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A Framework for Implementation of Adaptive Autonomy for Intelligent Electronic Devices

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Abstract: This research letter introduces a novel framework for the implementation of Adaptive Autonomy for Intelligent Electronic Devices (IEDs). The study aims at achieving an optimum function allocation between IEDs and humans in automation systems. The function allocation should be adapted to the changes in environmental conditions, thus referring to as Adaptive Autonomy (AA). Performance Shaping Factors (PSFs) concept is utilized to represent the environmental conditions. Moreover, Experts' Judgment method is used, to tackle the complex issue of human reliability assessment. The framework is implemented to the power distribution automation system of the Greater Tehran Electricity Distribution Company (GTEDC) and the obtained results are discussed then. Furthermore, the trends of the IED autonomy levels are investigated versus the situation criticality and the automation stages. Apart from introducing a novel implementation framework for IEDs' AA, this letter discusses on the application-oriented issues, due to the context-based nature of the Human-Automation Interaction (HAI). The developmental relevance of this study is significant, as it is performed in a Metropolitan area of an Asian/Middle Eastern developing country, thus generalize-able to the similar applications to a reasonable extend.

Key words: Human-automation interaction, performance shaping factors, experts' judgment, power distribution automation, utility management automation

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INTRODUCTION

Intelligent Electronic Devices (IEDs) are gaining widespread usage in modern supervisory control and data acquisition (SCADA) systems; especially, where the distributed control and intelligent processing concepts are utilized (McDonald, 2003; Lehtonen *et al.*, 2003; Nordman and Lehtonen, 2005; Hor and Crossley, 2006). IEDs are devices containing electronics that can process data and communicate with external devices (Lehtonen *et al.*, 2003). Therefore, IEDs can be regarded as automatic components of automation and SCADA systems, who executes the function; task or job previously performed or conceivably could be accomplished by a human (Parasuraman *et al.*, 2000). Humans collaborate with these automatic components, which are referred to as IEDs or automation, in this study.

Human-Automation Interaction (HAI) has been intensively studies in the recent half century (Parasuraman and Wickens, 2008). One of the main goals of these studies was to provide analytical methods to allocate functions between the humans and the automation. P.M. Fitts proposed a fixed list of human-machine (here: human-automation) function allocation, in 1951 (Parasuraman *et al.*, 2000). Contrary to Fitts' approach of considering a fixed all or none automation philosophy; Sheridan and Verplank suggested that the automation can vary across a continuum of levels, from the lowest level of fully manual to the full automatic (Parasuraman *et al.*, 2000). They proposed a ten-level scale of computers' autonomy for tele-operation systems, which was welcomed by Parasuraman *et al.* (2000), Endsley *et al.* (2003), Itoh and Inagaki (2004), Fereidunian *et al.* (2007a, b), Endsley and Kaber (1999) and Kaber *et al.* (2005). Furthermore, Parasuraman *et al.* (2000) and Endsley and Kaber (1999) presented a more comprehensive qualitative model that provided a general framework for representation of the Level of Automation (LOA) versus the stage (or type) of automation (TOA), which is referred to as LOA-TOA model in this letter. The proposed AA framework of this letter is based on the LOA-TOA model.

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Humans and IEDs are both highly sensitive to environmental conditions, which clearly affects their overall performance in collaborating with each other. IEDs are more prone to errors in large complex systems (McDonald, 2003; Lehtonen *et al*., 2003) and humans may also fail to express an error-free performance (Parasuraman *et al*., 2000; Endsly *et al*., 2003), because of their cognitive and situational awareness limitations. Therefore, though determination of a fixed LOA for automation and SCADA systems provides better results than the systems designed based on the automate-as-possible design philosophy. However, these fixed LOA designs fail to maintain the full advantages of the overall system, because of the changes in environmental conditions. Consequently, the automation systems should be smart enough to adapt their LOA to the changes of environmental conditions. This concept is known as adaptive automation (Parasuraman *et al*., 2000; Kaber *et al*., 2005) or adjustable automation (Bradshaw *et al*., 2003). This is referred to as Adaptive Autonomy (AA), in this study, to prevent the confusion with the phrases like adaptive control and adaptive automation in systems control terminology.

