Modeling Team Performance in the Air Defense Warfare Domain[1]

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Abstract

A task centric approach to interface design entails an explicit representation, of actions – tasks – that need to be performed by the operator. The interface may represent tasks in the form of icons on a display screen that the system has determined actionable given the current tactical information and Rules of Engagement (ROE). The representation of work in terms of a task serves as a trace in the system that enables designers to track workload in addition to the task progress and flow of tasks among team members. Using Queueing Theory statistics, performance for two Air Defense Warfare Teams were analyzed. This analysis revealed that task allocation, work- flow and the internal dynamics of the two teams were very different. Interestingly, neither team allocated tasks to team members as envisioned by the system designers. Bottlenecks, unforeseen by the system designers, had been introduced by the dynamics of the team. These bottlenecks were more pronounced for one of the teams and led to quantifiable differences in the queuing statistics. In particular, substantial differences in the average life of a task and average number of outstanding tasks operators had to perform were observed.

Introduction

In future Combat Weapon Systems (CWS) three important system design trends are: 1) focus on increasing capability while retaining constant or reduced manning levels, 2) increased system automatic functions in a Total Ship Computing Environment (TSCE), 3) expected use of re-configurable, collaborative task teams. Automation will assist in meeting these design requirements; however, with increased automation combat systems require human supervision and control. The change from manual control to automatic monitoring alters the role of the human operator from that of controller to supervisor in CWS. This change of roles generates design requirements for systems that provide information tailored for supervisory control tasks. For team leaders and decision-makers, this requires monitoring of both humans and automation in distributed teams, across multiple mission phases. The collection of system support services includes an array of computer technologies in a collective system, we have termed “Intelligent Mission Management & Monitoring” (IM^3). These services include both individual and team task and workload management, with decision support for both critical thinking and naturalistic decision styles.

Future multi-tasking environments will require that supervisory tasks shall span mission planning, rehearsal, execution and assessment phases of missions. Optimized manning implies concurrent activities that would otherwise be performed by multiple individuals in today’s ship can instead be performed through a multi-tasking process. This complex, multi-task environment shall require operators to: maintain an awareness of overall system functioning, prioritize tasks, and allocate resources in ways consistent with their new roles and new objectives. An understanding of these unique needs will become a critical element for success in key mission areas such as joint land-attack warfare in a littoral environment. The problem for designers is defining the information requirements, display formats, and controls needed to support adequate task performance for these newer supervisory control activities. What is needed is an understanding of these unique needs that can readily be translated into system design requirements.

The goal of our research is to develop quantitative models of Operator and System performance that will form the basis of a scientific design approach that can be utilized by future Combat System Design Engineers. In general, the purpose of modeling is to: 1) Predict impact of design on human performance before the system is built; 2) Compare alternative designs; 3) Compare alternative job structures, positions, team definitions; 4) Predict and compare performance results for design reference missions; 5) Reduce design risk; 6) Identify design changes and corrections before costly mistakes are made.

These models are being developed for Air Defense and Land Attack combat systems, and are being incorporated into prototypes of the future Multimodal Watchstation (MMWS) and Land Attack Combat System (LACS). These models will guide system design in an efficient manner, contributing to a scientifically supported design process. Several projects (e. g., MMWS, LACS, and Combat Supervisory Support Systems) have demonstrated tools that form the foundation for further development of interface concepts that will enable operators to plan and execute complex tasks within dynamic and multiple warfare areas. There is a growing need to model these interface concepts so that future interface designs may evolve in a principled and systematic fashion. The payoff would be the creation of a "true engineering method for interface design" (Kieras, 2002).

Approach

In order to explicitly present the multitasking within a system, a Task Manager (TM) Display was incorporated into the design of the MMWS and LACS. The TM Display represents tasks, in the form of icons on a display screen, that the system has determined actionable given the current tactical information and Rules of Engagement (ROE). As a reflection of the type and amount of work to-be-done, the TM display provides a basis for attention allocation for each operator and task allocation among a team of operators. Tasks represented may range from information updates to important tactical responses. This supports human cognitive functions relating to work planning, management, strategy, projection and task allocation. Thus, the TM display embodies a task centric approach to design in that the interface explicitly represents, to the operator, what actions (tasks) need to be performed. For further details of the MMWS and Task Manger Display see Osga, Van Orden, Campbell, Kellmeyer, and Lulu (2002).

