HYBRID SWARM INTELLIGENCE ALGORITHM FOR OPTIMAL COGNITIVE ARCHITECTURE DESIGN OF OPERATORS IN NUCLEAR POWER PLANT

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Abstract - A hybrid swarm intelligence algorithm is proposedto determine thenear-optimal human cognitive performance of operators under various initiating events that would lead to accidents in Nuclear Power Plants. A three-parameter Weibull distribution model is used to estimate Human Error Probability (HEP), a measure of the Human Cognitive Reliabilitye valuated under dominant cognitive processes associated with the task being performed by the operators during an emergency situation. In conventional Human Cognitive Reliability (HCR) model, the cognitive coefficients that depict the human characteristics are treated as constants. However the values of these coefficients that represent various operator behavior should be carefully assigned for better estimates of HEP. In this study, critical human cognitive factors such as attention, perception and memory under different cognitive levels are evaluated in order to design an optimal human cognitive architecture that minimizes the HEP.The results obtained from the proposed algorithm revealed that the hybrid swarm intelligence algorithm outperformed the generic Ant Colony Optimization (ACO) algorithm.

Keywords - Cognitive Architecture Optimization, Human Error Probability, Hybrid Swarm, Intelligence Algorithm, Nuclear Power Plant.

I. INTRODUCTION

Modern nuclear power plants (NPPs) are equipped with advanced instrumentation and control systems. However,these are managed by human actions for safe operation of the plant and so the accidents due to human error are a serious threat to nuclear industry. There is a possibility of occurrence of human error during situations that call for prompt and more reliable human intervention for avoidance of major nuclear power plant accidents.The International Atomic Energy Agency -IAEA TECDOC report [1] showed that 40% to 50% of the severe accidents were due to human error. Fukushima nuclear accident in Japan is one such accident. The human contribution to safety of nuclear power plants can be assessed and quantified using Human Reliability Analysis (HRA) models [2]. Human Cognitive Reliability (HCR) model uses a simple analytical process to provide quantitative result on Human Error Probability (HEP) which is a measure of Human Reliability [3]. The HCR model is based on a normalized time-reliability curve, which shows the human cognitive behavior pattern associated with any response to his emergency task expected to be completed in a given span of time.

The different modes of human behavior during decision making viz. skill-based (SB), rule-based (RB) and knowledge-based (KB) are inbuilt into the three-parameter Weibull probability density function of HCR. A set of three distinct coefficient valuesunder each mode can be independently analyzed for better design that represent the mental processing of human behavior [4]. These critical coefficients which define the human cognitive architecture play a vital role in the estimation of HEP. Standard values of these coefficients derived based on the simulated time during emergency operations under conventional control room environment are available in the NUREG 1921 report [2]. Optimal values of these coefficients would facilitate to obtain an accurate prediction of human error occurrence.There is a need to investigate the correctness of the values assigned to cognitive coefficients in HCR model to reveal the true human cognitive architecture of the nuclear power plant operator. Therefore, this study proposes an evolutionary algorithm to determine the optimal HCR coefficients that would minimize the HEP.

The organization of the paper is as follows: the literature review on human cognitive models and the application of evolutionary algorithms that addressed human reliability studies are presented in Section 2; thescheme and formulation of the problem aregiven in Section 3 and Section 4.The implementation of the proposed Hybrid Swarm Intelligence algorithm is presented in Section 5. The results obtained and conclusions are presented in Section 6 and Section 7.

II. LITERATURE REVIEW

The determination of optimal human cognitive behavior of operators in nuclear power plants is a problem that involves cognitive psychology, reliability, performance, and safety [5]. Human cognitive studies in nuclear applications mainly focus on psychological and thinking process of an operator while responding to an emergency situation[6]. Human Cognitive Reliability (HCR) model is one such Human Reliability Analysis (HRA) model

widely employed in nuclear power plant applications[7-9]. Three kinds of mental processing characteristic are modeled for three types of human behaviors viz. skill-based, rule-based, and knowledge-based.

Researchers have examined the validity of the model and have suggested modifying the coefficients of the cognitive behavior[10], [11]. These studies proposedschemes to modify the HCR coefficients to obtain more precise HEP. It appears that the study on determining the optimal values of these coefficients to define the human cognitive architecture of NPP operators is limited. Evolutionary algorithms are widely used to identify the best combination of a set of variables to derive maximum benefit [12], [13].

