A MODEL FOR A HUMAN DECISION-MAKER IN A COMMAND AND CONTROL RADAR SYSTEM: SURVEILLANCE TRACKING OF MULTIPLE TARGETS*

Sofia Giompapa1, Alfonso Farina2, Fulvio Gini1, Antonio Graziano2, and Riccardo Di Stefano2

1 Dept. of “Ingegneria dell’Informazione”, Univ. of Pisa via G. Caruso 14, 56122 Pisa, Italy
Tel: +39-050-568550, Fax: +39-050-568522
E-mail: {sofia.giompapa, fulvio.gini}@iet.unipi.it

2 SELEX Sistemi Integrati (formerly AMS S.p.A.)
Analysis of Integrated Systems Group
via Tiburtina Km. 12.400, 00131 Rome, Italy
Tel: +39-06-4150-2279, Fax: +39-06-4150-3755
E-mail: {afarina, agraziano, rdistefano}@selex-si.com

Abstract – This work presents a deterministic approach to the problem of modelling the human behaviour in a Command and Control radar system and it considers the fusion of information between the operator and the system. The implementation and the results of a case study are presented where a human operator performs a tracking operation of multiple targets in a sea region. The mission performed by the operator is the surveillance of a coast area and the selection of a system action against possible threat targets, in order to check their identity. An analytical model of human memory has been investigated where the human decision maker is represented as a subsystem involved with two operational blocks, corresponding to the Situation Assessment process and the Response Selection process that he performs. The operator performance is evaluated by mean of his error probability in these two processes.

Keywords: Radar tracking, human decision making, classification, situation assessment, response selection, resource allocation.

1 Introduction

It is widely recognized that a cognitive overload and a wrong situation assessment have been critical factors in many incident occurred in the past. This kind of problems show up in many different application fields, as air traffic control, naval control and homeland security, that has becoming an increasing need for several countries [16]. In this application fields the context where the operator performs his action is represented by the interaction of several components: the external environment, the sensors network, the communication network between different components of the system, the decision aid subsystem and the action subsystem [18].

The following factors have a determining role in defining the complexity of the application: the difficulty of the controlled environment and the difficulty of the surveillance operation (noise, target density, etc.); the number of integrated sensors that belong to the system (radar, EO, IR, etc.); the high false alarm probability; the need for a continuous monitoring and the high level of attention required, especially during emergency situations; the pressure coming from emergency and the need for a real time action.

Considering all of these, it can be very important to use the information engineering technology to create an analytical model that allows to transform the human operator (HO) in one or more mathematical variables and to insert this model into the overall system model. In fact, the prediction of operator performance can be useful in order to reduce the cognitive workload, to give more aid to the fusion of information coming from multiple sources, to better define the needed action (planning, intervention, optimal resource management) and to verify if the overall system performance remains above a tolerance threshold, despite of the human behaviour.

The variables involved in the definition of a complete operator model are numerous and it is hard to convert them into a mathematical model: variables linked to the human nature of the HO (motivation, training, workload, stress, fatigue), technical variables linked to system features and components, and environmental variables [12]. The need to model this behaviour forces us to make a sort of quantization in order to identify the main performance metrics of the operator, so that most of the previously described variables must not be considered.

The performance parameters that will be considered in the rest of this paper are: the response time of the operator and the delay in one decision, the error probability in the decision making process, the information processing in human memory, the HO cognitive workload and his constraints when he acts as an information processor.

The issue of human factors have been widely addressed in the literature, especially in relation to military strategies and air traffic control applications [9, [16].
These studies have shown that the HO model and its performance are strongly related to the nature of the mission that he performs into the system and to the technical features of the system. In [3, 4, 10] Levis and Boettcher proposed a mathematical description for the decision making process, based on information theory. Using this theory they define the decision making as a mathematical process consisting of the following four steps: Situation Assessment, Information Fusion, Command Interpretation (when more than one decision maker are present in the system), and Response Selection. In this model the decision maker performance is measured in terms of cognitive workload and bounded rationality, i.e. the limit of a human decision maker when he acts as an information processor. The former is defined as the total activity of the system, dependent on the amount of input information that comes out from the system, and the latter is defined as a constraint in the total activity of the system, dependent on the operator maximum processing rate and on the input rate of information coming in memory.

In the rest of the paper we describe an operator model related to a case study were the HO performs a decision making process in a surveillance tracking application, with the ultimate goal of classifying the identity of a target.

2 The human operator model

The context where we want to model the human factor is an integrated system, i.e. a multi-layer system given by the interconnection of several components. In the simplest case these components are: the external environment, one or more sensors monitoring the environment, a communication network used for the exchange of information among system’s components, a decision aid subsystem (e.g. a display) and a fusion network used to combine the information coming from the different sensors. The HO acts inside this complex system and his performance affects the overall performance of the integrated system [8].