The representation of work in terms of a task serves as a trace in the system that enables designers to track workload in addition to the progress and flow of tasks among team members. The posting of tasks to the TM display for operators to perform is also analogous to service calls arriving at a Help Desk. Quantitative models and methods to analyze system performance have been developed for these systems in the domain of Queuing Theory (Kleinrock, 1975). We have modeled the team of 4 MMWS operators from the point of view of a Queuing Network. A queueing network (Hock, 1996)is a collection of queueing systems connected to each other in certain ways. Each queueing system in its general form consists of:

A) The input or arrival process is usually modeled as a stochastic process, such as a Poisson process in which the arrival rate is simply the reciprocal of the mean inter- arrival time of customers. In our case, the customers are tasks arriving on the TM display.

B) The service mechanism refers to the number of "servers" and the lengths of time the customers hold servers. This is usually modeled with a negative exponential, and in our case this is the number of operators and the distributions of reaction times it takes operators to perform various tasks.

C) The queueing policy entails the method by which the system selects customers: first-come-first-served (FCFS), last-come-first-served (LCFS), by priority, or at random.

The relationships among the combat system team members and the manner in which they must process tasks may be modeled as a network of interactive queues. For example in an "open" queuing system, "customers" (contacts) are processed and passed from one server to another. Thus the customer sequentially arrives at different queues, is waited upon by a server (and sometimes must "feedback" and return to a previous server) and eventually leaves the system.

In Figure 1 we have diagrammed an open queuing network for the Air Warfare Coordinator (AWC), Air Intercept Coordinator (AIC) and Information Quality Coordinator One (IQC1) - all of whom are operators of the MMWS Air Defense team.

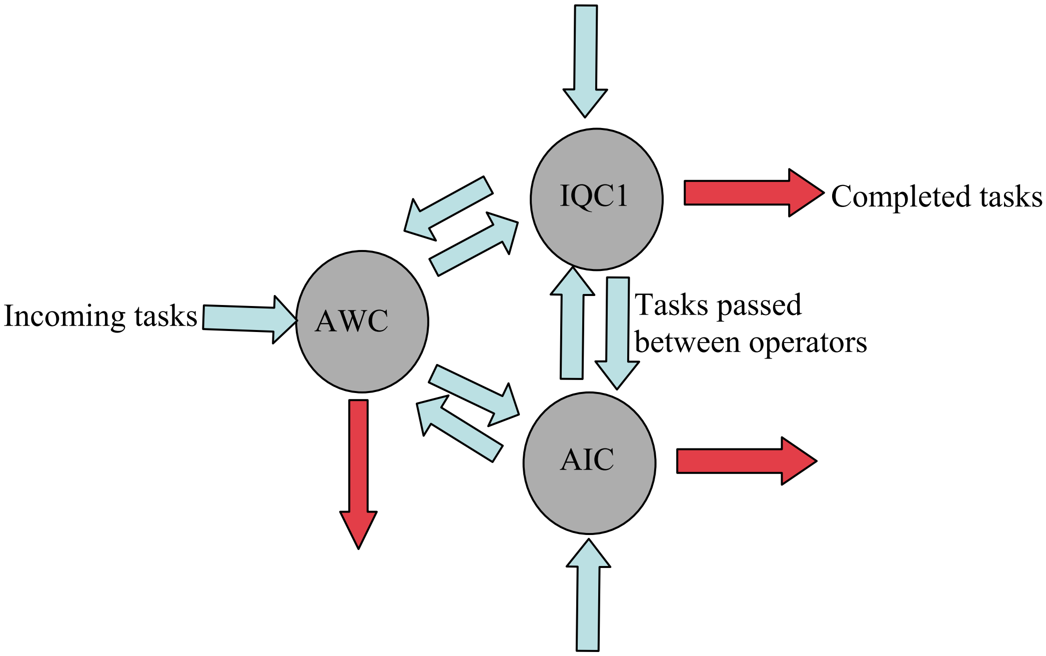

Figure 1. General Open Network Queueing Model. Circles represent operators. Arrows represent tasks that flow into and out of the system. Operators also pass tasks among themselves.

