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SIMULATION OF THE ADVANCED INTEGRATED ROBOTICS REARM SYSTEM: AN EXAMPLE OF NETWORK MODELING IN SUPPORT OF MUNITIONS PROCESSING

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ABSTRACT

The Advanced Integrated Robotics Rearm System (AIRRS) project, conducted by Oak Ridge National Laboratory, developed semiautomated munitions handling system concepts for the U.S. Army. Specifically, AIRRS provided concepts for a vehicle that would rearm the Crusader self-propelled howitzer. The AIRRS concept featured integration of existing munitions handling techniques with advanced tools and robotic munitions processing. The goal of the project was to develop a system that would process munitions more efficiently than the current manual approach and reduce soldier exposure to hostile fire and nuclear, biological, and chemical threats. This report documents the task network modeling performed to support the development of AIRRS concepts. Task network modeling is a technique that allows predictive modeling of activities that can be subdivided into discrete elements (or tasks).

The task network modeling effort was undertaken to support the AIRRS development (1) in early concept selection, where network models were used to assess processing rates, and (2) in integrating test stand data into complete AIRRS models to allow predictive evaluation of options for the final concept. Models were developed to support the second phase, but this work was not completed because of the curtailment of the project.

The validity of the AIRRS models was established by (1) modeling manual processing, (2) integrating into the model data collected during manual processing tests conducted at Ft. Sill, Oklahoma, and (3) comparing model predictions of processing efficiency with actual processing efficiency observed at Ft. Sill. The model predictions closely matched the observed manual processing results, indicating that the modeling approach can accurately predict processing performance for manual processing, and implies equivalent accuracy for modeling automated and semiautomated systems.

The value of task network modeling is that it allows evaluation of total system performance by combining performances of subtasks into a realistic, though virtual, whole. This provides developers with a method for manipulating system components to achieve optimal processing rates without requiring construction and modification of prototypical systems. Task network models can predict the impact on system performance of newly proposed designs by allowing the constituent tasks of the model to be manipulated. Computer-based simulations are cost-effective because they delay the need for fabrication until the value of modifications is already known.

The simulations described in this paper predict the performance of the semiautomated munitions handling system being developed for AIRRS. Data from the trials conducted with the simulations support the conclusion that accurate processing prediction is possible using these methods. Using estimated data and data from Ft. Sill, the Advanced Robotic Concept Model predicts that the AIRRS selected concept could, on average, process 130 projectiles in approximately 48 min.

1. INTRODUCTION

This report describes the methodology and results of a network simulation study conducted in support of the Advanced Integrated Robotics Rearm System (AIRRS) project. The AIRRS project was an effort undertaken by Oak Ridge National Laboratory (ORNL) to develop and demonstrate the technology necessary for semiautomated processing of artillery ammunition onboard the U.S. Army's next generation battlefield resupply vehicle. Current manual projectile processing operations such as lifting eye removal, fuzing, weighing, and marking ammunition were to be automated through the use of prototypical equipment capable of being fitted onboard the resupply vehicle. The goals of the project were to (1) develop an overall concept of how ammunition could be processed in a semiautomated fashion, (2) develop equipment and controls techniques for accomplishing each task, and (3) demonstrate operation of the hardware in a prototypical setup to validate the concept.

Network simulations were built at various stages of AIRRS concept development to help accomplish these goals. To meet the first objective, a series of models was designed to select the optimal concepts and equipment from the various proposals put forth by the project engineers. These models, described in Sect. 2, were used to predict the processing efficiency of each approach. Another set of models was developed to simulate the manual munitions handling procedures in order to validate the accuracy of the network model approach. These models, described in Sect. 3, were based on a task analysis of the process and used task times generated in a series of experiments conducted at Fort Sill, Oklahoma.[1] Because the task times were empirically generated and represent an actual procedure, these models were used to validate the predictive accuracy of the network modeling approach. Towards the final objective of demonstrating the efficiency of semiautomated munitions handling, a model was created to integrate components from the first two sets of models; it represents the complete AIRRS concept as it is currently proposed. This final model, while using task data gathered disjointedly, provides a predictive tool for estimating the effectiveness of the finished AIRRS (see Sect. 4).

Part of the value of a network simulation lies in its ability to estimate joint processing times from a series of distinct tasks. This is accomplished through the sequential execution of the subtasks, which constitute the procedure. Consequently, discrete subtasks can be manipulated and the impact of change to the system can be evaluated.

Evaluation of the sensitivity of a system to change is an important consideration in the design and engineering of AIRRS. The AIRRS platform was designed to include the stations necessary to assemble a projectile automatically. By simulating the entire munitions processing and handling procedure, developers can evaluate the impact of individual station modifications by inserting data collected during discrete testing into the simulation and predict the overall processing rate. Should it appear that discrete operations could be optimized or combined, this model would be used to provide a predictive evaluation of the impact of changes on overall system efficiency.

A network simulation can also be used to provide quantitative evidence of the value of AIRRS. Once a model has been constructed, virtual experiments can be conducted. By varying subtask times, the model can collate parametric statistical data that can be confidently regarded. Alternative design concepts can be exhaustively tested virtually, and the optimal design can be chosen before any system fabrication has taken place. Simulation is an effective cost-cutting option when compared with fabricating several design concepts and conducting empirical tests to elicit the best design.

The network simulation study described in this report is a compilation of many models developed throughout the AIRRS project. One set of models was developed to determine the optimal processing path (vertical or horizontal) of the projectile as suggested in the AIRRS Concept Selection Package. A final model was developed to simulate the entire procedure as proposed at this juncture in development.

1.1 ROLE OF NETWORK SIMULATION IN AIRRS DEVELOPMENT

Network simulation played a role in two stages of the AIRRS development program: (1) in concept evaluation, early in the program, and (2) as a tool for integrating the results of test stand testing into predictive models for the final AIRRS concept. Unfortunately, the last use was not possible given the curtailment of the project.

1.1.1 Network Modeling Validation

Given the prominent role of network modeling in the ORNL approach to AIRRS development, it was important to establish that the network models could predict processing efficiency as advertised. An opportunity to conduct a comparative evaluation of model predictions against observed processing time presented itself during the project. ORNL developed advanced tools for use by soldiers during manual munitions upload. Testing conducted at Ft. Sill, Oklahoma, evaluated the efficacy of these tools. The testing provided an opportunity to evaluate the merit of the network modeling approach by allowing comparison of model predictions to the results of real-world operations. Network models were developed to simulate manual processing so that model predictions could be compared to real-life observations. (The network modeling effort also helped identify and clarify data collection requirements and refine the comparison of manual processing with the new tools to current-practice manual processing.)

1.1.2 Concept Evaluation

Preliminary concepts were evaluated in two ways. First, the collaborative engineering judgment of the development team was ascertained using a formal decision-making procedure. Second, as a check of the engineering judgment, task network models of the concepts were developed and time estimates for each task in the network were collected. Simulation runs were used to determine for each concept the processing time required for a 130-round load. Engineering judgments and network simulation results agreed, and both contributed to the selection of a reference concept for AIRRS.

