affected the behavior of the USMC loaders during their term at ORNL. An example of a negative USMC comment was, "There was confusion over the orientation of the driving handle. [They] expected the axes of the handle to line up with the axes of the vehicle." (The current driving handle configuration is designed to be *ergonomically* correct, that is, oriented for the most comfortable alignment with the normal human hand in the driving posture. However, this orientation may not be *cognitively* optimal because it is not aligned with the forward-aft and left-right axes of the vehicle.) The USAF loader comments were mainly suggestions for improving the system (suggestions were uniformly assigned a neutral valence). Table 8 shows the percentages of comments by valence and loaders.

Table 8. Comments by loader service and valence (percentages of total comments)

	Total	Negative	Neutral	Positive
USAF	48	18	21	9
USMC	52	30	15	6

Many loader comments (33%) during the second test were about the handles used at the driving station or the end-effector. Of the total number of comments, 24% were negative comments about the handle. An example of the latter was, "Handedness is a problem with the current handle design," which refers to the design of the end-effector handles and a perception that these are more convenient for right-handed users than for left-handed users. Table 9 shows the percentages of comments by topic and valence.

Table 9. Comments and valences by topic (percentages of total comments)

TOPIC	Total	Positive	Neutral	Negative
General	55	12	18	24
Handle	33	3	6	24
Suggestion	12		12	

Task and subtask completion times are presented in Table 10. Munitions loading was efficient, requiring (on average) 520 seconds for a single participant to acquire a weapon, move it to the rack, and install it on the rack. For the four munitions used in testing (AIM-120, AIM-7, and 2000-lb and 500-lb bombs), the longest loading times were for the AIM-120. The shortest time observed was for the 500-lb bomb. From the data in Table 10, it seems that the mass of the weapon had no impact on task times. It appears that the greater accuracy required to attach a missile to a rack, compared with bomb loading, is the source of the difference. Bombs also appeared to require less time to acquire and transport. However, the differences may be more the result of user inexperience than real differences across munitions. Within the context of unstructured observations like these, it is impossible to separate differences caused by the equipment from differences in training and practice.

Table 10. Subtask and task times (in seconds)

	Subtask				
Weapon	*Acquire*	*Transport*	*Load*	*Total*	*Time (min.)*
AIM-120	180	360	240	780	13.00
			120		
			60		
			60		
			120		
			120		
			50		
			50		
			50		
			50		
	188	301	207	696	11.60
2000-lb bomb	115	191	99	405	6.75
AIM-7	161	114	204	479	7.98
			206		
			123		
500-lb bomb	34		23		
	24				
	126		26		
			17		
	156	55	27	238	3.97
			17		
			17		
	118		52		
			17		
Averages	122.44	204.20	85.00	519.60	8.66

4.5.3 Discussion

The NGMH testing program provided preliminary data about human interaction with a unique new manipulator system. The purpose of the testing was to gather preliminary reactions of experienced load crew to the HDM, and it succeeded in that purpose. Analysis of user comments provides interesting insights but no definitive conclusions because of the preliminary, and informal, nature of the testing program. Much of what follows in this section is speculative and should be verified in formal testing to be conducted using the NGMH in the future. Future testing should also include fatigue as an evaluation parameter.

User reactions to the HDM were generally positive. All of the USAF personnel were favorably impressed with the capabilities of the system, as Table 1 shows. Fine-tuning operating parameters created a system even more favorably regarded by the load crews. Further adjustment to control system parameters will result in a system that is operationally efficient, easy to use, and well accepted by users.

At this time it is difficult to decide whether the preference expressed for the viscous mode represents a real difference in ease of use or is related to either training or improper parameterization of the acceleration mode. These data are not conclusive enough to come to any definitive verdict about the value of acceleration mode, given the latter considerations and the exploratory nature of the testing reported in this manuscript. However, the user reactions do point to a problem that should be addressed in future testing programs. To adequately evaluate the relative merits of the two extremes in control modes, it will be necessary to ensure that users have enough practice to reach asymptotic performance with both modes.

The sensitivity problem reported by users in acceleration mode can be ameliorated by several approaches. First, reducing overall system gain will make the system less sensitive. Second, provision could be made for selecting slewing and fine-adjusting modes from the HMI to match gain to the task phase. Both options have been implemented and experimented with. In particular, the second option has been incorporated in the new set of HMI handles and displays that have been implemented on the system. The operator now can select three different loading conditions, and consequently three set of control parameters, by the simple push of a button on the end-effector-mounted HMI displays. Figure 10 shows the new HMI display, as mounted on the end-effector of the extension system for loading the bomber fleet. The user-selectable operation mode (platform, arm, etc.) is displayed through the green buttons on the right, while the user-selectable control mode, expressed as a payload type (e.g., 500 lb, 2000 lb, or missile), is displayed through the yellow buttons on the left.