Results

Queueing Theory provides a set of global statistics that allows one to analyze the overall system performance as well as the performance of any one server. For example, the average number of tasks each operator has to perform, and the average total number of tasks that are in the system may be determined. Other valuable performance statistics include: 1) The average life of a task – from its birth (arrival to the system) to its death (task completion), and 2) Waiting time - the average time a task must wait before it is started. Another characterization of a queueing system is to determine the percentage of time the system spends in various "states". A state refers to the total number of customers that are in the queue at any one time (those customers that are either being served or waiting for service). In our application, a state represents how many tasks an operator had to perform on the Task Manager display. Over the course of testing a system and a team of operators on a scenario, the total amount of time the system spends in any one state is a measure of workload management since this represents the degree to which operators kept pace with tasks appearing on the TM display.

Data from an ADW team consisting of four operators (AWC, IQC1, AIC, and Tactical Action Officer – TAO) were collected from an one hour and thirty minute ADW scenario entitled the Sea of Japan (SOJ). Data from this scenario were analyzed from the viewpoint of queueing theory. Analysis of two ADW teams revealed two very different patterns of workload management.

First, we demonstrated that a shift from periods of low to high workload corresponded to a shift in states. For example, during the low workload interval, for nearly 60% of the time, the Team 1 AWC had no outstanding tasks to perform on the TM display. This percentage drops sharply to roughly 5% during the high workload period (see Figure 2). This same shift can be seen in the data for the AWC of Team 2 (see

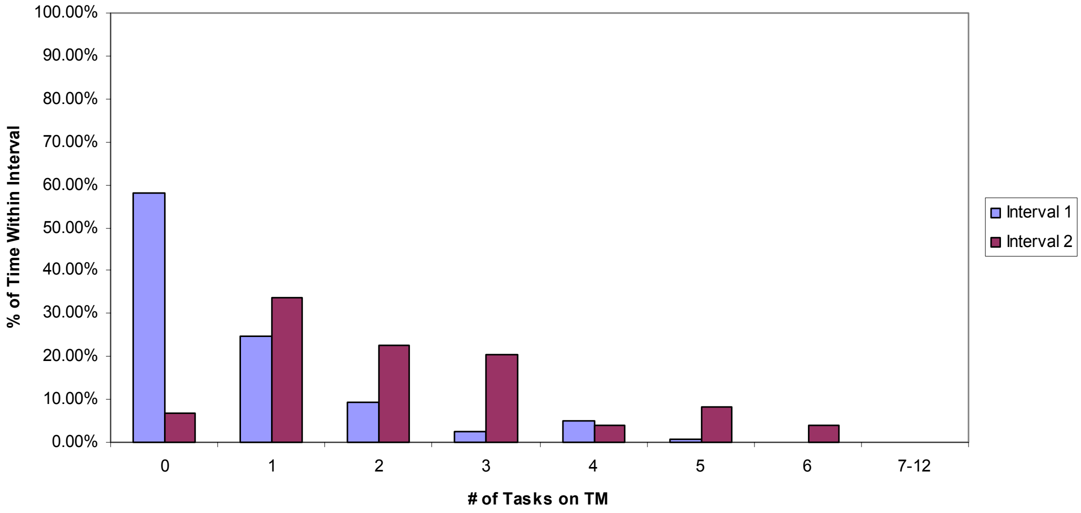

Figure 2. System states or percentage of time the AWC of Team 1 had 0 - 12 tasks to perform - Interval 1 low workload, Interval 2 high workload.

Figure 3), only now the shift is more pronounced – for 50% of the time this AWC had 7-12 outstanding tasks to perform. In addition to this backlog during the high workload period, the data revealed that the Team 2 AWC generally had more outstanding tasks during the low workload interval than the Team 1 AWC. This plot is supported by comparing the average task life (Figure 4) and the average number of tasks outstanding (Figure 5) for the Team 1 and Team 2 AWCs. In Figure 4 and 5 the Intervals 1 and 4 correspond to relatively low workload periods where as Intervals 2 and 3 correspond to high workload periods. Across all intervals, the average number of tasks and task life was considerably greater for the Team 2 AWC than the Team 1 AWC.