The AA concept is a young-yet fertile-field of research, since most of the few AA implementations reported in literature are within the aerospace, aviation and military industry. These implementation reports (Parasuraman *et al*., 2000; Kaber *et al*., 2005; Bradshaw *et al*., 2003) declare the need for more AA implementations in various applications, in order to pave the way toward commercial implementation of the presented HAI and AA models.

This study contributes to the literature in two ways: firstly, by presenting a complete adaptive autonomy implementation framework for IEDs, based on an extension of LOA-TOA model (Parasuraman *et al*., 2000; Endsley and Kaber, 1999), as well as using Experts' Judgment and Performance Shaping Factors (PSFs) concepts (Holmberg *et al*., 1999; Rosqvist, 2003; Sutcliffe and Gregoriades, 2007; Chang and Mosleh, 2007). Secondly, by extracting the experimental facts through the observations on the results of the implementation to the power systems automation systems of the GTEDC. A comprehensive investigation of the HAI models is presented by Fereidunian *et al*. (2007a), along with discussions on the main faced-by challenges.

This study reports the first implementation of LOA-TOA model to IEDs autonomy in power distribution automation systems, to the best of our knowledge, according to the Science Citation Index® and the IEEEXplore®. Furthermore, it can be regarded as one of the first application reports of LOA-TOA model of Parasuraman *et al*. (2000) in the civil services, except to the aviation and cruise control.

The objective of this study is to find out an optimum function allocation between IEDs and human in automation systems.

MATERIALS AND METHODS

The basic ideas of this research were developed in Helsinki University of Technology, Finland in 2005 and 2006. The rough ideas developed there were expanded and represented as quantitative models in University of Tehran, Iran from 2006 to 2008. The practical data (such as the practical list of PSFs and Experts' Judgments interviews) were obtained from the Greater Tehran Electricity Distribution Company (GTEDC) in 2006 and 2007. GTEDC delivers electric power to the Greater Tehran metropolitan area, feeding more than 12000 medium voltage (20 kV/400 V) substations. Considering the vital role of electric power in economic development and daily life, reveals the importance of improving its service reliability (Ghaderi *et al*., 2006). This short communication with its limited space-shortly introduces the general framework that we have devised for implementing the AA methodology. However, more details about deployment of the Experts' Judgment, PSFs and the developed mathematical models are left for longer research study, to be presented in near future.

The proposed framework is shown in Fig. 1, in which the upper loop sequentially checks for the changes in PSFs. PSFs are used to introduce the environmental conditions to the adaptive IED autonomy implementation process. PSFs represent the most influential factors that shape the performance of humans and their electronic counterparts (IEDs). PSFs are used in this framework, to tackle the issue of quantitative representation of the SCADA system environmental conditions.

Each time the environmental conditions are changed according to the monitored field dynamic data- PSFs are updated. Subsequently, the performance of the humans is analyzed, comparing to those of the IEDs. Then, the new IED autonomy level is determined by a tradeoff analysis between the humans and the IEDs, in light of the subjective knowledge of Experts' Judgment. Since the aim of the human performance evaluation is to compare it to those of IEDs, this research does not seek to focus on direct methods of human mental models, i.e., the objective methods; instead, we referred to the subjective knowledge of the filed experts. The Experts' Judgment was gathered through interviews with GTEDC's SCADA and dispatching experts, based on a standardized questionnaire, where each interview took at least 1 h time.