Data that provide evidence of differences between loaded and unloaded operations verify expectations of the system designers. During unloaded operations, users desire a system that is responsive and speedy. During loaded operations, more care must be taken to move carefully, particularly in proximity to the rack and loading trailer, so users find responsiveness and speed less important.

The HMI testing reported in this document concentrated on preliminary identification of “good” operating parameters for the HDM, using USAF load crew comments as the primary figure of merit. Future testing should identify optimal operating parameters through more formal testing, using a wider range of figures of and correlated measurement of user workload and fatigue. The testing reported here is an important first step in the overall plan to empirically identify and verify optimal HDM control system parameters. Further testing should probably be performed on the future prototype(s) to provide data valuable for, and representative of, the actual systems that will be used in future field work.

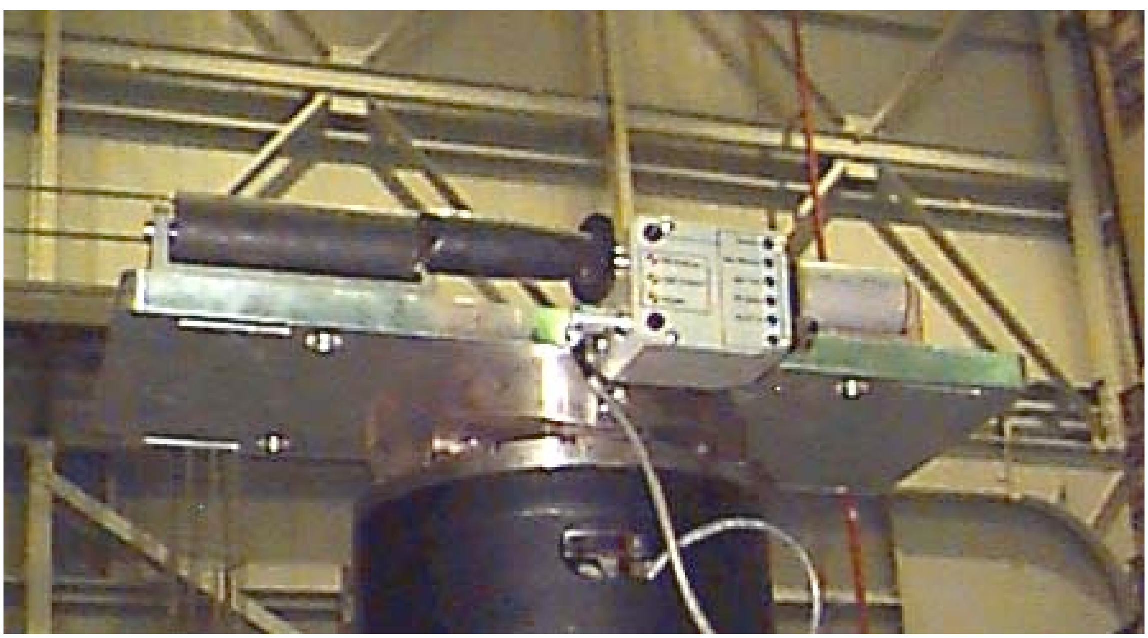


Fig. 10. New HMI showing the feasibility of implementing user-selectable operation modes and control modes with their corresponding displays.

5. CONCLUSIONS AND SUMMARY

The long-term objective of the NGMH Program is to improve weapon-loading tasks. Overall loading improvement objectives were given by the USAF sponsor as follows:

- Reduced overall time (e.g., improved platform motion capability, improved arm positioning capability, and reduced jamming potential).
- Reduced crew size (e.g., enhanced HMI systems, enhanced human-machine synergy, and enhanced functionality).
- Enhanced reachability, manipulability, and maneuverability, with better controls.
- Reduced soldier workload (e.g., reduced fatigue, reduced communication needs between crew, "near-weightless" operations, decreased jamming occurrences, and task space control).
- Reduced equipment footprint and weight.

These improvements in the loading process are thought to be feasible through the use of emerging telerobotics technologies. However, some of these technologies have never been implemented, either separately or in an integrated fashion, on systems with the size, payload, scale, and working environment that is expected for the NGMH. Additionally, no data exist on the feasibility of the implementation and/or the preferred configuration of these technologies for producing advanced weapon-loading systems. Therefore, the NGMH program managers decided that before initiating the development of a prototype, an Advanced Telerobotics Technologies Demonstrator (ATTD) should be developed.

