Effect of Augmented Reality on Faults Leading to Human Failures in Socio-technical Systems*

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***Abstract*—With the ultimate purpose of assessing risk within augmented reality-equipped socio-technical systems, in our previous work, we systematically organized and extended state-of-the-art taxonomies of human failures to include the failures related to the extended capabilities enabled by AR technologies. The result of our organization and extension was presented in form of a feature diagram. Current state-of-the-art taxonomies of faults leading to human failures do not consider augmented reality effects and the new types of faults leading to human failures. Thus, in this paper, we develop our previous work further and review state-of-the-art taxonomies of faults leading to human failures in order to: 1) organize them systematically, and 2) include the new faults, which might be due to AR. Coherently with what done previously, we use a feature diagram to represent the commonalities and variabilities of the different taxonomies and we introduce new features to represent the new AR-caused faults. Finally, an AR-equipped socio-technical system is presented and used to discuss about the usefulness of our taxonomy.**

***Index Terms*—augmented reality, immersive visual technology, human failure, fault, risk assessment**

I. Introduction

Augmented reality (AR) technology, augments human capabilities such as hearing and observing to hear and observe more than others [1]. Visual augmented reality technology, augments human visual perception, by integrating digital content with the real world view of the user. For example, providing safety visual alerts on the windshield of the car through this technology can augment human visual perception to perceive risks and to drive safely. Using new technologies might introduce new types of dependability threats (specifically new faults and failures) that should be considered while analyzing risk. It is necessary here to clarify exactly what is meant by fault. If we consider a human as a component within a component-based system representing a socio-technical system, based on Avizienis et al. [2] terminology, a human failure is a deviation in human functioning from correct functioning (failure in the last subcomponent of human, which provide the output of human component) and the cause for the human failure is fault, which would be internal or external. Internal fault is failure in another subcomponent of human component and external fault is failure in another component, which its output is input for human component.

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For example, an experiment on a virtual reality game, shows reduction of perception and balance of children immediately after the game [3]. Physical and mental states are influencing factors on human functions, thus they are subcomponents of human, which failure in these states might cause failure in human functioning or human failures. Another experiment on augmented reality guidance during manual tasks, shows decrement in user performance due to AR-based technical faults. The focal length of available head-mounted displays that were used for experiment are at least 2 meters and it is not appropriate for manual tasks that require high precision [4]. In this example AR-based technical fault is an external fault for human, which is coming from technical component. Augmented reality can also cause reduction in human depth of focus, reaction time and distance perception while driving, if not properly designed [5]. Design fault is an external fault for human component.

As it is shown in Fig.1, internal or external faults in socio-technical systems are the reasons for human failures and human failures may lead to risk, thus to analyze risk in socio-technical systems containing AR, it is required to consider effect of AR on human failures and faults leading to these human failures. Socio-technical systems are systems containing technical components, human and organization. External faults to human, may originate from technical components or organizational components and internal faults originate from other subcomponents of human. AR would influence on internal and external faults and would introduce new types of faults causing to human failures.

In [6], we provided an AR-extended human failure taxonomy by considering state-of-the-art taxonomies as a product line and proposing a feature diagram containing human functions and including AR-extended human functions as extended features. In [7], we used this taxonomy for extending human modeling elements used in risk analysis tools.

Currently, there are different taxonomies of faults leading to human failures, which can be used as the foundation for risk analysis in safety-critical socio-technical systems. However, much uncertainty still exists about the effect of new technologies such as augmented reality and new types of faults to human failures that would be introduced to the system while using these technologies. In this paper, we concentrate

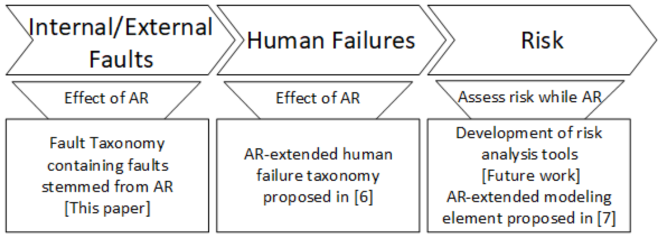

Fig. 1. Risk-related causality chain in socio-technical systems.

on effect of AR on faults leading to human failures and by inheriting the strategy from [6], first, we review state-of-the-art taxonomies and vocabularies used for these faults with the lens of terminological framework on dependability. Then, we provide a feature diagram, because it is powerful to capture common and variable characteristics of different taxonomies. Finally, we extend the feature diagram by considering augmented reality effects and new faults that would cause human failures while using these technologies. The final outcome can be used as the foundation for risk analysis tools for safety-critical socio-technical systems.

The rest of the paper is organized as follows. In Section II, we provide essential background information. In Section III, we review state-of-the-art taxonomies of faults leading to human failures. In Section IV, we propose a taxonomy with the extension of faults stemmed from AR. In Section V, we discuss about the use of this taxonomy on an automotive AR-equipped socio-technical system. Finally, in Section VI, we present some concluding remarks and discuss about future work.

II. Background

In this section, we provide essential background information about visual augmented reality technology and feature diagram.

A. Visual augmented reality technology

Visual augmented reality technology superimposes computational elements and objects on the real world view of the user. There are three types of AR displays containing head-worn, hand-held and spatial. Head-worn displays can be attached to the head, hand-held displays can be shown on a device or by a device that can be handled by hand and spatial displays are placed within the environment statically for cases with limited interactions. Head-up displays (HUDs) are an example of spatial displays that can be used by projecting information on the windshield of the car [1]. HUD is "any transparent display that presents data without requiring users to look away from their usual viewpoint" [8]. For example in Fig.2, navigation information is shown on the windshield of the car using AR.