In a general sense, the human behaviour includes the following aspects: perception of stimulus from the external environment; processing of information in human memory; a cognitive process including learning, situation awareness, decision making and planning activities; a motor behaviour dependent on the neuromuscular delay in operator movements [13, 17]. The HO analyzes the observed situation and he attempts to recognize familiar aspects and to find a satisfactory solution in his mind, acting as a database based on his previous experience [7, 11]. From this point of view operator’s action is reduced to a matching operation with a set of reference situations, stored in human mind as discrete events. The storage of information in human memory is typically modelled by mean of two types of memory [6]: the short term memory, where data are stored for a short period of time, about 20-30 seconds without a rehearsal process; the long term memory, where data are stored for a period of time that can be theoretically unlimited.

Experiments on human cognitive capability proved that no more than 7±2 one-dimensional variables can be stored in short term memory [14]. The model described here doesn’t consider long term memory.

The proposed model primarily considers the cognitive activity of an operator during a decision making operation, with reference to the following application field: air traffic control, naval control, and homeland security. Since decision making is a cognitive activity, it is not really observable and it is a very hard issue to define the process bounds. In spite of this, it is necessary to clarify some issues in order to analytically formulate the problem: what the system does, where the system is used and how it is used [5]. The model represents the human decision maker as a subsystem composed of two sequential blocks modelling the different steps of decision making: the Situation Assessment (SA) step and the Response Selection (RS) step.

![Figure 1: The HO subsystems.](image)

The input to the system is a vector \( x \) containing data from sensors used to monitor the external world; the output is a decision \( s \) about the assessed situation in the SA phase, and an action \( r \), representing the appropriate reaction, in the RS phase. During the SA process the operator can identify the event looking up in his memory or perceiving a new relation about the observed scenario. After creating the event relation, the HO classifies the event and he decides an appropriate action. The decision can be memory based, if the event was identified looking up memory, or rule based, if a new perceived relation was created. The sequence of events and actions that occur in operator mind is shown in figure 2.

![Figure 2: The HO model.](image)

The operator acts with a delay on decision, dependent on his stress and workload conditions. This delay can be included in the model as a deterministic delay and its numerical value can be selected according to data reported in literature [6]. The selection between more options in Situation Assessment depends on how much delay is allowed, so that the performance can improve if the available time for decision increases. The operator error arises because the information he can process is limited. From this point of view his error
probability can be described in terms of a blockade of human memory that occurs when the information input rate exceeds the operator processing rate. This model does not consider a systematic bias, which could be the result of tacit knowledge of the operator (training, previous mission, possible traumas, etc.). Moreover, the model has been derived under the following assumptions: the operator is well-trained in the mission that he performs, he is not affected by a learning effect, the overall system is memory-less, i.e. its history is not considered.

3 Case study

3.1 Description

We now describe a case study where an HO is involved in the tracking of multiple targets. The mission performed by the operator is the surveillance of a coast region and the selection of a system action against possible naval threat targets, to check their identity. The simulation scenario is given by the target mission performed by the operator is the surveillance of a coast region and the selection of a system action against possible naval threat targets, to check their identity. The simulation scenario is given by the target identity. The simulation scenario is given by the target and a reference system, defined by the geographical area considered, the sensor position in this area, an off-limit region and a warning zone [1, 2]. The operator observes the tracks belonging to NTi input targets that are the targets visualized on the display. These tracks are vectors containing the parameters of each target, generated by a single radar sensor: target instantaneous position, target speed and direction, cooperativeness index of the target, i.e. a parameter extracted by an Automatic Identification System (AIS) on the base of on-board devices. The operator makes a decision about the target dangerousness according to the numerical value of the previous parameters (Situation Assessment process, SA), and he classifies the target as: cooperative target, suspect target, threat target, non cooperative neutral target. This decision is made in a deterministic way, by mean of a comparison between target parameters and some allowed values, defined by tolerance thresholds. These thresholds are: the maximum speed allowed for a target passing in the area under surveillance without representing a threat situation; the minimum distance allowed between the target position and the bounds of the off-limit region; one parameter stating if the target is approaching the off-limit region or not. The logic used to classify the target is shown in Table 1.

The described logic considers the distance of the target from the off-limit region as a prior information in terms of target dangerousness. Speed, distance and direction are not checked for a cooperative target.

After this, the operator selects an appropriate intervention from the system (Response Selection process, RS), according to the decision made during the SA phase about target identity. The intervention is selected only for threat targets and it consists in the allocation of one resource by the system. Two type of resources are considered for target inspection: an helicopter (resource A) and a patrol boat (resource B).