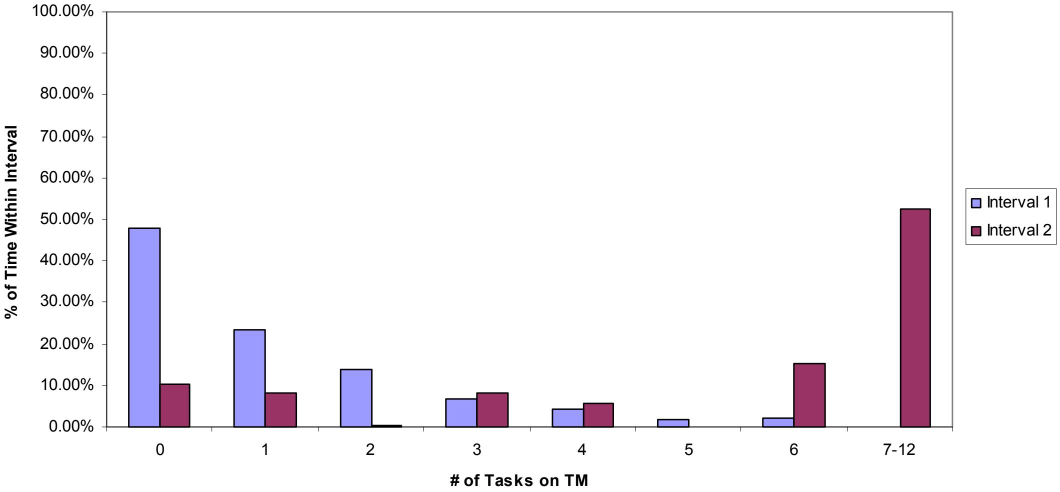

Figure 3. System states or percentage of time the AWC of Team 2 had 0 - 12 tasks to perform - Interval 1 low workload, Interval 2 high workload. AWC is falling behind on completing tasks.

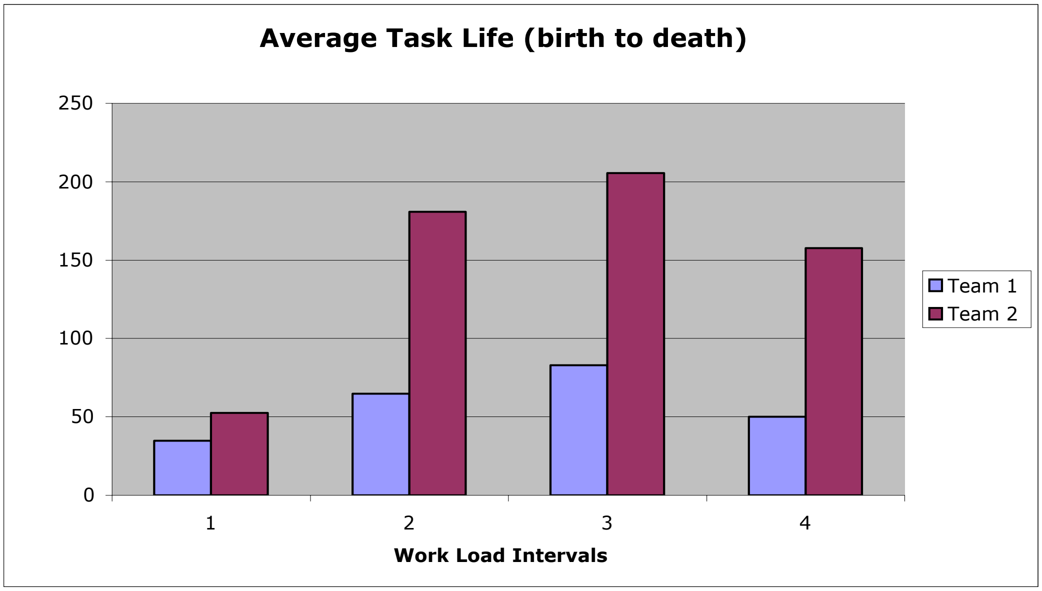

Figure 4. Average Task life for AWC of Teams 1 and 2. Task life is much longer for Team 2 than 1.