1.1.3 Test Stand Data Integration and Manipulation

The AIRRS test stand was planned to allow evaluation of technologies for the various processing stations independently or as they interacted with other processing stations. Task network models were to be used to integrate the test stand data into models of the AIRRS concept. The network models would have allowed accurate predictions of munitions processing times, given real data about processing station performance. The network models would have supported decisions about, for example, the number of stations and the processing steps to be included at each station. Network modeling would have provided a means to evaluate alternative AIRRS concepts without building prototypes so that when a concept was selected for prototyping, the development team could have been assured of the performance of the system prior to fabrication.

2. METHOD

The AIRRS models were developed with the MicroSAINT package, a network simulation modeling tool kit for Macintosh and Windows-based personal computers. This section briefly describes the basic modeling concept, provides a description of the task network simulations developed, including the data necessary for the study and the methods used to obtain it, and explains and validates assumptions of the model.

2.1 NETWORK SIMULATION

Network simulation is a valuable tool for modeling systems that can be decomposed into a set of discrete sequential tasks. The building blocks of task network models are activities or tasks. These include (1) some action that must take place (e.g., fuze a round), (2) the objects of the action (e.g., the fuze and the round), and (3) descriptive information about the action (e.g., time to complete the action and error rates). The descriptive information may be provided by data collected during work sample tests or by estimation.

Resembling a multidimensional flowchart, the task network is a serial assembly of tasks. It is hierarchical in nature with the uppermost tier representing the general process and descending levels or subnetworks representing more specific details of the system. Tasks are indicated by geometric shapes. Squares depict the presence of subtasks; ovals represent discrete, stand-alone tasks. Decision nodes are indicated by diamonds, and tasks are connected with bidirectional pathways.

It is advantageous to break a complex system into smaller steps because it is often easier to understand and describe the behavior of constituent parts of a process rather than to describe the whole. Counters can be assigned to monitor each task or certain behavior patterns such as lag time or bottlenecking. Also, the performance of the whole system can be studied by varying the behavior of the composing parts.

The behavior of the system is reflected in the route taken by a "token" as it travels throughout the model. For the AIRRS network simulations, the token represents a munition component (warhead or fuze) and the components of the model (tasks) represent things that happen to the component as it passes through the various stages of processing. The token, which is assigned a tag at the start task, progresses through the model and encounters tasks. The tasks are activities executed by a soldier or a machine. The tasks have release and launch conditions that must be met for the token to continue. Upon completion of the task, the variable catalog is updated and the token continues along the path until it encounters another task or a decision node. The decision node branches the path into two or more paths. The route the token chooses might depend upon the requirements of each path (called a tactical decision node), the token might be split into multiple entities if requested by the decision node (multiple decision node), the token might have a single option of travel (single node), or the path could be chosen based on the probability of certain events happening (probabilistic node).

The multiple decision node can be used to create several tokens running concurrently throughout the model. This feature was used for the AIRRS models. Three tokens were created at the start task of each AIRRS simulation to represent the three soldiers typically used in munitions handling. Each token can be described as being dependent upon the other tokens or can be set to travel independently of the others. For the purposes of the AIRRS models, the tokens were subjected to the requirements met by the other tags. For example, the soldier who fastened the fuze to the round could not do so unless a fuze had been started by another soldier.

The network simulation can be designed to model very complex systems. The parameters of the simulation are established by the designer of the model through the assignment of task times and standard deviations. Task execution rates are randomly determined within the assigned limits. With each run of the model, a different result can be obtained. This allows the system to be tested with a resulting set of data falling within a determined distribution pattern.

2.2 ADVANCED ROBOTIC CONCEPT MODELING

The initial application of task network modeling techniques was the examination of advanced concepts for robotic munitions handling and processing onboard the vehicle. Models of several alternative concepts were developed in MicroSAINT. Testing conducted at Ft. Sill, Oklahoma, provided data for estimating soldier task times common to manual handling and the semiautomated AIRRS concept, and subject matter experts provided estimates of task time for automated tasks.

Sensitivity studies were conducted to evaluate the performance of the model concepts. Sensitivity studies manipulate variables within a model and measure the impact of the manipulation on overall task completion time. This method allows identification of critical technology areas within the concepts. Tasks which impact the overall time when manipulated are critical technology areas; they deviate from the planned task completion time and affect the overall time. Tasks that do not demonstrate an impact on overall time are not critical technology areas.

The objectives of this phase of the modeling task were to (1) evaluate ammunition handling and processing concepts and (2) provide a means for predicting processing rates, using test data where available and experts' estimates where data were not available. In this context, task network modeling provides an inexpensive means for comparing concept alternatives. It allows identification of critical-impact technologies before design, fabrication, and testing. It may also serve as a basis for future reliability, availability, and maintainability analysis.

2.2.1 Model Development

Model development began with the development of flowcharts of the semiautomated concepts under consideration. Following flowchart development, expert opinions were solicited to provide the timing information for model tasks.

To conduct the study, a model was developed for each alternative. Three of the highest-rated concepts identified in the AIRRS Concept Selection Package were selected for further investigation via modeling and are referred to in this section as Conveyor, Conveyor2, and Upload2. The subsystems represent concepts which began with manual material handling tasks performed by a soldier(s) and concluded with automated assembly work. Once the simulations were completed on the computer, they were used to perform sensitivity analyses to reveal which tasks caused bottlenecking or other impediments in the processes.

All of the models developed during this phase began with the same ten tasks. In the models, the (virtual) soldiers were required to:

1. remove the material handling equipment,
2. inventory/inspect the flatrack,
3. remove manifold containers,
4. remove straps from flatrack,
5. remove fuze crates from flatrack,
6. open fuze crates,
7. inspect and mark the fuze,
8. cut pallets and remove pallet tops,
9. kick off grommets, and
10. determine whether or not to cut more pallets.

The times for these tasks were provided by AIRRS I tests conducted at Ft. Sill. The remaining tasks in the models involved the automated subsystems. These tasks comprised the bulk of the sensitivity analyses and included:

1. lifting eye removal,
2. fuze insertion,
3. weighing, and
4. marking.

The times for these tasks were estimated by subject matter experts at ORNL. The various devices used to transfer rounds among the four stations and perform work at the stations were the main focus of the AIRRS time study.

2.2.2 Upload2 Model

The Upload2 concept featured a semiautonomous upload manipulator that removed shells from pallets. The concept required that a soldier guide the manipulator arm onto the first shell in each pallet, allowing the manipulator to determine pallet position. The remaining seven shells were removed from the pallet robotically. The upload manipulator placed the shell onto a four-station turntable in a vertical orientation. The turntable rotated, taking each shell to one of four stations for (1) lifting eye removal, (2) fuzing, (3) weighing, and (4) marking. A downender then tipped each shell over, and a second robotic manipulator moved the finished projectile to storage. Figure 1 illustrates the Upload2 Concept Model.