Thus, the ATTD was developed, not as a prototype, but as a test-bed system to demonstrate the *feasibility* of integrating and using novel concepts and telerobotics technologies. The telerobotics technologies that were identified as candidates to meet the objectives of the ATTD system were as follows:

- Controls and actuation for high-precision positioning (submillimeter, sub-tenth-of-degree) and insertion tasks (force control) under high payload (2,500 lb).
- Omnidirectional platform motion.
- Hand-on-the-system telerobotics control.
- Human-machine synergistic interface with:
  - human-strength-amplification (with gravity compensation) for manipulation, and
  - come-along mode for the platform.
- System's joint motion coordination with real-time kinematic redundancy resolution.
- High-payload, high-impact-rated, high-resolution force/torque sensing.
- Active compliance control for operator aid in complex insertion tasks.

Performance measures for meeting the ATTD objectives with respect to these technologies were identified in an objective document provided by the USAF (shown in Fig. 1).

All these technologies were successfully developed, implemented, and demonstrated on the ATTD. The feasibility of integrating and using these technologies toward improving the weapons-loading process has been ascertained. All these telerobotics technologies, except one, are evaluated as ready for transition to a prototype development phase. The only exception is the high-payload, high-impact-rated, high-resolution force/torque sensing device that is essential for advanced force control methodologies and the novel HAT. An on-going task is addressing the design and development of a new sensing technology that should remedy the problems encountered on the ATTD.

All performance measures stated for the ATTD led to highly satisfactory results. The only exception being the overall ATTD system weight. Preliminary studies indicate that significant weight reductions are feasible at the prototype phase. The feasibility of several other technologies and/or features was demonstrated that were not initially planned in the scope of the ATTD. Among these are the new "operator lifts himself with the weapon" concept to achieve very high reach (e.g., for loading the bomber fleet); a new actuated missile end-effector with positive grasp and control of the weapon; a quick-connect concept to mount and use tines (e.g., for loading guns, for loading missiles directly out of containers, and for compatibility with USMC loading adapters and fuel tank loading adapters); a quick-connect adapter for rack loading in pylons and for pylon loading onto wings; and several adapter concepts for F-22 maintenance tasks.

The ATTD development also provided significant experience toward identifying the technological improvements that would be needed if the requirements for the future NGMH prototype(s) were to change significantly from those of the ATTD. Among the most likely of these is the need for an alternative omnidirectional wheel system if platform speeds in excess of walking pace or operations on "nonuniform" and nondeveloped surfaces were desired.

Of course, many other technologies that were not part of the ATTD scope (which focused on a particular set of emerging telerobotics technologies) will be necessary at the prototype phase. In particular, technologies specific to particular versions of the possible future NGMH prototypes (e.g., ship- or land-based versions) will need to be specifically developed, integrated, and tested. However, from the results of the ATTD phase, several activities can be identified that have generic and pervasive applicability to all future potential prototype(s) and that constitute high priority with respect to the overall NGMH Program. Some of these are discussed earlier in this report and are as follows:

- A high-payload, high-resolution, high-impact-rated force/torque sensing technology with outdoor weather resistance, in particular to large temperature ranges and temperature gradients.
- Weight mitigation studies to achieve even higher payload/weight ratios than the already excellent value of the ATTD.
- Related to the previous item are needs for detailed analyses of power requirements versus tasks to be performed, as any amount of "overkill" in the requirements may have a dramatic impact on other design areas. Additionally, depending on the sought performance levels in the future prototype(s), studies and experimental investigations related to alternative power supply and to power transmission modes and technologies are highly recommended because they could result in significant global savings for the ultimately deployed systems.
- A control/computational architecture that is better suited to large-quantity manufacturing than the development-oriented one used on the ATTD will be needed for the prototypes, which also allows ready implementation and maintenance of the novel human-amplification and related technologies.
- A related activity concerns the need for an innovative sensing bus architecture, which would allow simpler signal networking and wiring (and consequently enhanced reliability and maintenance), while assuring the controls and safety characteristics needed for the human-amplification and related technologies.
- Investigation and experimental comparisons of the OCSW design to achieve holonomic, omnidirectional, high-payload platform motion on nonuniform terrain or at high speeds should be performed to meet the expected USAF and USMC requirements for the land-based prototype.
- When the preceding studies, as well as those related to the other specific characteristics that will be desired in the future potential prototype(s) have been accomplished and the corresponding EMD phase prototype(s) have been produced, formal system and component Reliability And Maintainability (RAM) studies should be undertaken.
- In a similar fashion, formal cost-mitigation studies based on conventional or innovative manufacturing methods should be performed during future EMD phases of prototype(s) development.
- Further human-machine interaction studies, focused primarily on the areas and results outlined in Sect. 4.5, should be conducted using the actual control components and systems that will be embodied in the future prototype(s) to respond to the probably different requirements of these systems. Therefore, our recommendation is to conduct these studies during the prototype development and/or EMD phases of the future program.