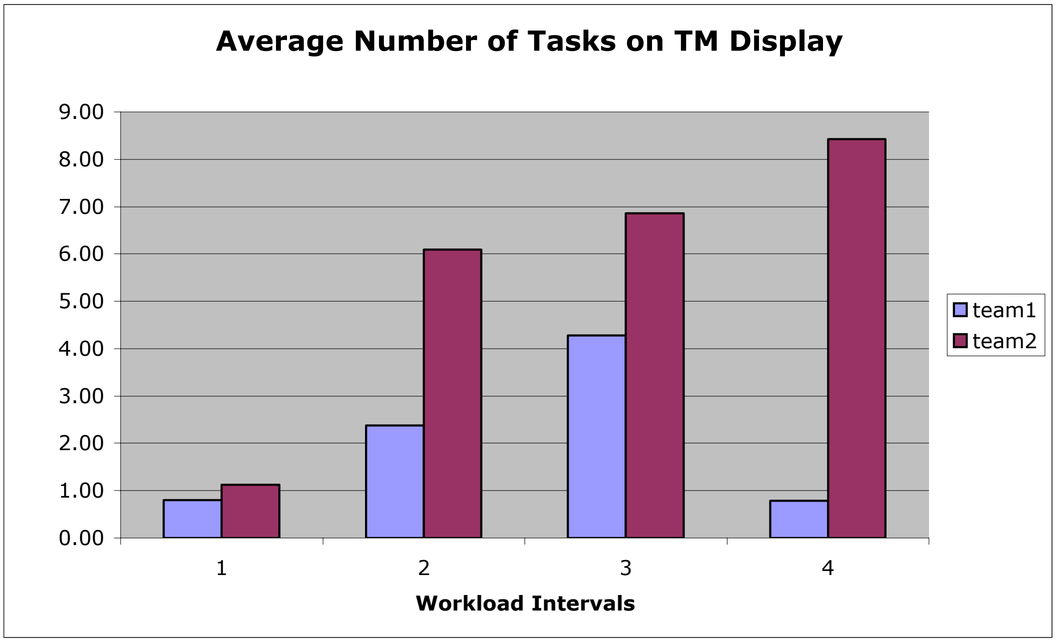

Figure 5. The Average number of tasks on the TM display for the AWC of Team 1 and Team 2. In general, the Team 2 AWC has more outstanding tasks to complete.

The immediate question was, why did the AWC of Team 2 fall behind to a greater degree than the Team 1 AWC? One might suspect that the AWC of Team 2 simply took longer to perform tasks; however, analysis of keystroke data showed that this was not the case. To answer this question, video recording of these teams taken during the experiment were analyzed. This analysis revealed that task allocation, work- flow and the internal dynamics of the two teams were very different. Interestingly, neither team allocated tasks to team members as envisioned by the system designers. In Figures 6 we depict the different task flows between an ideal team (that envisioned by the system designers) and Teams 1 and 2. These figures represent different networks of queues and each is a variation of the network of queues depicted in Figure 1.

The main difference between the ideal team and the tested teams is the degree to which the team members passed tasks between themselves. The ideal team members handle tasks independently and in parallel; however, for teams 1 and 2 there were various degrees of "meddling" between team members when it came to specific tasks. For example, for both teams, Queries and Warnings were never issued by the IQC1 unless the AWC specifically ordered the IQC1 do so. In order to give this order the AWC had to spend some time evaluating the task, hence the load of tasking for the AWCs was greater than that envisioned for the ideal team which allowed the IQC1 to handle Queries and warnings autonomously.