2.2.3 Conveyor and Conveyor2 Models

The Conveyor and Conveyor2 models featured a conveyor that moved shells into the vehicle for processing. Soldiers loaded shells onto the conveyor in a horizontal orientation. Once the shell was inside the vehicle, a robotic manipulator moved it from station to station. The Conveyor and Conveyor2 models were identical except for transit from station to station. In the Conveyor2 Concept Model, a second conveyor was added to move the shells

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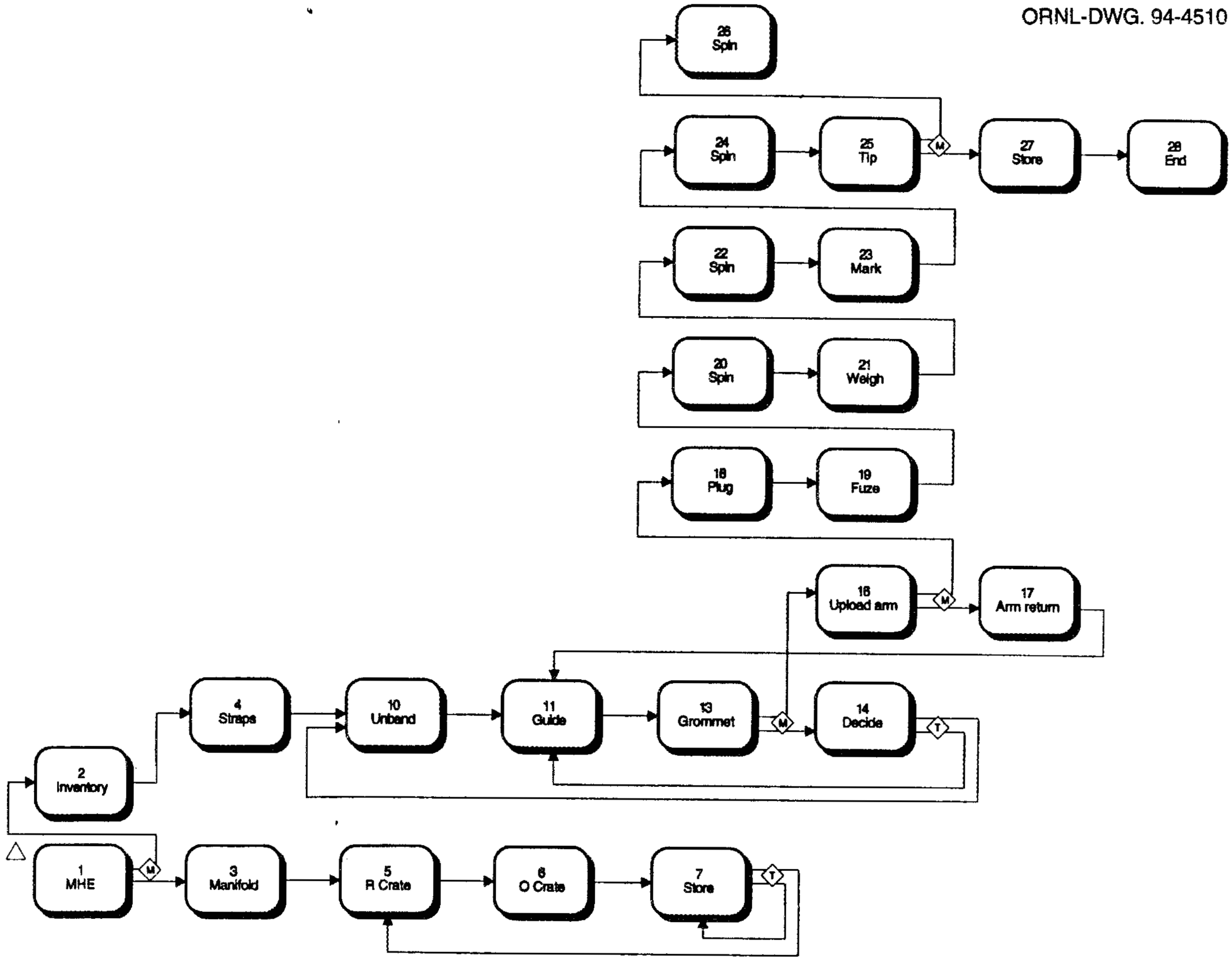

Fig. 1. Upload2 Concept Model.

from station to station, and the robot was programmed to move the shell from the last station to storage (see Fig. 2).

2.3 SENSITIVITY STUDIES

A sensitivity analysis was performed on the models to compare performance among the different processes and to observe which tasks accounted for the most elapsed time during processing. The AIRRS Time Study, as these series of simulations were called, focused on tasks such as the conveyor, the upload boom, and the pick-and-place robot, all of which operated throughout the entire simulation. The analysis indicated that tasks which began only after two or three other tasks had finished (i.e., Lazy Susan) were extremely sensitive to changes in their duration. For example, doubling the pick-and-place robot time in the Conveyor model or doubling the upload boom times in the Upload2 model caused the simulation run times to double (for the purpose of quickly identifying tasks that affected overall processing efficiency, task times were alternately halved and doubled during the sensitivity studies; when a particular task time was manipulated, all other tasks times were held constant). It became clear that elimination of tasks requiring "waiting periods" was essential for efficiency.

The results of the time studies were used to evaluate each concept and provided an aid to concept selection. Vertical processing with the upload arm (Upload2 model) was less efficient because of arm transit time. Horizontal processing concepts (Conveyor and Conveyor2) were more efficient.

Upload2 model performance was the most lengthy of the three simulations. The 10-s duration of the upload boom task, along with the slowness of the Lazy Susan, contributed to run times that surpassed the other simulations by almost 600 s. For the Conveyor and Conveyor2 models, adding a second soldier to help with the manual material handling tasks reduced the run time considerably. The Conveyor model was a shorter simulation and was slowed by the waiting periods of the pick-and-place robot. Conveyor2 was the most efficient of the three models. Replacing a pick-and-place robot step with an additional conveyor allowed the model to run approximately 1100 s faster than the original conveyor model. The time study concluded that unless the other models were shown to be more compact and much less expensive, the Conveyor2 system should be the first choice for a munitions handling subsystem design.

Methods for transferring rounds from the pallet to the vehicle were the critical concern. The upload arm was shown to cause a bottleneck in the vertical processing concept.

In these studies, the network simulation approach proved to be an effective and efficient tool and MicroSAINT demonstrated its usefulness. The method provided reasonable estimates of actual processing rates based on the discrete tests and models.