6. SAMPLE PHOTOS TAKEN DURING SOME OF THE DEMONSTRATION AND EVALUATION SESSIONS WITH THE LOAD CREW

The following set of photos is provided mainly as illustrative information about the experimental setup used during the demonstration and evaluation sessions.

Fig. 11. The NGMH-ATTD in its configuration during the latest demonstration.

Fig. 12. Practicing with precision handling for weapon acquisition at the trailer.

Fig. 13. Experimenting with weapon acquisition at the trailer.

Fig. 14. Experimenting with the force feedback and automated insertion aid features during the loading of a 225-kg (500-lb) MK-82.

Fig. 15. Loading an MK-82 on a self-locking BRU-32A rack, 36 in. from the ground.

Fig. 16. A navy engineer experimenting with the loading of a 1,000-kg (2,200-lb) MK-84 with a lateral approach (perpendicular) to the pylon.

Fig. 17. Loading a 1,000-kg (2,200-lb) MK-84 from a frontal approach (parallel to the pylon).

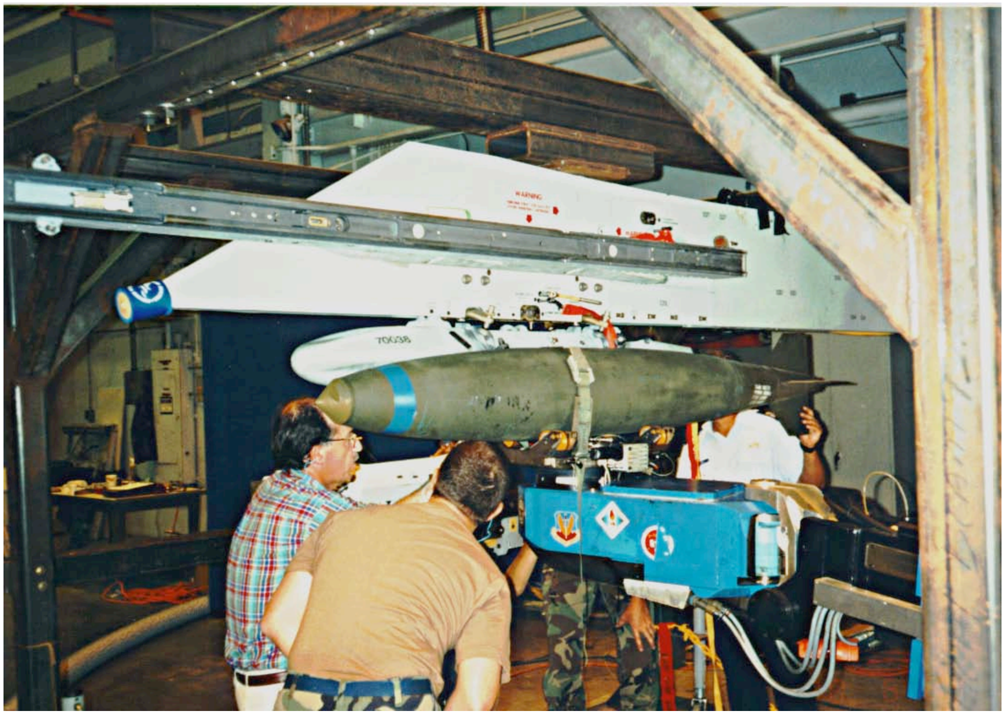


Fig. 18. Loading an upper station of a TER (loading orientation is 45 degrees from vertical).

Fig. 19. Experiments with omnidirectional maneuvering of the ATTD, loaded with a weapon, in a 10- by 10-ft confined and obstructed space, using the platform HMI.

Fig. 20. Experiments with maneuvering and precise positioning of the ATTD platform from one of the end-effector-mounted HMIs.

Fig. 21. Loading an AIM-120 missile on a wing pylon-mounted launcher. View from the back of the ATTD platform.