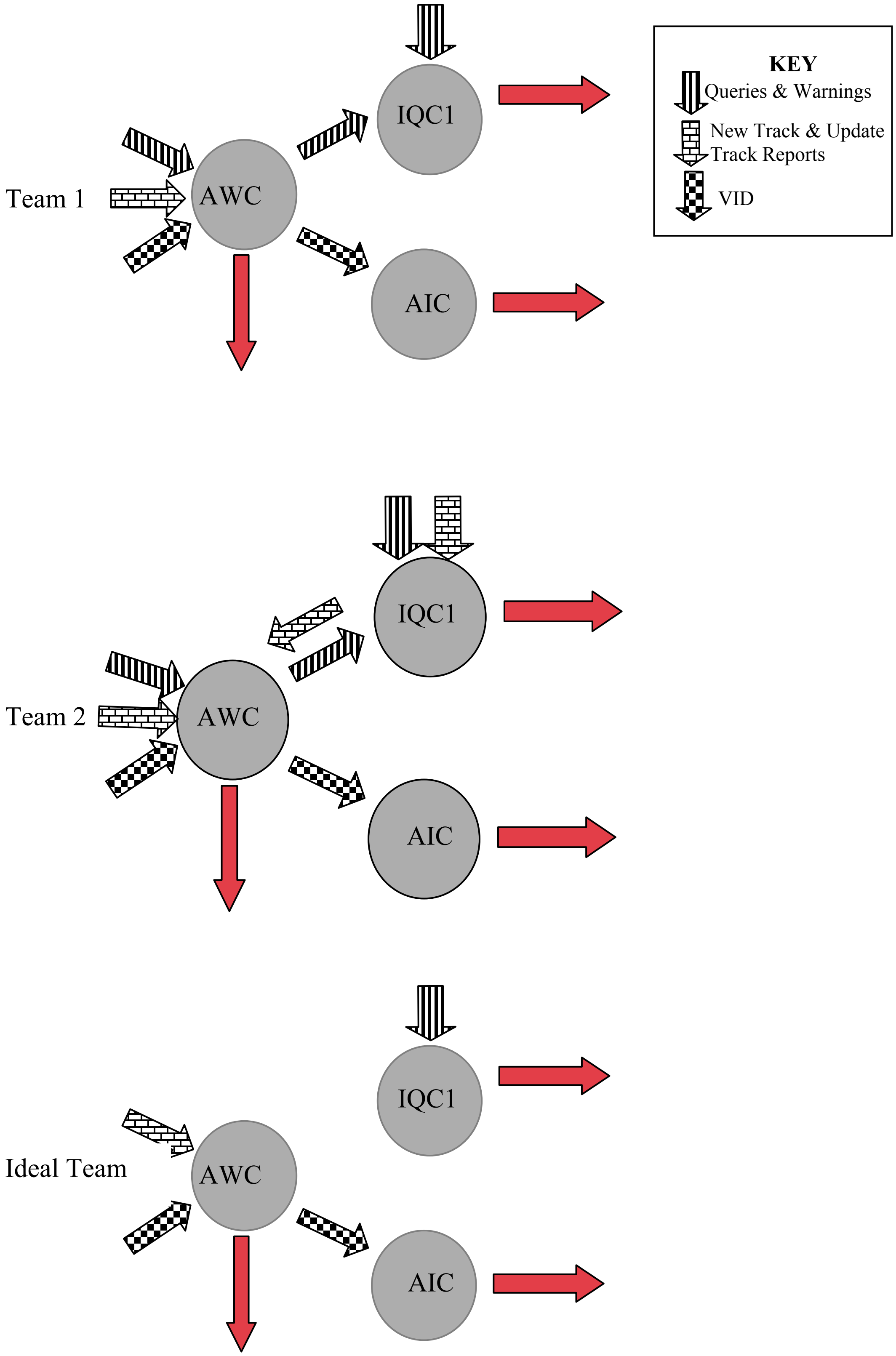

Figure 6. Analyzed work flow data from SOJ Scenario. Task allocation and internal team dynamics were different for the two teams. Neither team allocated tasks to team members as envisioned by system designers.

In Figure 7, we depict one of three cases that describes the interaction between the AWC and IQC1 in order to perform the query task. In this case, IQC1 has finished his evaluation but cannot send the query because he has not yet received an order to do so. The IQC1 begins another task and at some later point, when ordered by the AWC, returns to this task to send the query and listen for a response. Thus bottlenecks, unforeseen by the system designers had been introduced by the dynamics of the team. These bottlenecks were even more pronounced for Team 2 because in addition to Query and Warning bottlenecks, Team 2 imposed bottlenecks for New and Update Track reports. The IQC1 of team 2 was required to read these reports aloud to the other team members before the AWC sent off the report. Thus in the video, one actually sees the AWC's finger poised over the send button of a new track report, as he waits for the IQC1 to complete the reading aloud of the message.