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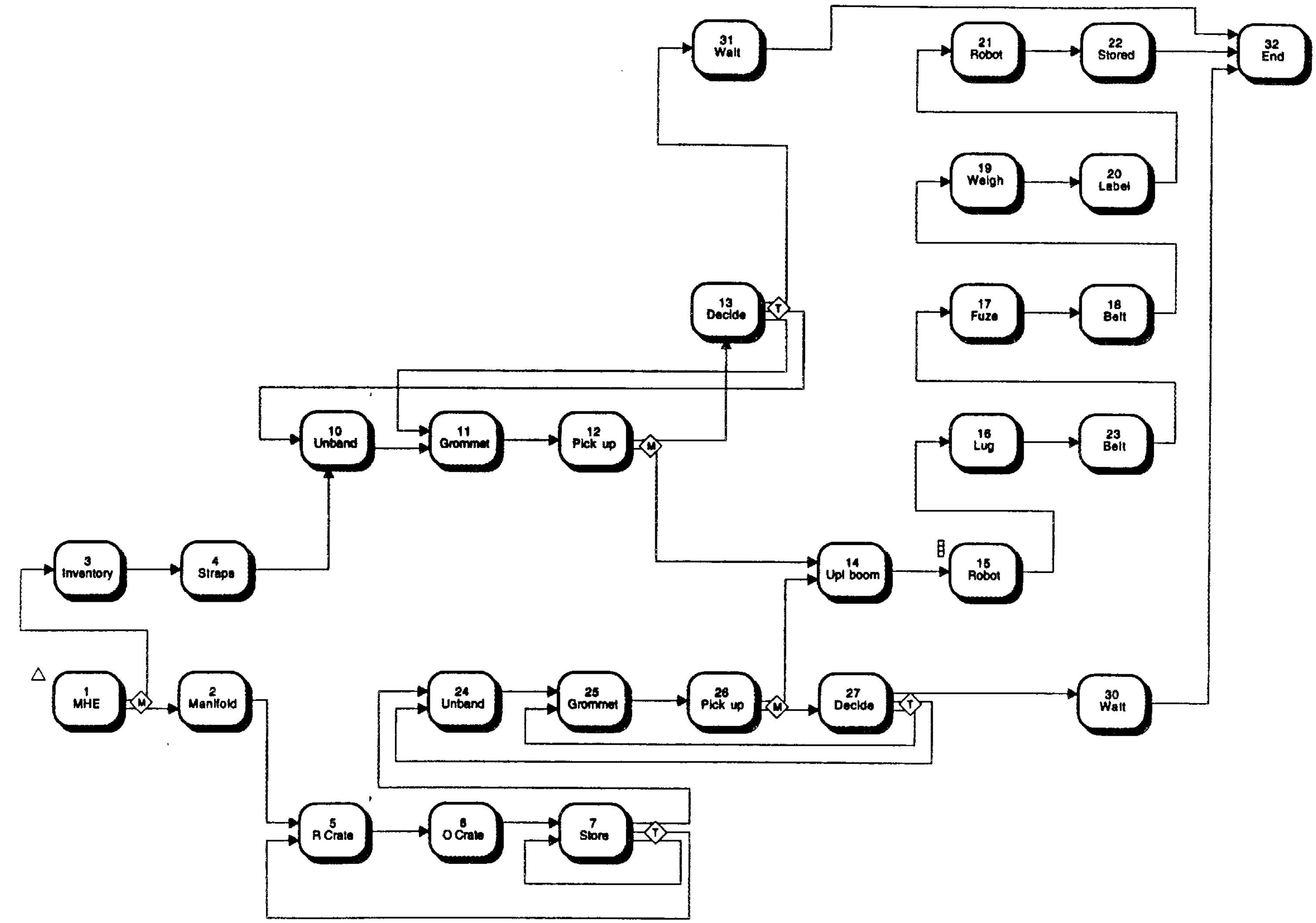

Fig. 2. Conveyor2 Concept Model.

3. NETWORK MODELING VALIDATION

Following the completion of the AIRRS time-motion study, data from the Ft. Sill testing[1] were used to provide precise times for the manual tasks involved in the munitions handling process, and a network model was developed to allow comparison of model predictions to actual task efficiency.

A function analysis was conducted to determine the tasks required to process the munitions manually. The analysis indicated the need to perform 20 tasks (see Table 1).

Table 1. Baseline test task list

Task	Description	Min	Sec
1	Remove equipment and put in place	1	31
2	Remove tie downs	2	22
3	Compare CCL inventory upload requirements	0	18
4	Input CCL into computer	5	37
5	Locate round components	1	05
6	Remove and connect LP hose	0	16
7	Move LP hose	0	07
8	Cut pallet straps and remove tops	1	06
9	Open fuze crate, carry two cans to work area	0	45
10	Remove grommet	0	03
11	Remove lifting eye, inspect	0	13
12	Select and inspect fuze	0	06
13	Fuze projectile start to finish	0	50
14	Move projectile to weigh and mark station	0	05
15	Enter round data into CPU	0	34
16	Weigh and mark	0	10
17	Load round on conveyor	0	05
18	Update CCL inventory	1	30
19	Return LP hose	0	26
20	Return equipment	0	57

A model was developed from the function analysis and adapted to incorporate five tools refined by the Robotics and Process Systems Division at ORNL. The tools were developed as improvements to existing equipment and were believed to significantly reduce the manual processing time. The enhanced equipment is described as follows.

- A pneumatic wrench with a socket designed to fit both the lifting eye and the fuze replaced the pry bar and M18 fuze wrench used in the baseline tests.
- A lighter and less expensive pallet-strap breaker was used in place of the heavy-duty strap shears of the baseline model.
- An internal weighing and marking station replaced the externally mounted swing-out station of the baseline model, eliminating the need to unload the round from the marking station.
- A four-hose manifold was introduced to fill the 12 55-gal drums of liquid propellant (LP), replacing the standard single-hose manifold.
- For projectile data entry, a bar code reader replaced the manual keyboard input of the baseline model.

The addition of the new equipment altered the function analysis slightly (see Table 2). Figure 3 illustrates the resulting network model; details of the model are presented in the Appendix.

To obtain data for the model, another series of experiments was conducted at Ft. Sill. Participants in the experiment were randomly assigned to five teams of three soldiers. They were given instructions on the baseline munitions handling method, and each team performed the experiment three times. Times were gathered for each task, and the process was videotaped for future analysis.

The teams were then instructed on the use of the enhanced equipment and proceeded through the experiment in the same manner as the baseline test. The results from both tests were collated by the Test and Experimentation Command Fire Support Test Directorate and presented in a report.[1] The report included the minimum, maximum, mean, and standard deviation of performance times for the 30 trials and explained unusual or outstanding results.

The Ft. Sill tests served two purposes. First, the tests validated the format of the function analysis by demonstrating that it accurately reflected the munitions handling process. Second, the experiments provided precise data points and a time distribution of the performances demonstrated by the five teams.