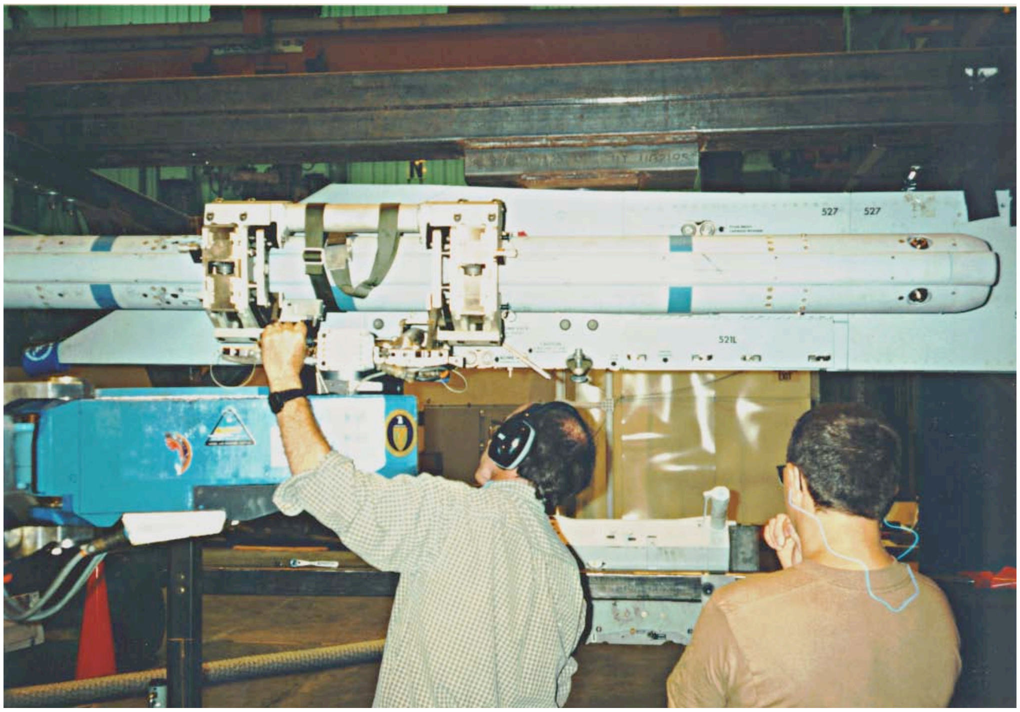


Fig. 22. Loading an AIM-120 missile on a wing pylon-mounted launcher. Side view (perpendicular to the pylon).

Fig. 23. Demonstrating the feasibility of operating under very low aircraft. Approach to clearing a 36-in-high mark with an AIM-120 missile on the end-effector.

Fig. 24. Demonstrating the feasibility of operating under very low aircraft. The high point of the ATTD passes under the 36-in-high mark.

Fig. 25. Loading an AIM-7 Sparrow missile on a LAU-116/A launcher. Approach motion.