The heuristic approach employed in these algorithms would search for an optimum solution iteratively trying to improve upon a candidate solution with respect to a given measure of quality. They are used to accelerate the process of finding a good enough solution with an intuitive judgment or expertise.Most search heuristics are nature-inspired and swarm-intelligence [14]. In recent years, swarm intelligence, a new category of metaheuristics, has emerged and attracted researcher's attention. 'Swarm Intelligence' is an attempt to design algorithms or optimization problem solvingtechniques inspired by the collective behavior of social insects [12].

Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) –the popular swarm intelligence algorithmshave been successfullyimplementedto solve many engineeringoptimization problems such as wind energy forecasting [12], vehicle routing problem[15]. In this study, a hybrid algorithm incorporating the strengths in both these algorithms to solve the human cognitive architecture optimization problem is presented.

III. THE SCHEME

The HCR model is applicable to the actions carried out in nuclear control room provided the operator performance times can be determined and the accident phenomenon is known 'a priori to predict the time available for the crew to respond.

If't' is the time available for the operator to respondduring a risk mitigation task and T_m is the time that the operator actually executed the task, the operator non-response probability for a given system time window t is given by.

$$P(t) = \exp - \left[\frac{\frac{t}{T_m} - B_i}{A_i}\right] C_i \qquad (1)$$

where, 't' is time allowed by the system for the operator to complete actions before a change in plant state.T_m = Median response time; A_i, B_i, C_i = i^{th}type of cognitive mental processing of the operator. The interim values of the parameters A_i, B_i, and C_i as presented in the report of Atomic Energy Regulatory Board, Mumbai [16] are considered in this study.

It is observed from the studies carried out by [5],[16], and [17]the cognitive parameters viz., attention, memory andperception have more influence on the likelihood of human error while executing the task. This is also found to be truein the study conducted on determining the critical drivers affecting the operator's performance in Indian Nuclear power plants [18]. A cognition based model, which uses unnamed variables of $A_{i,}$ $B_{i,}$ and $C_i$areconsideredin this study as- attention, memory and perceptionrespectively.

IV. FORMULATION OF THE PROBLEM

The objective of the study is to design the optimal human cognitive architecture that would minimize the Human Error Probability (HEP).The HEP is represented by a three-parameter Weibull distribution based on the Human Cognitive Reliability (HCR) model. A_i, B_i and C_i are the cognitive coefficients associated with the i^{th} type of mental processing viz., Attention, Memory and Perception under the cognitive decision making behavior of skill, rule or knowledge which can be generated using simulator data. Hence the objective function is

$$\text{MinZ} = \exp\left(-\left[\frac{\left(\frac{t}{T_m}\right) - B_i^s}{A_i^s}\right] C_i^s\right) + \exp\left(-\left[\frac{\left(\frac{t}{T_m}\right) - B_i^k}{A_i^k}\right] C_i^k\right) + \exp - tTm - BirAirCir \qquad (2)$$

where Z is the non- response probability of the operator while performing emergency actions, 't' is the total time available for action, T_m is the median time to complete the action. A_i^s, B_i^s and C_i^s are coefficients for skill-based behavior, A_i^k, B_i^k and C_i^k are coefficients for knowledge-based behavior and A_i^r, B_i^r and $C_i^r$are coefficients for rule-based behavior. The determination of optimal values of the coefficients for the operator's cognitive characteristic is a complex combinatorial optimization problem.

4.1 Proposed HCR Coefficient Levels

The standard values for each of the variables A_i, B_i, and C_i corresponding to SB, KB and RB behaviors are obtained the values proposed by Hannaman et al. [5]. These values are taken as the mean value of the normal distribution and the levels are representative of the 1σ, 2σ, and 3σ values on either side of the mean. The various proposed levels that represent different human cognitive behaviorsare given in Table1.

Table 1: Different Cognitive Levels

Level	Perception (A_i)			Memory (B_i)			Attention (C_i)		
	SB	RB	KB	SB	RB	KB	SB	RB	KB
1	0.136	0.200	0.166	0.233	0.200	0.264	0.400	0.300	0.266
2	0.271	0.400	0.333	0.467	0.400	0.527	0.800	0.600	0.533
3	0.407	0.600	0.500	0.700	0.601	0.791	1.200	0.900	0.800
4	0.543	0.800	0.666	0.933	0.801	1.055	1.600	1.200	1.067
5	0.814	1.200	1.000	1.400	1.202	1.582	2.400	1.80	1.601

The meaning of proposedcognitive characteristics for each level under the three parameters are given in Table 2, (refer [19] for definitions on each characteristic).