3.1 MODEL VALIDATION USING FT. SILL DATA

Recreating reality in a virtual environment presents certain problems. Modeling of complex human-machine systems is often more difficult than modeling of physical systems because (1) there are few fundamental laws or "first principles" in behavioral science; (2) relevant procedural elements are often more difficult to describe and represent; (3) strategies and policies often guide or constrain behavior, and their impact is hard to quantify; (4) random components may be significant elements in many aspects of behavior; and (5) human decision making and problem solving are often integral parts of such systems.[2]

Validation consists of determining that the simulation model is a reasonable representation of the real system. Testing for reasonableness involves a comparison of model and system structure. Similarity of input and output between the model and the real system is a good predictor of validation. Several statistical tests lend support to the validation.

Table 2. Enhanced equipment test task list

Task	Description	Min	Sec
1	Remove equipment and put in place	0	35
2	Remove tie downs	2	03
3	Compare CCL inventory upload requirements	0	24
4	Input CCL into AIRRS (use bar code)	NA	NA
5	Locate round components	0	09
6	Connect LP manifold connections	0	47
7	Change LP manifold connections	0	58
8	Break pallet straps and remove tops	0	46
9	Open fuze crate, carry two cans to work area	1	01
10	Remove grommet	0	03
11	Remove lifting eye, inspect	0	35
12	Select, inspect, and start fuze	0	06
13	Fuze projectile using power tool	0	02
14	Move projectile to conveyor	0	04
15	Scan and enter round information into CPU	NA	NA
16	Weigh and mark	0	10
17	Update CCL inventory	1	25
18	Return LP manifold	0	47
19	Return equipment	0	46

When constructing a simulation, the developer must decide which tasks from the human performance to include. Adversely, this means that the developer must also decide what to exclude. The assumption, therefore, must be that the exclusions were not dramatically important to the system. To eliminate most of this assumption, the function or task analysis used as a template for the model must be highly detailed or the model must be subjected to verbal input from the human performer if possible.

In the case of the AIRRS simulation project, generating an accurate model of the Enhanced Equipment project was possible for several reasons. The Ft. Sill tests provided precise data points and distributions for the model. The times generated by the soldiers were an accurate indication of the entire munitions-handling population of the U.S. Army because the soldiers were randomly chosen from that population. The testing also proved to a reasonable degree that the function analysis was a legitimate reflection of the real system because the tests were based fully on the analysis.

Outcomes from the Ft. Sill experiments would lend credence to the model if the results were significantly similar. The performance of the Enhanced Equipment experiment indicated that after 15 trials by 5 teams (3 runs per team) the mean execution time was 39 min 29 s with a standard deviation of 6:57. The Enhanced Equipment model was executed 100 times and processed the required 130 rounds in a mean time of 35:56 with a standard deviation of 3:14.

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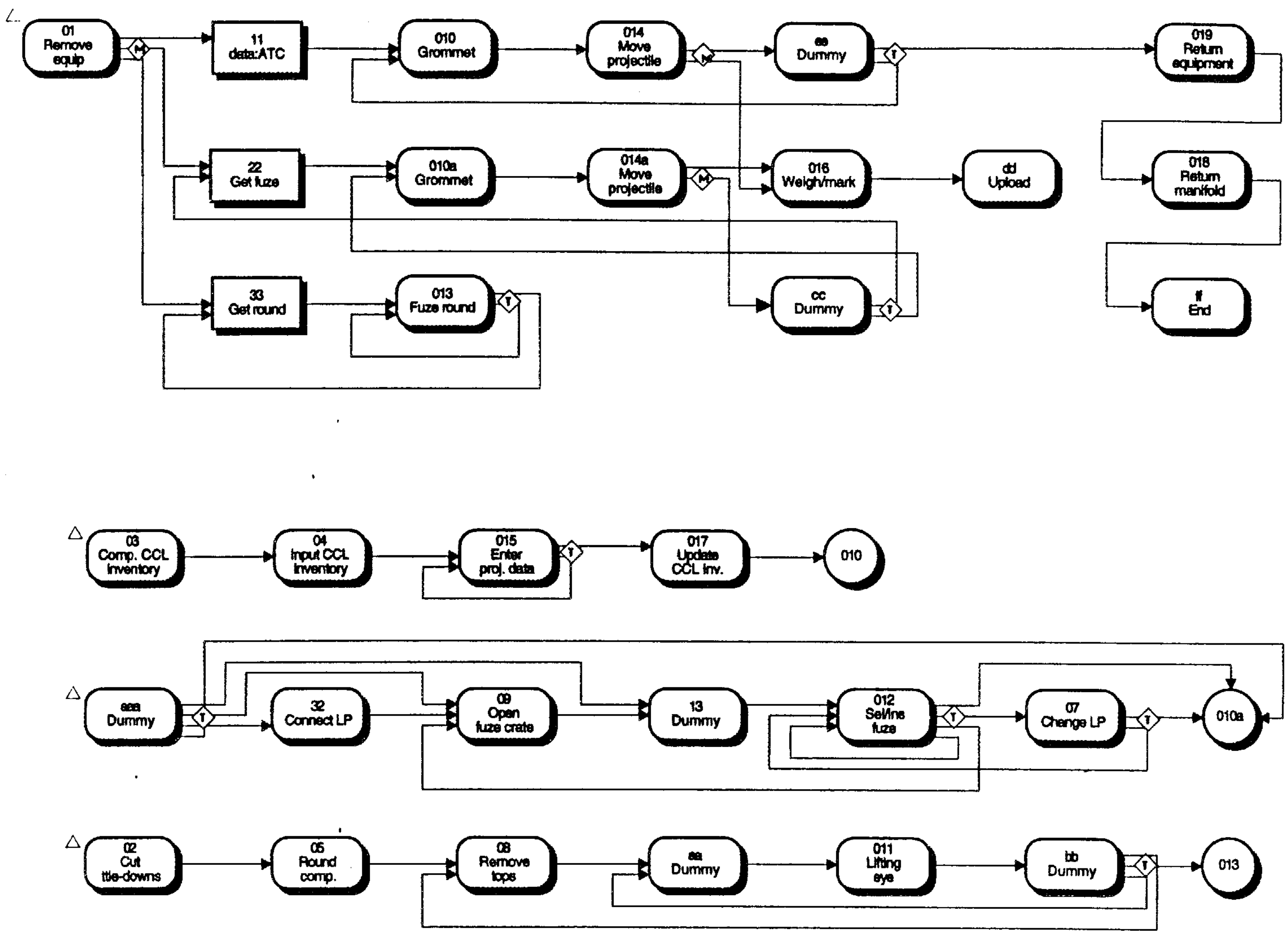

Fig. 3. Enhanced Equipment Concept Model.

A two-sample t-test was conducted on the mean results from the 5 teams and the 100 runs of the model. Analyzing the five individual team performances, one team, Team B, stood out from the other teams.