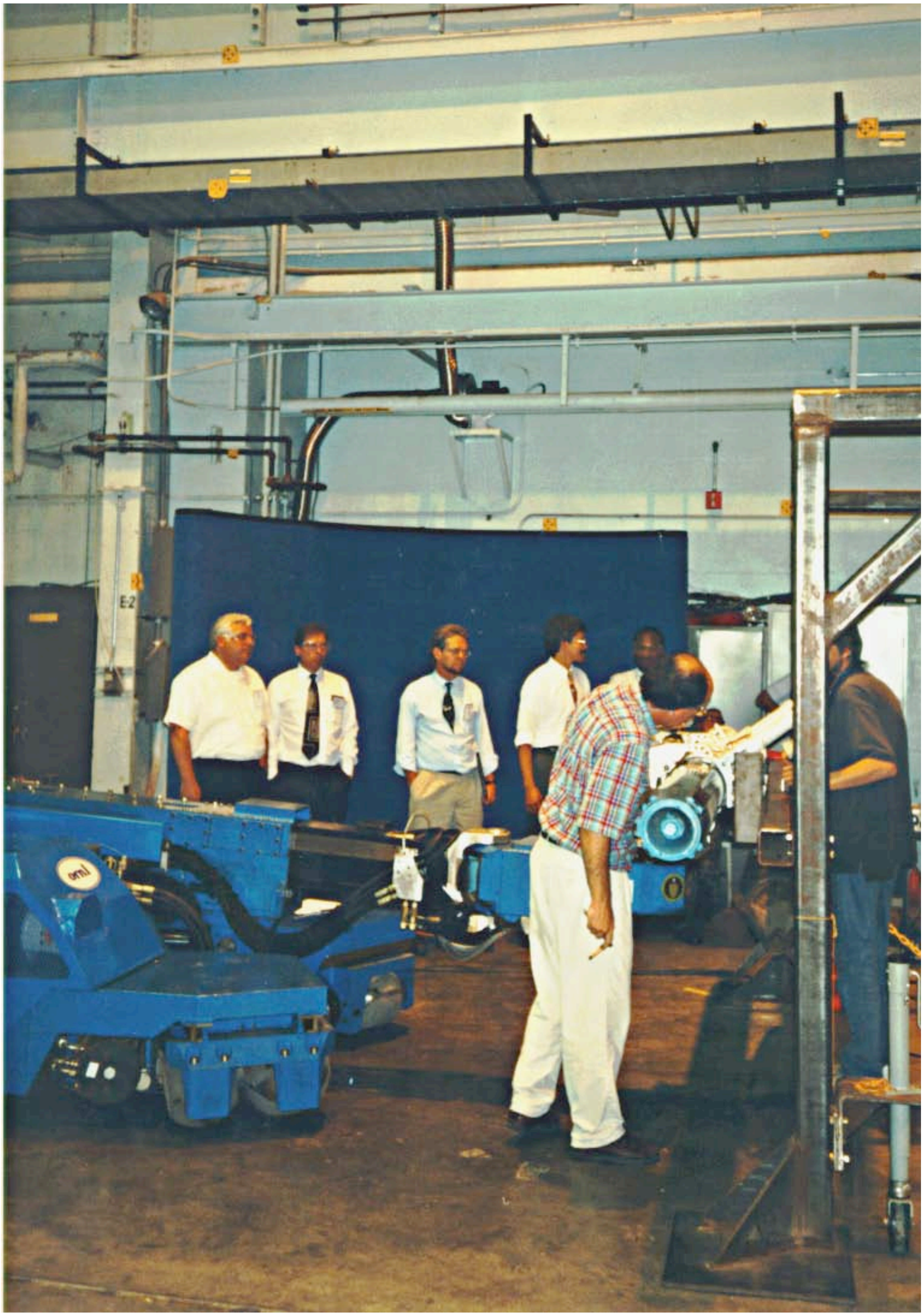


Fig. 26. Loading an AIM-7 Sparrow missile on a LAU-116/A launcher. Locking the missile in place after insertion.

Fig. 27. Navy engineer performing the loading of an AIM-7 Sparrow missile on a LAU-116/A launcher with the ATTD.

