

NEXT GENERATION MUNITIONS HANDLER: HUMAN-MACHINE INTERFACE AND PRELIMINARY PERFORMANCE EVALUATION

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ABSTRACT

The Next Generation Munitions Handler/Advanced Technology Demonstrator (NGMH/ATTD) is a technology demonstrator for the application of an advanced robotic device for re-arming U.S. Air Force (USAF) and U.S. Navy (USN) tactical fighters. It comprises two key hardware components: a heavy-lift dexterous manipulator (HDM) and a nonholonomic mobility platform. The NGMH/ATTD is capable of lifting weapons up to 4400 kg (2000 lb) and placing them on any weapons rack on existing fighters (including the F-22 Raptor).

This report describes the NGMH mission with particular reference to human-machine interfaces. It also describes preliminary testing to garner feedback about the heavy-lift manipulator arm from experienced fighter load crewmen. The purpose of the testing was to provide preliminary information about control system parameters and to gather feedback from users about manipulator arm functionality. To that end, the Air Force load crewmen interacted with the NGMH/ATTD in an informal testing session 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. Later, formal testing will concentrate within this range to identify optimal operating parameters.

User reactions to the HDM were generally positive. All of the USAF personnel were favorably impressed with the capabilities of the system. 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.

INTRODUCTION

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

Improvements sought for the loading process are thought to be feasible through the application of emerging telerobotics technologies. However, some of these technologies have never been implemented, either separately or in integrated fashion, on systems with the size, payload, and working environment that is expected for NGMH. Additionally, no data exist on the feasibility of the implementation or the optimal configuration of these technologies for weapons loading. Therefore, the NGMH program has developed an Advanced Telerobotics Technology Demonstrator (ATTD). The purpose of the ATTD is allow investigation of the feasibility of using emerging robotics technology in the NGMH role.

The NGMH/ATTD was developed at the Oak Ridge National Laboratory (ORNL), in the Robotics & Process Systems Division. It comprises two key hardware components: a heavy-lift dexterous manipulator (HDM) and a nonholonomic mobility platform. In addition, the NGMH features an advanced control system. The NGMH will be capable of lifting weapons up to 4400 kg (2000 lb) and placing them on any weapons rack on existing fighters (including the F-22).

This report describes preliminary testing to garner feedback about the heavy-lift manipulator arm from experienced fighter load crewmen. The work was sponsored by the USAF and USN, and performed at ORNL. The purpose of the

testing was to provide preliminary information about control system parameters and to gather feedback from users about manipulator arm functionality. To that end, the USAF load crewmen interacted with the NGMH/ATTD in an informal testing session 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. Later, formal testing will concentrate within this range to identify optimal operating parameters.

METHODS

Participants

The participants in the testing program were expert munitions loaders provided for the testing program by the USAF. All of the participants were senior non-commissioned officers with many years of experience loading munitions, supervising loading, and training load crews. None of the crewman had seen or operated the NGMH/ATTD prior to participation in the testing program, but all had been informally briefed about the project prior to arrival at ORNL.

Apparatus

The principal apparatus for the experiment was the heavy-lift dexterous manipulator component of the NGMH/ATTD. A fully functional NGMH/ATTD is operational at ORNL and it was used in the testing. Figure 1 shows the NGMH/ATTD.

At the start of testing, the NGMH/ATTD was positioned in front of a typical USAF bomb trailer, as currently used on flight lines at air bases. Bomb and missile racks typical of F-15E Eagle fighters were positioned about 30-ft from the trailer and mounted with ground clearance as per the F-15E. Several types of (inert) conventional munitions were positioned on the bomb trailer.

Procedures

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 project and on safety procedures for the NGMH/ATTD.

Testing itself was conducted using an informal format that encouraged the participants to interact with the NGMH/ATTD in a manner that allowed them to become familiar with its capabilities. At the end of each exercise with the NGMH/ATTD, the participant was briefly questioned about his experience with the machine. Any evaluative comment made by the user was recorded, as were suggestions or improvements. The observer also noted important events or noteworthy differences in operating style during the task, and then briefly questioned the participant about problems with the system and reactions to the control system set-up for that task. Comments were recorded in a logbook for later review and analysis.