Single-sample t-tests were conducted comparing each team to the model. A one-sample t-test was performed comparing the sample mean against a hypothesized population mean of 2088. The sample mean of 2156 was found to not be significantly different from this value, $t(2) = 0.7219$, $\alpha = 0.10$, two-tailed, suggesting that the MicroSAINT Enhanced Equipment model mean time is within the acceptable range of Team A's performance.

A one-sample t-test was performed comparing the sample mean against a hypothesized population mean of 2790. The sample mean of 2156 was found to not be significantly different from this value, $t(2) = -1.46$, $\alpha = 0.10$, two-tailed, suggesting that the MicroSAINT Enhanced Equipment model mean time is within the acceptable range of Team B's performance.

A one-sample t-test was performed comparing the sample mean against a hypothesized population mean of 2393. The sample mean of 2156 was found to not be significantly different from this value, $t(2) = -1.55$, $\alpha = 0.10$, two-tailed, suggesting that the MicroSAINT Enhanced Equipment model mean time is within the acceptable range of Team C's performance.

A one-sample t-test was performed comparing the sample mean against a hypothesized population mean of 2088. The sample mean of 2130 was found to not be significantly different from this value, $t(2) = 0.6256$, $\alpha = 0.10$, two-tailed, suggesting that the MicroSAINT Enhanced Equipment model mean time is within the acceptable range of Team D's performance.

A one-sample t-test was performed comparing the sample mean against a hypothesized population mean of 2446. The sample mean of 2156 was found to not be significantly different from this value, $t(2) = -1.341$ within the acceptable range of Team E's performance.

Removing Team B from the calculations, the Enhanced Equipment Model was clearly very similar to the soldiers' performance. The mean time, without Team B, is 2264.30 s compared with the 2156.00-s execution rate of the model. The standard deviations align even closer: 193.5 s for the Ft. Sill test and 194 s for MicroSAINT (see Figs. 4 and 5).

The close alignment of standard deviations is a very important indicator of similarity. Standard deviations reflect the level of variance in multiple performances. The homogeneity of standard deviations indicates that the model is performing the tasks in a manner very similar to that of the soldier's.

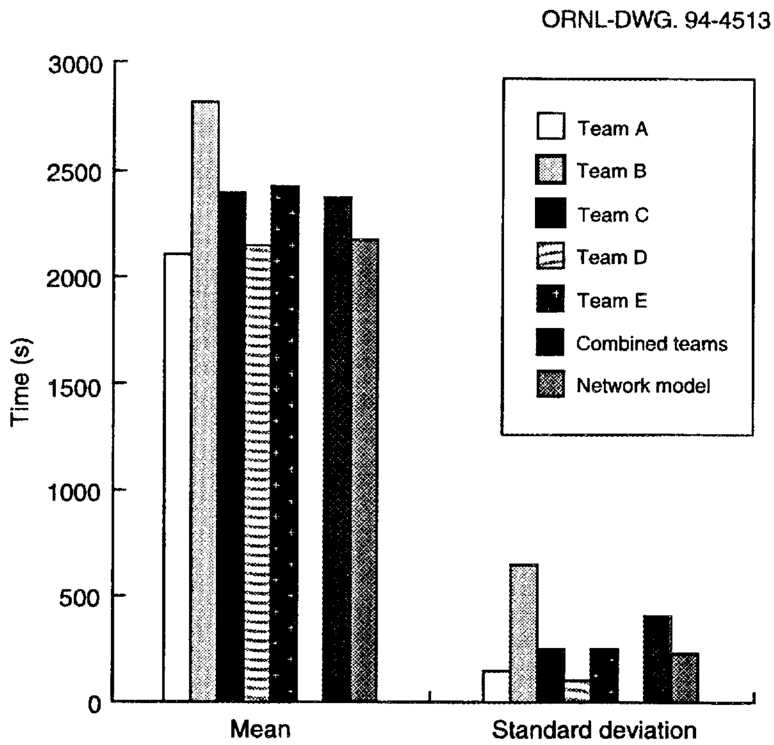

Fig. 4. Statistics for Ft. Sill testing teams vs network model statistics.

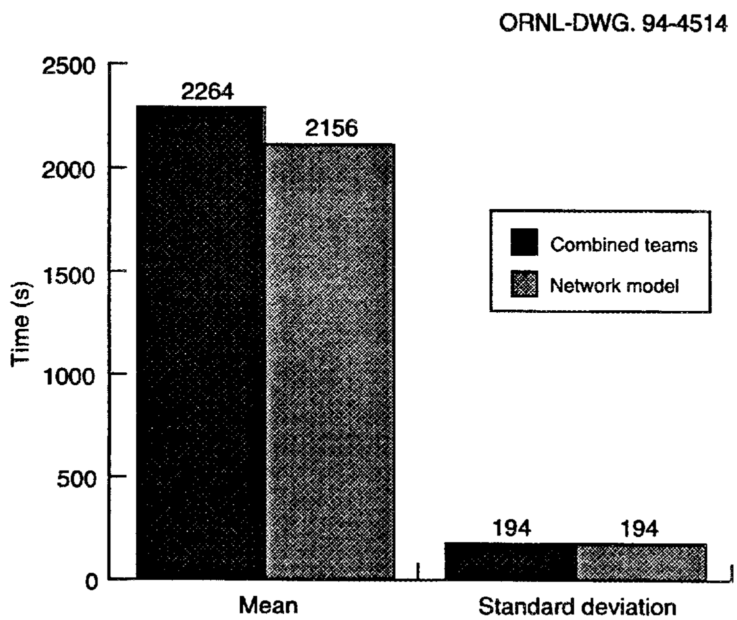

Fig. 5. Combined team statistics, with Team B removed, compared to network model statistics.

4. ADVANCED ROBOTIC CONCEPT MODEL

A final model, called the Advanced Robotic Concept Model, which represents the AIRRS selected concept, was developed to integrate the concept chosen from the time-motion study and manual handling tasks identified during the network model validation study (see Fig. 6). Manual handling steps included preliminary tasks of unpacking the components (see Table 3). However, instead of manually assembling the projectile, the fuzes were placed in a storage bin and the shells were placed on a conveyor belt. When the round reached the end of the conveyor, a robotic arm moved it to the first station for lifting eye removal. Upon completion of the task, the round was advanced to the next station for fuzing; a new round was then moved to the vacant eye removal station. When both stations had completed their tasks, the rounds were transferred simultaneously to the succeeding station. At station 3 the rounds were weighed, and at station 4 the rounds were marked. When a round completed the last station, the robot moved it to storage.