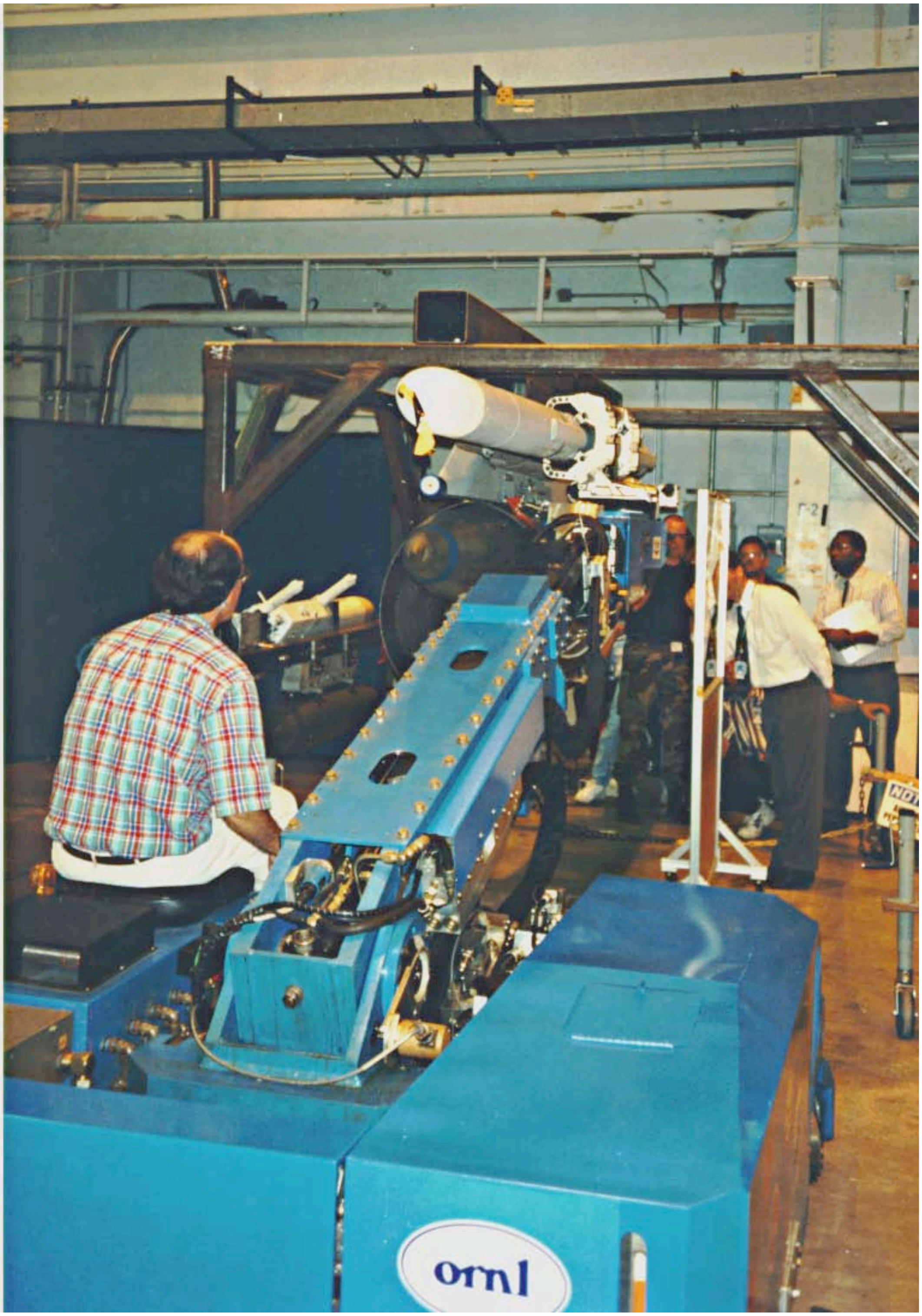


Fig. 28. Loading an AIM-120 missile on an inboard pylon in a very constrained environment simulating an F-15/E with conformal and wing pylon fuel tanks. Approach motion using the platform.