The selection of one of these two resources depends on how much time is available for reaction. This time is related to the operational context, especially to the approaching time of the target and to the resource parameters (resource speed and number of available resources).

Using the information about target’s direction, the system estimates the resource response time, i.e. the time that the resource needs to intercept target’s trajectory. This value is then compared to the target approaching time, in order to evaluate the available time for the reaction. If the available time is greater than zero and if there are resources available, the system will allocate one of them for target’s inspection. If there is not enough time for the reaction a missed detection will occur.

The time that the operator spends for SA and RS processes is included in the simulation as a deterministic delay, whose value depends on how many parameters the operator must elaborate to perform the decision making process. This is shown in Table 2.

The simulation is structured in NTi sections, each one corresponding to one hour’s work for the operator. Each section is divided into 120 independent time slots, called update, each having the duration of 30 seconds. Each update corresponds to an inter-update of the operational context and of the display. The initial number of input tracks is constant during all the section and it is uniformly distributed in the interval [N_rnin , N_rnax]. At the nth update the number of input tracks is

\[ N_{Ti} (n) = N_{Ti} (n-1) + k , \]  

(1)

where k is a discrete random variable assuming values \{-1,0,1\} with the same probabilities; when as a result
\( N_{T_{\text{res}}}(n) \) should assume a value outside the interval \([N_{T_{\text{res}}}, N_{T_{\text{res}}}]\) the value of \( k \) is forced to be zero.

The goal of the simulation was to evaluate HO operator performance within a decision making process, independently of the performance of the other components of the system. To this purpose the following hypotheses were assumed: the radar has ideal performance (\( P_o = 1, P_{o1} = 0 \)); the tracker is also ideal; the communication devices inside the system do not introduce any delay; information on the target can be released from human memory when the decision is made. Even though these assumptions are very simplistic, the case study represents a starting point for a more complete analysis. The case where we consider the real performance of the system’s components is under investigation and it will be described in a future paper.

Figure 3 shows the plot of the trajectories during one update, for the simulated scenario.

![Figure 3: Trajectories during one update.](image)

The dotted circle represents sensor’s coverage area. The line \( r_0 \) represents the bounds of the off-limit region and the dotted line \( r_1 \) defines the warning zone. The figure shows an intervention of the system on a threat target: the point \( P \) in figure represents the point where the resource (in this case resource B) will intercept the trajectory of the threat target \( T_i \).

### 3.2 Performance analysis

Performance has been evaluated in terms of operator error probability during the Situation Assessment (SA) and Response Selection (RS) processes, and in terms of system error probability during the Resource Management (RM) operation.

The operator error probability, \( P_{\text{e}}^{(\text{SA+RS})}(N_{T_i}) \), is calculated as a function of the number of input tracks. In this calculation it was taken into account that an error occurs when the number of tracks processed by the operator during one update is less than the number of threat tracks generated in that update. The number of processed tracks depends on the type of targets that enter the system during the update and on the corresponding operator processing time, according to Table 2. In this way the error in Situation Assessment and the error in Response Selection are considered in the same performance metric. The system error during Resource Management doesn’t depend on the operator, but it is related to the system parameters and to the operational context: number of available resources, approaching time of the threat target, resource speed, reaction time. This probability has been calculated with respect to the threat targets, since in the context described here a resource allocation occurs only when a threat target enters the system. This calculation can be performed in two ways: with respect to the total number of threats or with respect to number of threats processed by the operator. In the first case an error in resource management occurs when the number of appropriate resource allocation during one update is less than the number of threat tracks that enter the system during that update. In the second case an error occurs when the number of appropriate resource allocation is less than the number of threat tracks processed by the operator. The event “missed intervention” depends on several causes: the threat target is not detected by the operator, there are not any available resources, the available resources are not able to intercept the target until its approaching time is passed. All these error probabilities are averaged over the total number of updates.

The average efficiency parameters of the system during Resource Management have also been evaluated. These parameter are defined as:

\[
\bar{\eta}_1 = \frac{\text{# appropriate resource allocations}}{\text{# total threats}},
\]

with respect to the total number of threat tracks, and

\[
\bar{\eta}_2 = \frac{\text{# appropriate resource allocations}}{\text{# processed threats}},
\]

with respect to the processed threats.

Figure 4 shows the HO performance in the decision making process in terms of error probability during the SA and the RS operations, represented as a function of the number of input tracks. This probability has been calculated considering the simulation scenario described in Table 3.