Table 3. The Advanced Robotic Concept task list[a]

Task	Description	Min	Sec
1	Remove equipment and put in place	0	35
2	Remove tie downs	2	03
3	Compare CCL inventory upload requirements	0	24
4	Input CCL into computer (use bar code)	NA	NA
5	Locate round components	0	09
6	Connect LP manifold connections	0	47
7	Change LP manifold connections	0	58
8	Break pallet straps and remove tops	0	46
9	Open fuze crate; carry two cans to work area	1	01
10	Remove grommet	0	03
11	Update CCL inventory	1	25
12	Return LP manifold	0	47
13	Return equipment	0	46

[a]Tasks and mean times extracted from the Enhanced Equipment task list used in the ACR model).

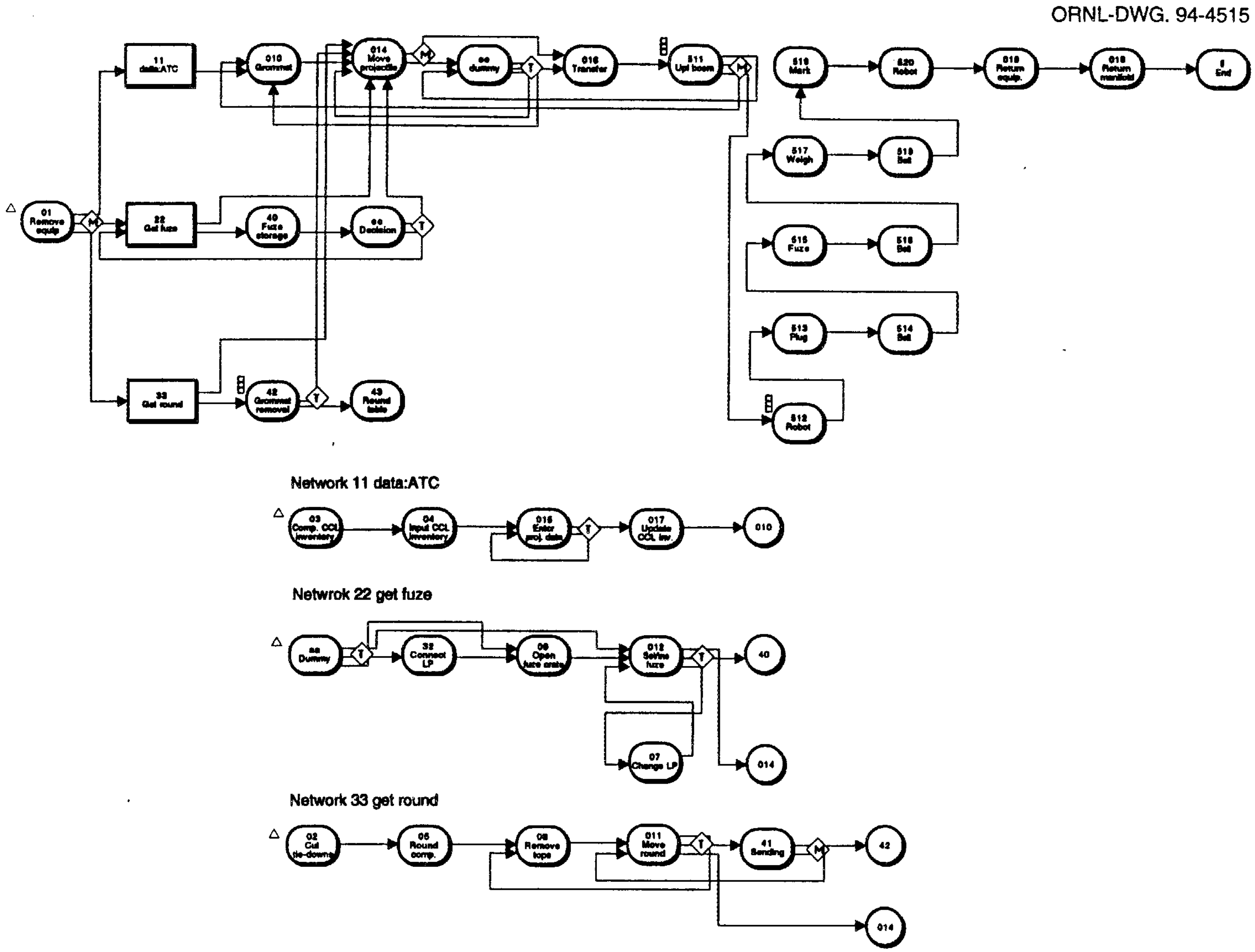

Fig. 6. Advanced Robotic Concept Model.

4.1 ADVANCED ROBOTIC CONCEPT MODEL RESULTS

The completed Automated Concept Model was executed 100 times, and the results were collated. An overall process time for 130 rounds was 47 min 35 s with a standard deviation of 4 min 5 s.

5. CONCLUSIONS

The AIRRS project was an effort by a team of engineers at ORNL to develop a semiautomated system for battlefield munitions resupply. Given the sheer number of components and concepts involved in AIRRS, building each concept and testing for impact to the system would not be feasible. Discrete tests can be conducted on components which have been fabricated, and processing times can be deduced for the system components. However, these tests do not provide a true indication of the overall processing rate of AIRRS. Also, discrete testing is not a cost-effective method of evaluating modification proposals. Therefore, task network modeling simulation software was used to amplify the per-dollar impact of development money by providing a virtual process prototyping capability. This was not virtual prototyping in the traditional sense of graphical representations for visualization of components but rather the development of task performance-based models of system functioning. While this lacked the visual impact of typical graphical representations, it was a much more powerful tool for predicting how a system might perform: the beauty of graphical simulations is only screen deep, and it was the effectiveness of the system that was truly interesting and important.

Fully evaluating system performance with the static analysis tools available to human factors engineers, such as job and task analysis or operational sequence diagrams, is especially difficult in a multiphase project such as AIRRS. The evolution of task-network model simulation software has effected a change in the manner in which concept proposals are assessed. Simulations provide a cost-effective method of pretesting the effects of design modifications on system performance by precluding the expense of performing real-time testing. For AIRRS, the simulations provided a means for predicting overall processing rates using estimated and/or empirical data. They were an inexpensive means of comparing concept alternatives and identifying critical-impact components before component fabrication. The simulations could also serve as a basis for future reliability, availability, and maintainability analysis.

Several simulation studies were conducted at different stages of AIRRS development. Alternative design concepts of the AIRRS subsystems were examined, resulting in the recommendation of a horizontal processing path which employed a conveyor belt system and a pick-and-place robot. A model of manual processing was developed to test the validity of the modeling approach. The Advanced Robotic Concept Model represented the culmination of the task-network simulation study. Its analytical capabilities offered empirical evidence that the components being developed would perform as a system to the satisfaction of the specifications provided by the customer. Unfortunately, the accuracy of this final model was compromised, as discrete processing times for automated components were unobtainable because of the curtailment of the AIRRS project.

The simulations described in this paper predict the performance of the automated munitions handling system being developed for AIRRS. Results of a validation study support the conclusion that accurate processing predictions are possible using these methods.