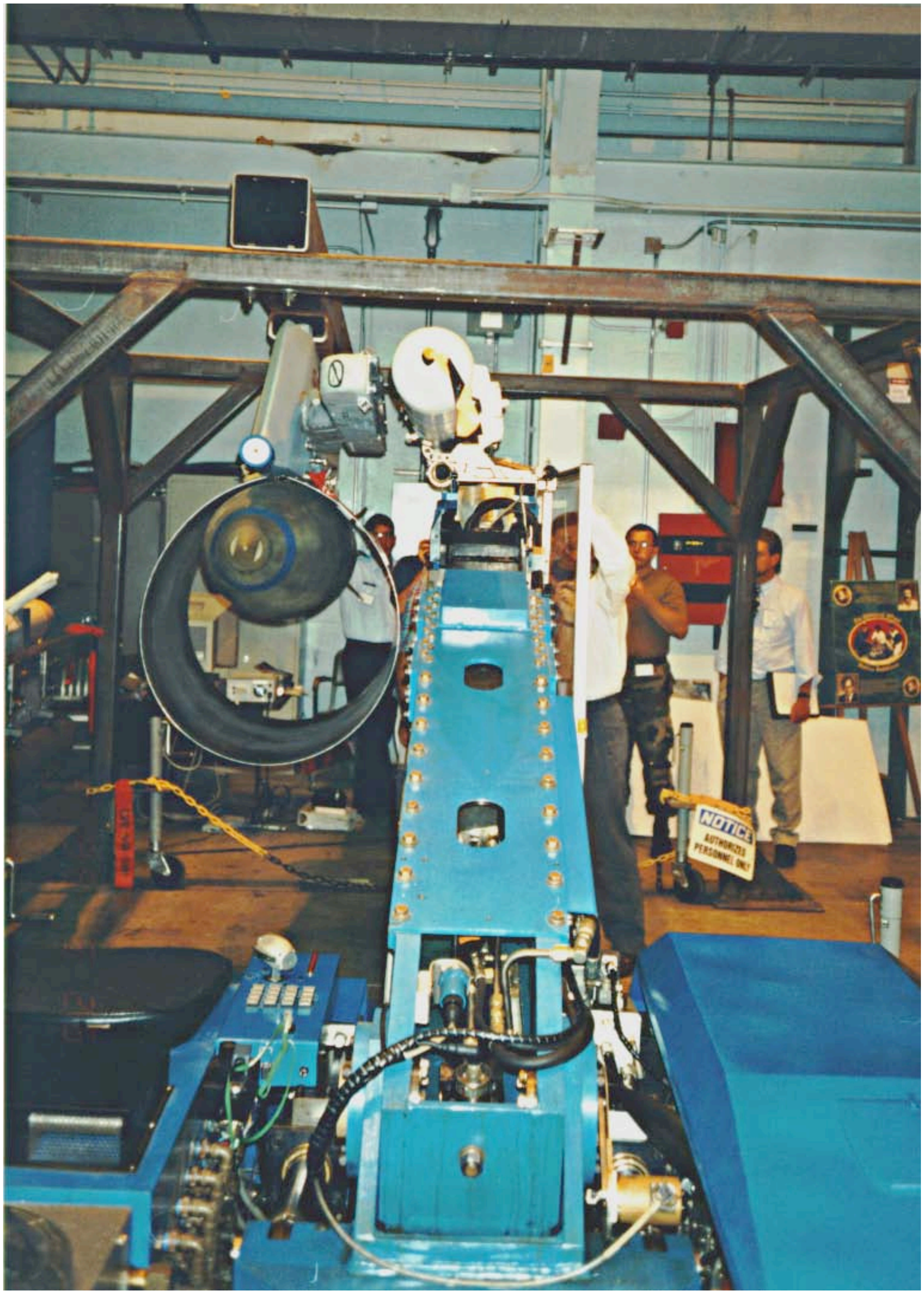


Fig. 29. Loading an AIM-120 missile on an F-15/E inboard pylon. The large cylinder hanging from the pylon simulates the wing pylon fuel tank, and the divider on the right simulates the conformal tank. In this view from the back of the platform, the operator is barely visible behind the arm.

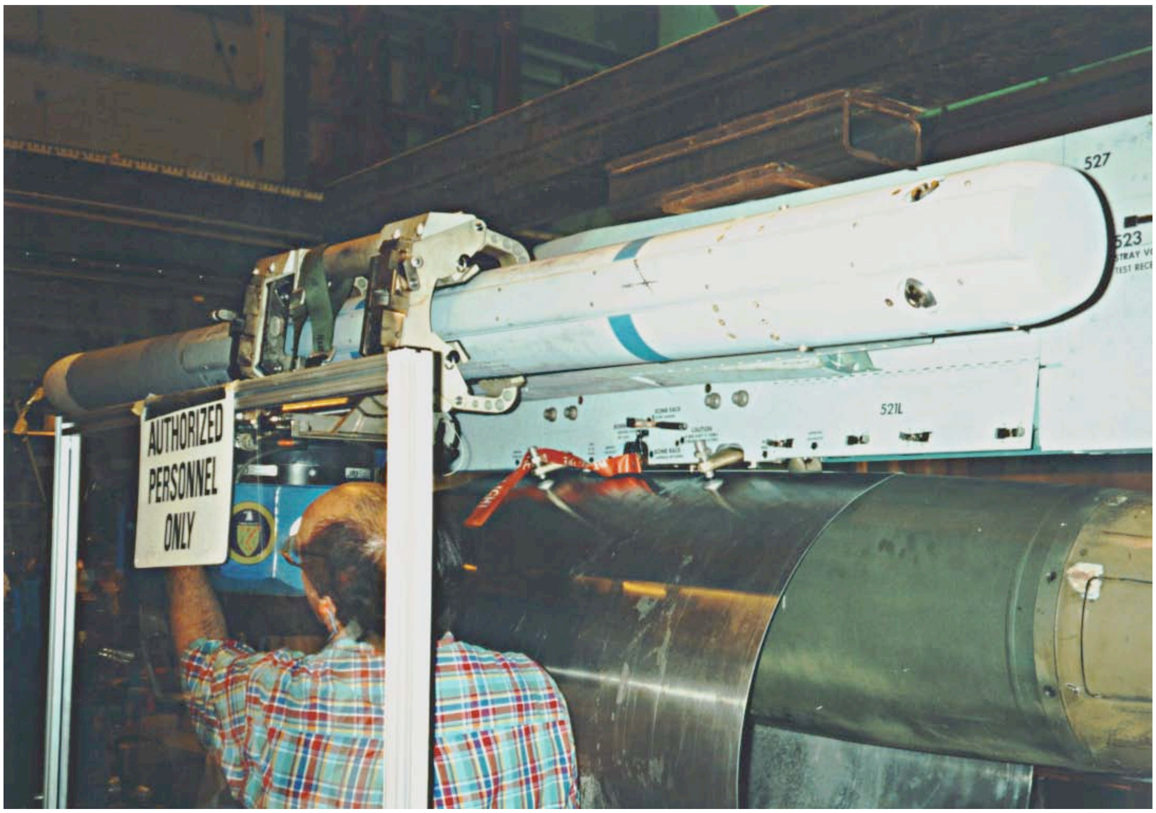


Fig. 30. Loading an AIM-120 missile on an F-15/E inboard pylon. The large cylinder hanging from the pylon simulates the wing pylon fuel tank, and the transparent plastic divider on the left simulates the conformal tank. In this view from the wing trailing edge, the operator is visible between the two fuel tanks. The complete loading scenario and downloading of the missile took less than 5 minutes.