Table 2: Proposed Cognitive Characteristics

Level	Perception (A_i)	Memory (B_i)	Attention (C_i)
1	Trivial Perception	Latent Memory	Focused Attention
2	Effective Perception	Procedural Memory	Sustained Attention
3	Passable Perception	Semantic Memory	Selective Attention
4	Veridical Perception	Episodic Memory	Alternating Attention
5	Conscious Perception	Flashbulb Memory	Divided Attention

V. HUMAN COGNITIVE ARCHITECTURE DESIGN

This Section deals with the proposed stepwise procedure adopted in Hybrid Swarm Intelligence (HIS) Algorithm.

5.1 Notations and Terminology

∂_x –Random vector define the search boundary
X_t^y – Current location for ant, y
X_{t+1}^y – Next location determined for ant, y
X^{best} –HEP value obtained from the best architecture so far
X^{gbest} –Best architecture obtained from ACO
W –Inertia Weight in search parameter used in PSO
C1, C2 – Learning factors
V_t^k – Current velocity for particle k
V_{t+1}^k –Next velocity for particle k
XP_t^k – Current location for particle k
XP_{t+1}^k –Next location for particle k
Rand1, Rand2–Random numbers uniformly distributed [0, 1]
$pbest_t$ –Best value of the objective obtained so far in PSO search
$gbest_t$ –Global best valueof the objective function
T –Total number of iterations

5.2 HSI Algorithm -Pseudo code

Initialization

Stoppage criteria: n * √T iterations
Use $\alpha_{initial}$ for initial values and specify the level limits using Normal distribution
For all Ants,
Generate the initial location in the search space (X_t^y)
Evaluate the location of each ant using the objective function F (X_t^y)
From the values obtained, choose the best as X^{gbest}
For all Particles,
Generate the initial location in the search space (XP_t^y)
Evaluate the location of each particle using the objective function F (XP_t^y)
Set the P^{best} initial and Determine the P^{best} as g^{best}

Manipulation

For all Ants,
Generate the random vector of ∂x with the limits of (-α, α)
Evaluate the location of each ant using the objective function and assign the best solution as X^{best}
Update the new position of the ant colony using the formula:

$$X_{t+1}^y = X^{gbest} \pm \partial x$$

$X^{best} = X^{gbest} + (X^{gbest} * 0.01)$
Assign X^{best} as X^{gbest}
For all Particles,
Generate the location of all particles using the equation:

$$V_{t+1}^k = W.\ V_t^k + C1.\,rand1.\,(gbest_t - XP_t^k) + C2\ .\ rand2\ .\,(pbest_t - XP_t^k)$$

Evaluate the location of each particle using the objective function and assign the best solution as P^{best}
Update the new location of the particles using the formula:

$$XP_{t+1}^k = XP_t^k + V_{t+1}^k$$

Assign P^{best} as g^{best}
g^{best} is the optimal valueof the objective function Z

VI. THE SOLUTION OBTAINED

The proposed HSI algorithm is implemented to solve the cognitive architecture problem in High pressure Process Water System (refer [9] for simulated failure data of operators) of a nuclear power plant in India. The human cognitive architecture design which minimizes the HEP obtained from the HIS algorithm is presented in Table 3. The set of optimal cognitive

coefficients corresponding best design for also presented.

Table 3: Optimal human cognitive architecture

Behaviour	Ai^s	Bi^s	Ci^s	Ai^r	Bi^r	Ci^r	Ai^k	Bi^k	Ci^k	HEP
Coefficient	0.057	0.152	1.743	0.494	0.478	0.848	1.513	0.666	1.133	0.00421
Level	2	1	4	3	3	3	5	3	4	-

The optimized skill based human cognitive architecture are -trivial perception, latent memory and alternating attention; rule based design are- semantic memory, passable perception, and selective attention and the knowledge based designare - flash bulb memory, passable perception and alternating attention. The management should take necessary action to inculcate these characteristics in the operators through training and/or other innovative measures.

CONCLUSION

Human Cognitive Architecture provides a generic framework of information-processing stages that people use to encode, store and modify information.A set of cognitive coefficients are used to generate several human cognitive architecture design. This study is an attempt to determine the best values of the critical cognitive coefficients that depict optimal human cognitive performance which would minimize the likelihood of occurrence of human error. In this study a Hybrid Swarm Intelligence Algorithm is proposedto design human cognitive architecture for operators in NPP in India.An attempt is made to explore the hybridized application of Particle Swarm Optimization algorithm and Ant Colony Optimization algorithm, which are co-operative, population based, solution search swarm intelligence meta-heuristics. The potential use of such hybrid algorithm to solve human cognitive architecture optimization problem has been demonstrated.

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