The development of the Advanced Robotic Concept Model means that as concrete data are obtained, they can be plugged into the model and the overall processing time of the AIRRS can be determined. Unfortunately, project curtailment makes it unlikely that these data will be collected. Using estimated data and data from Ft. Sill, the model indicated that AIRRS could process 130 projectiles automatically in 47 min 35 s, with a standard deviation of 4 min 5 s, well within the requested 90-min time frame allotted by the Army.

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APPENDIX
ENHANCED EQUIPMENT MODEL DETAILS

All soldiers begin the model at a single start task and are separated into three entities at the first encountered multidecision node. This appendix describes the steps taken in the model. Words in bold reflect the counters maintained in the variable catalogue.

A.1 NETWORK 11: DATA ATC

1. The Ammunition Team Chief (ATC) first compares the combat-configured load (CCL) inventory upload requirements. This step occurs only once.

2. Using a bar-code reader, he then inputs the CCL information into the simulated AIRRS computer.

3. Next, the ATC enters projectile data into the computer by scanning each round. This step is repeated for the 130 rounds and fuzes. A counter is set that indicates the number of **Data_entered**.

4. A decision is made here. If **Data_entered** = 130, the ATC assists in removing grommets and carrying rounds to the weighing and marking station. If not, he continues to enter data.

A.2 NETWORK 22: GET FUZE (FUZE SOLDIER)

1. The soldier attaches the four-hose manifold to the 55-gal LP tanks. This task occurs only once during the run. Because the **LP_counter** is incremented in this task, the preceding decision node directs the token to skip this task for the remainder of the run. The clock **LP** is set equal to the model clock for the purpose of timing when the next LP manifold change must be made.
2. The soldier opens the **Fuze_crates** (decrementing Fuze_crates by 1, setting Fuze_cans to 2). The soldier removes the first fuze crate (setting **Initial_F.C.** to 0). This sets the variable clock for fuzing to Fuze_crates := 11; **Fuze_cans** := 2.
3. He then moves to the dummy step. This step "opens" the two Fuze_cans (setting Fuze_cans to 0) and removes 16 **fuzes** for processing.
4. The next step is the selection, inspection, and start fuzing step. In order for this step to release, **Rounds_Avl** must be greater than zero. This is because a round with the lifting eye removed must be available for the fuze to be inserted. The soldier pauses at this step if a round is not yet available. The ending effect of this step decrements the fuze by 1, increments **Fuze_started** by 1 (this is a counter to alert the soldier processing the rounds when to start tightening the fuzes down with the power tool), increments the **Used_fuzes** (this is a counter which tells how many fuzes have been removed from the

original stock and installed. It should indicate 130 when the model has run completely), and decrements Rounds_avl (indicating to the round soldier that he needs to prepare another round). The counter for changing the LP connection, **manifold**:= (clock - LP), is adjusted.

5. At this point, there is a junction where a decision must be made. The first decision is whether the manifold clock is greater than or equal to 240 s and LP_counter is less than 3 to decide whether the 4-min refueling time has elapsed and if the LP manifold has been changed less than the required three times. If so, the soldier moves to the change LP task. If not, the soldier looks to see whether 130 projectiles have been completed. If so, he moves to return equipment. If not, he decides whether the round soldier has tightened 16 or more fuzes to the rounds (**Fuzed_Rnd**). If so, he starts removing the grommets from the Fuzed_Rnd and carrying them to the weighing station. Otherwise, he checks if any fuzes are available to select, inspect, and thread into the round. If not, he returns to get another crate of fuzes (open fuzecrate).
6. If a decision was made to advance to the Remove Grommet task, he can do so only if **Load_ready**>0. Load_ready is a counter indicating the rounds ready for uploading. The beginning effect of this step decrements the Load_ready counter, and the ending effect decrements the fuzed round counter. This is done so that the fuze soldier can return to preparing fuzes (removal of grommets is dependent upon the number of fuzed rounds being less or equal to 16).
7. He then moves the fuzed round to the weighing and marking station. This step can take place only if the weighing station has less than five rounds (as indicated by the **Weigh_status** counter). Once he has moved the round, the weigh_status is incremented.
8. After moving the round to the weigh station, he moves to a dummy step where a decision is made. If Fuzed_rnd is 0, he returns to getting fuzes. If not, he looks to see if Load_ready is greater than zero; if so, he goes back and removes another grommet. If Load_ready is zero, he moves to returning equipment.

A.3 NETWORK 33: GET ROUND (ROUND SOLDIER)

1. The round soldier cuts the tie-downs which secure the round pallets to the flatbed. This is a step which occurs only once. This sets the **Full_pallet** counter in the variable catalog to 22.
2. He then locates the round components. Again, this step occurs only once.
3. Next, he removes the top of one pallet, uncovering eight rounds, with lifting eyes in place. (Full_pallets is decremented, and **round** is set to 8.)
4. The next step, called dummy, is a null step used to decrement the round counter so that there is an accurate counter of the number of rounds remaining in the pallet.
5. He removes the lifting eye of one round, incrementing the Rounds_avl counter and increments the **Used_round** counter. The Rounds_avl counter alerts the fuze soldier that there is a round ready for a fuze; the Used_round counter keeps track of the number of rounds which have been removed from the pallets. This counter should indicate 130 when the model has been completely run.
6. The next step, called dummy, is a null step to allow for a decision node to be inserted.

7. Here a decision must be made. First the soldier looks to see if the number of rounds he has used (Used_rounds) equals 130. If so, it means that he has prepared all that he needs and can move the weighing and marking station. If Used_rounds is less than 130, he decides if **Fuze_started** is greater than or equal to 16. If it is, he knows that he must fuze more rounds (each time through Fuze Round decrements the Fuze_started counter). If under 16, he goes back to the dummy AA step where he checks for more than zero rounds and then proceeds to remove the lifting eye. If round equals zero, he removes another pallet top for eight more rounds.
8. Once he moves to fuze rounds, he does so only if Fuze_started is greater than zero (he cannot fuze a round that has not been threaded). After fuzing a round, the Fuzed_Rnd is incremented; the Fuze_started is decremented; and the **Load_ready** is incremented.
9. A decision is then made. If fuze_started is greater than 1 and **Projectile** is less than 130 (he only needs to fuze 130 rounds), he fuzes another round. If not, he looks to see if Rounds_avl is zero and Used_fuzes is less than 130; if so, he gets another round. If Used_fuzes equals or is greater than 130, he goes to return equipment, because at this point, all 130 rounds should have been moved through the weighing station and sent to the Upload area (a null step created as for mocking the storage of projectiles in the test).

The Enhanced Equipment model used task times generated at the AIRRS II. An analysis of the performance of the five new tools indicated that four of the tools improved performance; the four-hose manifold proved to be slower than the single hose. This might be attributed to inexperience with the manifold and will be taken into further consideration.

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