<table>
<thead>
<tr>
<th># of sections</th>
<th>Initial number of tracks</th>
<th>Target Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_s = 5000 )</td>
<td>( N_{T_{\text{res}}} = 1 )</td>
<td>( P \mid \subseteq U (0.80 \text{Km/h}) )</td>
</tr>
<tr>
<td>( N_s = 16 )</td>
<td>( D_{\text{threshold}} )</td>
<td>( \theta \subseteq U (0, 360^\circ) )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Target direction</th>
<th>Dangerousness threshold</th>
<th>Available Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta \subseteq U (0, 360^\circ) )</td>
<td>( R = 40 \text{Km/h} )</td>
<td>( N_s = 3 )</td>
</tr>
<tr>
<td>( d = 30 \text{Km} )</td>
<td>( V_s = 300 \text{Km/h} )</td>
<td>( \bar{\eta}_2 = 7 )</td>
</tr>
<tr>
<td>( V_s = 60 \text{Km/h} )</td>
<td>( N_{T_{\text{res}}} \geq 6 )</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4 shows a saturation in operator’s capability of processing tracks when the number of input tracks is greater than or equal to six (\( N_{T_{\text{res}}} \geq 6 \)).

Performance during Resource Management process has been evaluated in terms of system error probability and in terms of system average efficiency parameters.
These metrics have been calculated considering a simulation scenario where all the tracks that enter the display during one update were threat tracks and then they necessitated a resource allocation from the system.

**Figure 4**: Operator error probability.

Figures 5 and 6 show system’s resource management error probability and the average efficiency parameters in resource allocation, respectively, represented as a function of the threat tracks. Both these metrics have been evaluated with respect to the total number of threats and with respect to the number of threats processed by the operator.

**Figure 5**: RM error probability of the system.

**Figure 6**: RM average efficiency of the system.

Since all the tracks that enter the system are threats, the operator is not able to process more than three tracks during one update interval (30 seconds), according to operator’s processing times shown in Table 2. Finally, system’s resource management error probability and system’s average efficiency in resource allocation were also evaluated considering a modified simulation scenario, where all parameters are the same as before except for the number of available resources, that are reduced to $N_A = 1$ and $N_B = 3$. The numerical results reported in Figures 7 and 8 show a deterioration in system’s performance.

**Figure 7**: RM error probability of the system when $N_A = 1$ and $N_B = 3$.

**Figure 8**: RM average efficiency of the system when $N_A = 1$ and $N_B = 3$.

### 4 Conclusions

In this work we investigate a deterministic analytical model for the behaviour of a human operator in a command and control radar system. In the case study the mission performed by the operator is the surveillance of a coast region and the selection of a system intervention against possible threat tracks that have been detected. The HO is modelled as a system made of two sequential blocks, corresponding to the “Situation Assessment” and “Response Selection” operations that the HO performs during the decision making process.

During the SA phase, the operator decides about the dangerousness of the tracks that he can see on the system display and he classifies the corresponding target as cooperative, suspect, threat, neutral. The decision is made by mean of a deterministic comparison between target’s parameters and the dangerousness thresholds, that are the maximum speed allowed for a target passing on the surveillance area and the minimum distance allowed between the bound of an off-limit region defined on this area. During the RS phase, the operator selects an intervention from the system, according to the classification he has made in
the previous phase. This intervention is selected only for threat targets and it provides the allocation of a resource (a helicopter or a patrol boat) in order to check target identity.

The proposed model represents the human constraints in information processing by means of a deterministic delay included in the decision making process, whose value depends on the number of data that the operator has to process to make his decision. The purpose of the work was to evaluate the human operator performance as a function of the quantity of received information and to evaluate how a possible blockage of the operator affects the performance of the overall system. Performance was evaluated in terms of operator error probability during SA and RS processes and in terms of system error probability during the Resource Management phase. These probabilities were calculated as a function of the number of input tracks. The average efficiency in resource allocation was also evaluated, in order to show how this metric depends on the system parameters and on the operational context. Performance of the system in the RM phase has been evaluated for a particular simulation scenario, where all the input tracks belong to threat targets and then they need a resource allocation from the system.

Results have shown a saturation in operator processing capability when the number of input tracks is greater than or equal to six. The resource management error probability shows a saturation when the number of threat tracks is greater than three. This is due to the fact that during the update time (30 seconds) the operator is not able to process more than three threat tracks, according to the values chosen for his processing time during SA and RS operations. The average efficiency parameters in resource allocation have been evaluated also for a modified scenario, where a reduced number of available resources was assumed. The results have shown a deterioration of the system performance in resource management.

Assuming the deterministic model described here, the HO performance can be predicted from the numerical values assigned to operator’s processing time and maximum time available for the decision (the update time). A future development of this work will consider a probabilistic model for the HO. In this case the operator will perform the decision making process considering the likelihood of the hypotheses that he constructs during the SA operation, estimated via a Bayesian inference. We will also investigate a more complex scenario where more human operators, corresponding to different sensors, perform independent decision making processes. In this case an additional problem to be investigated is the data association and the data fusion between the information processed by different operators.

References