Participants first 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 munitions at the trailer, moved them to the appropriate rack, and attached them to the rack. They also unloaded the munition and returned it to the trailer.

Two different extremes of human amplification controls were tested: one was termed "viscous" mode and the other was termed "acceleration" mode. The viscous mode provided resistance to the user's movements, much like a damper, e.g., the damper used on screen doors in one's house. The acceleration mode was comparable to moving an object in space with external forces being cancelled. Within these modes, parameters were varied to help fine tune the control system. Parameter modification during testing changed linear velocity, orientation velocity, linear force amplification, or moment force amplification gains.

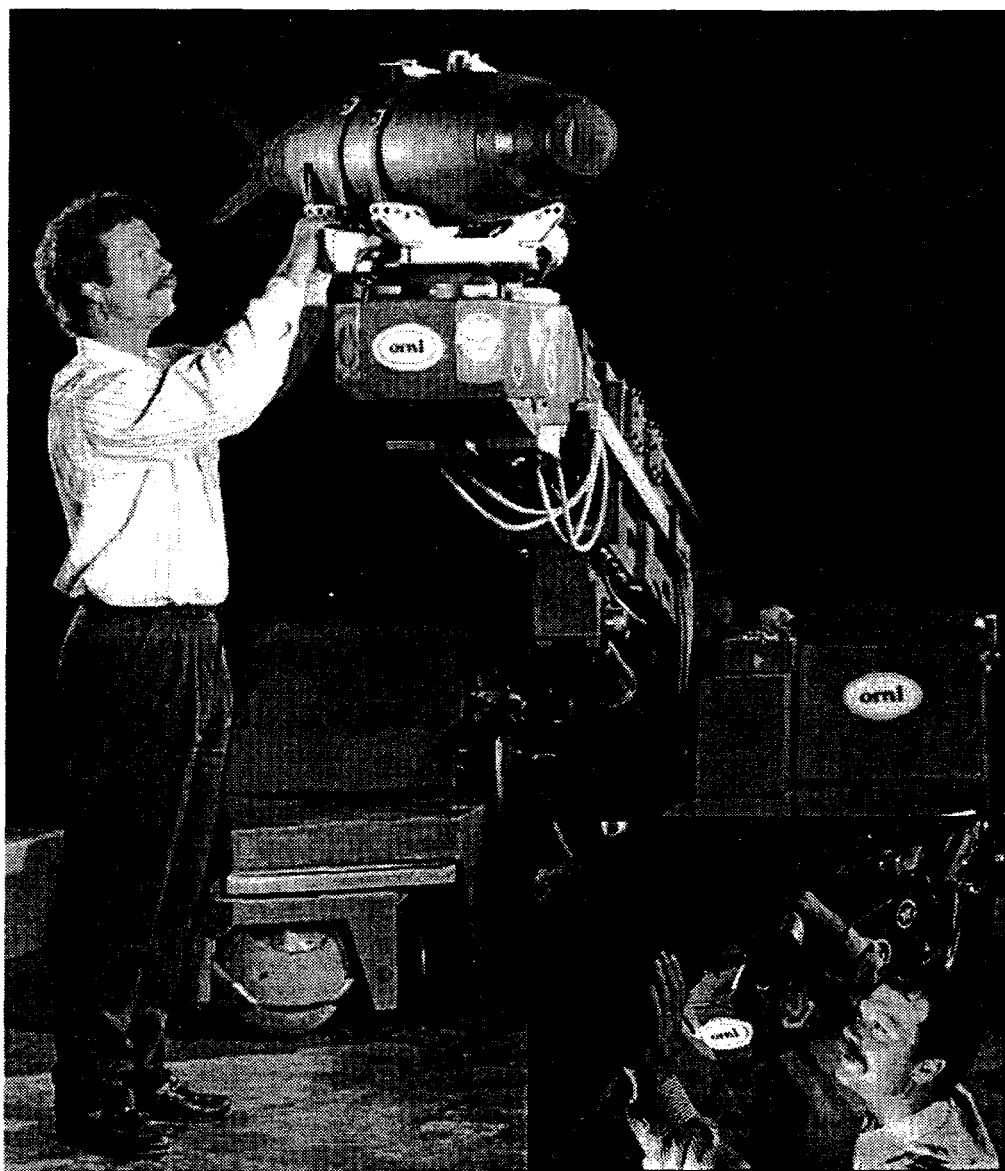


Figure 1. The NGMH/ATTD. Insert shows close-up of end-effector controller.