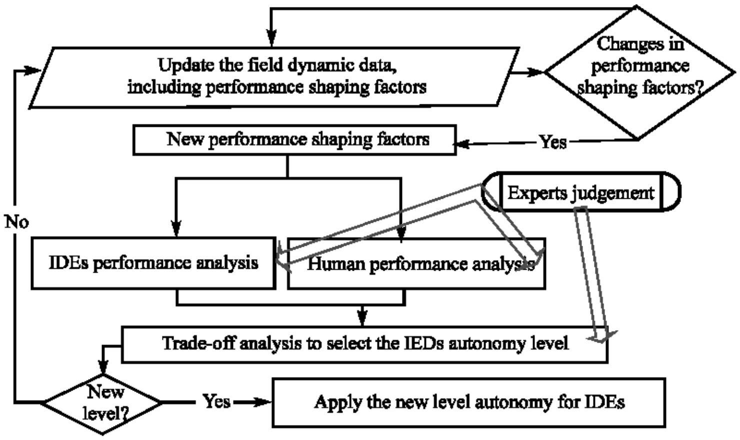

Fig. 1: The proposed framework for implementation of adaptive autonomy

An extended version of the LOA-TOA model of (Parasuraman *et al*., 2000) is used in present proposed method: level 1 of the original Sheridan's taxonomy is shifted down to form a new level 0* and a new level of 1* is introduced as a new LOA. Hence, our adaptive IED autonomy framework deals with eleven LOAs. The justification for the necessity of the new level is given by Fereidunian *et al.* (2007a) and the definitions of the LOAs, TOAs and HAI model can also be found in the Appendix, by Parasuraman *et al.* (2000), Fereidunian *et al.* (2007a, b) and Endsley and Kaber (1999). Furthermore, since this short communication is limited in space, more details about the deployment of the Experts' Judgment are left for longer research papers in near future.

RESULTS AND DISCUSSION

Present proposed framework was presented to one of the power distribution automation functions, known as restoration by reconfiguration. This function is referred to as feeder reconfiguration of utility management automation (UMA-FRF). The UMA-FRF system which has been introduced by Fereidunian *et al.* (2002) to restore the network after occurrence a fault, by reconfiguring the power distribution system, leading to a more reliable power. IEDs are widely used in UMA-FRF systems for measuring, monitoring, communicating, processing and command and control tasks.

The UMA-FRF is implemented in the Greater Tehran Electricity Distribution Company (GTEDC), therefore the application is tailored to the specific situation of the GTEDC. However, the obtained experimental results can be generalized to a reasonable extent, especially for the companies having similar characteristics in terms of factors such as: geographical area (Asia and Middle East), population (Metropolises), developmental factors (a developing country) (Ghaderi *et al*., 2006).

An automation task is broken into the 4 stages (types or TOAs) of information acquisition (Stage 1), information analysis (Stage 2), decision making (Stage 3) and decision action (Stage 4) (Parasuraman *et al*., 2000). In the UMA-FRF case, these TOAs are defined as: fault indication (Stage 1), fault location (Stage 2), restoration scheme decision making (Stage 3) and switching action (Stage 4). IEDs are able to act as all of these four TOAs.

We made our first use of Experts' Judgment on identification of the main PSFs for UMA-FRF. According to the experts of GTEDC, the most influential PSFs for UMA-FRF are: day or night (because of humans' less situation awareness at nights), ease of access to the network asset, type and importance of the customers, concurrency of the network faults, the age of the network asset and the loading of the network facilities.

Operational scenarios are widely used to investigate the behavior of the designed systems. We devote this effort to show the validity (and usefulness) of our proposed framework, using practical scenarios. Thus we developed the following four scenarios, to evaluate the performance of our proposed framework. The considered scenarios are intentionally picked to show how different can the proper IED autonomy levels be. By selecting this specific scenarios, we aimed to show how important is the adaptation of the LOA, due to the dynamism of the PSFs in a typical civil service automation application. The scenarios are as follows:

- **Scenario 1: Happy condition:** Occurrence of one fault per two hours at day-time low-loading in a newly-constructed un-crowded residential urban area.
- **Scenario 2: Hard situation for human agent:** Occurrence of one fault per two hours at night-time low-loading in an early-constructed highly-crowded residential urban area.