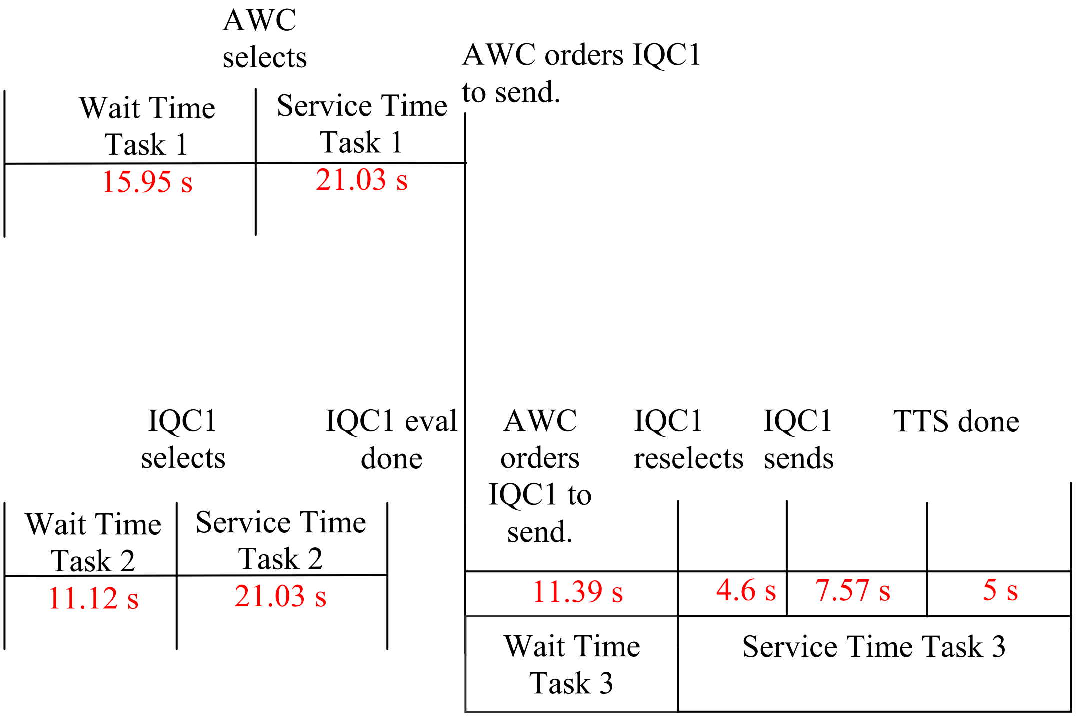

Figure 7. Interaction between AWC and IQC1 in order to perform the task of Querying an aircraft. The IQC1 has completed his evaluation but waits to perform the query until specifically ordered to do so by the AWC.

Further evidence for Team 2's collaborative handling of new track reports can be found in the data. For example, Team 2 took 36 % longer to complete New Track reports and sent 21% fewer New Track reports than Team 1. In addition, the number of New Track tasks that were selected solely by the Team 2 AWC, was one third that of Team 1. Selection of a task by only one operator suggests that the team did not collaborate on that task.

To conclude, bottlenecks, unforeseen by the system designers, had been introduced by the dynamics of the team. These bottlenecks were even more pronounced for Team 2 because in general, Team 2 made task completion a collaborative effort, hence the slower task through-put. Collaborative task sharing raises the broad and important issue of team situational awareness that must be further explored.

Conclusion

Our research approach supports model-based design as opposed to creative engineering. We believe that the latter approach lacks the ability to predict human performance. Performance predictability is essential to good design. In addition to providing a set of useful global statistics that may be used to analyze team and system performance, Queuing theory provides formulas - quantitative predictions for these statistics. These formulas are based on assumptions of input and output task flow and task prioritization. We are currently developing a predictive model for the ADW team viewed as a queueing network. Our ultimate goal is to use these formulas to predict and evaluate operator and system performance. These quantitative models may then be used to simulate and quantify the effects of increasing and decreasing team size and will provide a model of manning and automation requirements. The nature of task allocation and dynamic task reallocation schemes among team members and autonomous agents may be tested with these models. Of course in all these cases, predictions need to be verified against actual teams of operators and automation. However, the quantitative nature of these models will guide the data collection by suggesting where designers should look for significant design improvements. Thus these models will guide system design in an efficient manner, creating a science of design.

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