Variables

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, each comment recorded in the experimenter's notebook was recorded in a database, which also included data about the context of the comment. The latter included the testing day and session; the task, whether free-space motion or loading operations; and an identifying tag for the source of the comment (participant or observer). Each comment was then interpreted in 2 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 velocity
- 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 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 that either 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, fatigue) seems particularly potent. However, bearing these caveats in mind, the use of the valence data does provide a clearer picture of user reactions to HDM operations.

Data Analysis

Qualitative analysis of user comments was done 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.

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 the participants referred to "fighting it" and reported an improvement in ease of use when speeds were increased. Users pushing harder on the handle when the HDM is moving more slowly than they'd like it to move probably caused this. The resulting higher forces, with the accompanying higher levels of muscle activation, was then interpreted (or at least reported) as "fighting" the HDM. This is similar to movement problems associated with teleoperators characterized by poor responsiveness (Draper et al., 1986a). Increasing the velocity capability of the machine can ameliorate this, but it must be done with appropriate consideration of the safety implications of higher speeds. Ease of use is not necessarily the most important criterion.

Several responses regarding the man-amplification mode had content like "too sensitive at first" or "I liked it when I got used to it." These comments may indicate a need for greater training with the man-amplification mode than with accommodation 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 2 stages: a slewing phase, in which the target is approximately reached, and a fine-adjusting phase, in which final target acquisition occurs (Van Cott & Kinkade, 1972). The former is characterized by high-amplitude, low-frequency inputs and the latter by low-amplitude, high-frequency inputs during teleoperation (Draper & Handel, 1993; Draper, 1994). It seems likely that the problems users reported with man-amplification 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 (Schmidt, Zelaznik, Hawkins, Frank & Quinn, 1979). 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 motoneuron) recruitment scheme (Ulrich & Wing, 1991). Recruiting motor units to participate in the force impulse generates limb forces; 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 man-amplification 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.

General User Acceptance

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. From the table, 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 (going 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	14%	7%	78%

Control Mode User Acceptance

There were differences in user acceptance of the 2 control modes (viscous and acceleration). Table 2 presents the percentages for each valence within each mode. A high percentage of comments about viscous mode were positive (68%) and a low percentage were negative (17%). Just under half of the comments about 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 acceleration mode was negative than for 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 very 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 X 3	20%	7%	73%
Unloaded	Viscous	OrVel X 3	0%	7%	93%
Unloaded	Acceleration	Initial	62%	23%	15%
Unloaded	Acceleration	Linear X .5	100%	0%	0%
Unloaded	Acceleration	Linear 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%

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 500-lb bomb, low gain settings led to higher percentages of positive comments.

Comments by Component

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, etc. 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%) was 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%

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 crewmen 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/ATTD in the future. It is important to note that no task performance data were taken during the current testing program; future testing should include metrics related to task performance and manipulator performance, as well as user opinions. Future testing should also more carefully measure ease of use, user workload, and fatigue.

User reactions to the NGMH/ATTD 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 viscous mode represents a real difference in ease of use or is related either to training or improper parameterization of 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 control modes, it will be necessary to insure that users have enough practice to reach asymptotic performance with both modes.

The controllability problem reported by users in acceleration mode can be ameliorated by several approaches. First, reducing overall system gain will make the system more stable. Second, provision could be made for selecting slewing and fine-adjusting modes from the HMI, to match gain to the task phase. Third, it may be possible to determine which groups of joints are characteristically used for fine-adjusting and slewing movements. If this can be done, gain could be set more appropriately for each joint within the context of and overall system gain (see Draper, Sundstrom & Herndon, 1986b). Fourth, a force input deadband could be applied to increase the control input amplitude required to initiate movement, thereby filtering out transient high-frequency inputs that contribute to user difficulties during final target acquisition.

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 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 will identify optimal operating parameters through more formal testing, using a wider range of figures of merit. These may include variables related to loading task efficiency, forces exerted on the controller handles and on weapons and racks, and more rigorous 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.

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