- **Scenario 3: Important customer:** Occurrence of one fault per two hours at day-time low-loading in a newly-constructed un-crowded, VIP customer in urban area.
- **Scenario 4: Catastrophe:** Occurrence of ten faults per two hours at day-time high-loading in an early-constructed highly-crowded residential urban area.

Figure 2 shows prescribed LOAs versus the TOAs, for each one of the four scenarios. As it can be shown in Fig. 2, LOA 2 is suggested for the operation of the UMA-FRF system in all four stages for the situation of Scenario 1 (happy conditions) by our proposed framework. The presented framework suggests LOA 5 for Scenario 2 (hard situation) in all four automation stages (Fig. 2). For the important customer (Scenario 3) case, LOA 4 has been adopted for all the stages (Fig. 2). The catastrophic condition (Scenario 4) takes the highest LOAs, within the four scenarios. This is expectable, due to the urgency and time-criticality of catastrophes (Fig. 2): LOA 7 is proposed for the information acquisition, information analysis, decision making. On the other hand, the decision action is proposed to be performed in LOA 6. In LOA 6 a veto authority is given to the human supervisor, before the execution of the selected (decided) action.

As shown in Fig. 2, a low LOA (level 2) is proposed for the happy conditions (Scenario 1); whereas, a higher level (LOA 5) is suggested for the hard situation for the human operator (Scenario 2). This is because of the difficulty of access to the network assets for information acquisition and decision action in the Scenario 2. It appears to be a wise selection, since Scenario 2 relates to the situation of highly-crowded area with one fault per two hours at night, when the human ability in information acquisition, information analysis and decision implementation considerably decreases.

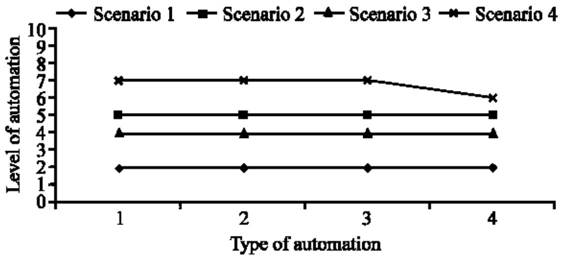

Fig. 2: The prescribed level of automation (LOA) versus type of automation (TOA), devised for UMA-FRF system in case of Scenarios 1-4: Scenario 1: Happy condition, Scenario 2: Hard situation for human agent, Scenario 3: Important customer and Scenario 4: Catastrophe

As Fig. 2 shows, the presented method suggests LOA 4 for the important customer, one level lower than that of the hard situations for the human operator. This might seem a little odd, since one may expect that the highest LOA should be given to the important customer. We interpret this controversy as the conservativeness of the power systems industry: the experts would prefer to supervise their important customers' service delivery by-person, instead of relying on the IEDs.

LOA 7 is proposed in the catastrophic condition (Scenario 4) for the information acquisition, information analysis and decision making and LOA 6 for the decision action. That is, the method gives the autonomy of information processing and decision making to a high extent, however, the action implementation is proposed to be performed autonomously, but, under the *veto* authority of the human supervisor, due to the lack of full trust in IEDs.

Figure 3 shows the trend of the prescribed LOA versus the criticality of the situation, according to the results shown in Fig. 2. The harder situations, the higher LOAs are recommended. Nevertheless, the security conditions limit the level of autonomy for the IEDs in the automation system; consequently, the curve in Fig.3 stops increasing at certain point of the criticality and declines due to the security constraints. As a result, the trend of LOAs for the four scenarios shows that the result of judgment of GTEDC's experts tends to prescribe higher LOAs for harder and more important situations. Furthermore, our study results also recommend lower LOAs for easier and less important situations; yet, by considering security constraints.

Another considerable issue in Fig. 3 is the increasing trend of LOA vs. criticality of situation, which is rather questionable. Because, in contrary, the basic (and historical) idea of automation, was to give the easy, repetitive and simple tasks to the machines and leave the more complex tasks-that need more intelligence and situational awareness-up to human supervisors. We suggest that this study-which has been performed in a developing country-should be repeated in the

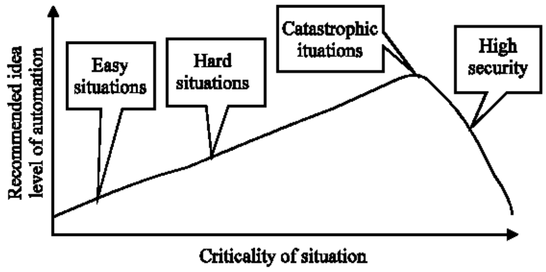

Fig. 3: The trend of IEDs autonomy level versus criticality

applications with different developmental, economical, cultural and geographical conditions, in order to investigate the effects of the mentioned situational conditions on the trend of LOA vs. criticality. We speculate that in the conditions with higher salary packages and higher levels of industrialization (in developed countries), the trend of the LOA versus the criticality of the situation might be decreasing, or at least flat. Our rationale for this speculation is that automation is used in higher levels of autonomy in the developed countries. Moreover, the designers of automation systems would prefer IEDs (automation) rather than humans in safety critical situations in developed countries, due to higher salaries, as well as higher risks of being sued, because of making humans to work in safety critical situations.

Another considerable matter is the flatness of LOAs versus automation stages (TOAs) in Fig. 2, which means in our specific application, there is a little distinction between the prescribed LOAs for different TOAs. We assume that this might be because of the less tendency of the power industry experts to un-manned systems comparing to the aviation, aerospace and missile industry, where the idea of the stages of automation (TOAs) is born (Parasuraman *et al*., 2000; Fereidunian *et al*., 2007a, b; Endsley and Kaber, 1999).

CONCLUSIONS AND FUTURE DIRECTIONS

An implementation framework for adaptive IED autonomy was introduced. The proposed framework was implemented to a power distribution systems automation case, called UMA-FRF. The Experts' Judgment method and the PSFs concept were utilized to tackle the implementation challenges such as quantification of the qualitative models, assessment of the quality attributes and introduction of the environmental conditions into the autonomy adaptation framework.

The importance of the adaptive autonomy was expressed, by showing the extent of variation in the prescribed autonomy level (LOA) for four practical scenarios occurring in the GTEDC's UMA-FRF, as a case study.

According to the experimental results presented in this paper, we believe that implementation of AA to the automatic systems can advance security for humanity, in terms of high-performance, reliable and cost-effective civil services. This is achieved by considering the humans' features regarding the automation systems.

We are working on the following research topics as the continuation of this work: more theoretical work on the HAI models, implementation of the proposed method to the automation applications in other civil services disciplines, implementation of the proposed method in other environments, in order to study the importance of customization of automation solutions for context-specific implementations.

Moreover, the increasing trend of the recommended LOAs versus the criticality of situation and flatness of the determined LOAs versus the automation stages in our study are matters of question and discussion and fertile grounds for further works.

Appendix: Definitions of the IED autonomy levels (LOAs), customized to IED concept, according to (Parasuraman *et al*., 2000; Fereidunian *et al*., 2007a) is as follows:

LOA description

- The IEDs decide everything; act autonomously, yet collaborating with other IEDs, ignoring the human
- The IEDs inform the human supervisor only if they - the IEDs- decide to
- The IEDs inform the human, only if asked
- The IEDs execute autonomously, then necessarily informs the human supervisor
- The IEDs allow the human supervisor a restricted time to *veto* before automatic execution
- The IEDs execute that suggestion if the human supervisor approves
- The IEDs suggest one decision action alternative
- The IEDs narrow the decision choice selection down to a few
- The IEDs offer a complete set of decision / action alternatives
- The IEDs acquire the data from the process and register them without analysis.
- The IEDs offer no assistance: the human decides and acts

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