Using an augmented reality warning in vehicles can improve driver awareness and reaction time efficiency, but can also increase cognitive-processing or distract the driver [9]. Schwarz and Fastenmeier [10] used augmented reality in a driver simulator study with 88 participants. The results

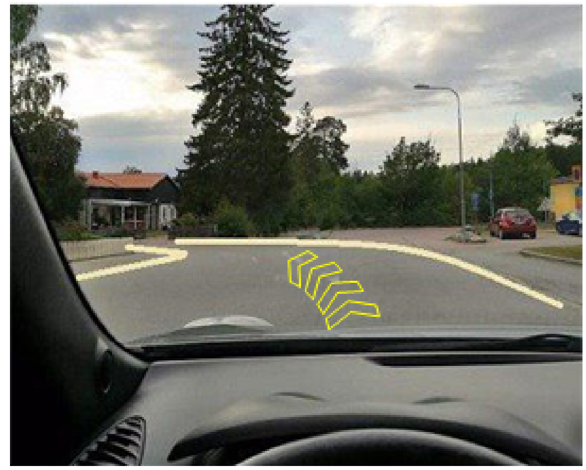

Fig. 2. An example of AR information on Head Up Display.

show that visual warnings are advantageous and effective. Miller et al. [11] found that AR influences on interpersonal communications and decreases social presence, which might lead to human failure. Thus, while using new technologies, new types of faults leading to human failures would be added and should be considered in risk analysis.

B. Feature diagram

A distinguishing characteristic of a family of systems that can be perceived by end-users is called a feature [12]. Families of products are also recognized as product lines [13]. To illustrate common and distinctive features of a product line, feature diagrams can be used. A simple example of a feature diagram is shown in Fig.3. As it is shown, feature diagrams are multi-level trees that nodes are features and edges are for decomposition of features to more specific features. Features can have different types, for example mandatory, optional and alternative [12]. Mandatory features shown by solid dot are essential in the system and all the products in a product line have these features, but optional features (a node with a circle) are optional and some products may do not have those features. Alternative features (XOR) are those features that only one of them are in each product of the product line. In the example shown in Fig.3, a family of AR devices are described that display is a mandatory feature, because all AR devices have display, but remote control and internet connection are optional, because there are some AR devices without remote control and internet connections. Display feature would be transparent or nontransparent that only one of them can happen, so these are alternative features.

III. Revisited Faults Taxonomies

In this section, we review state-of-the-art taxonomies of faults leading to human failures. In particular, we reconsider previously studied taxonomies such as: Rasmussen [14], HFACS (Human Factor Analysis and Classification System) [15], SERA (Systematic Error and Risk Analysis) [16] and Driving [17] fault taxonomies. In addition, in this paper,

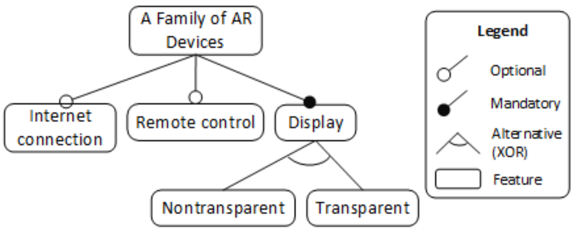

Fig. 3. An example of a feature diagram for a family of TVs.

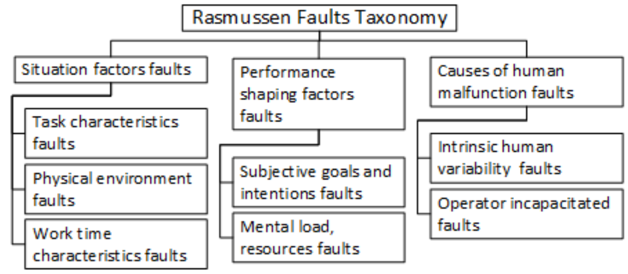

Fig. 4. Rasmussen faults taxonomy.

we also consider SPAR-H (Standardized Plant Analysis Risk Human Reliability Analysis) [18] taxonomy, which provides influencing factors to human functions as a list of performance shaping factors.

As it was discussed in Section I, we use the term "fault" based on Avizienis et al. [2] terminology, for defects in influencing factors leading to human failures. There may be some other faults leading to technical failures, but in this paper by fault, we mean faults leading to human failures. In order to follow the strategy in [6], for citing definitions we use quotations and to complement fault definitions, we use Oxford dictionary [19] meanings in cases which are necessary (shown in italic).

A. *Rasmussen faults taxonomy*

Rasmussen et al. [14] provided a taxonomy including faults to human failures in industrial installations based on analyzing mental processes. Faults based on this taxonomy (Fig.4) are divided to three groups including situation factors, performance shaping factors and causes of human malfunction faults.

1) **Situation factors faults** include:
   a) **Task characteristics faults** arise when task is complicated or has some special characteristics which would cause human failure.
   b) **Physical environment faults** arise when there are light or weather or other physical problems.
   c) **Work time characteristics faults** arise when there is time pressure in doing the task.
2) **Performance shaping factors faults** include:
   a) **Subjective goals and intentions faults** arise when the goals and intentions are not defined correctly. Subjective means *based on or influenced by personal feelings, tastes, or opinions*.
   b) **Mental load, resources faults** arise when operator is not able to process huge amount of information mentally.
3) **Causes of human malfunction faults** include:
   a) **Intrinsic human variability faults**: intrinsic means *belonging naturally*. For example, low physical strength.
   b) **Operator incapacitated faults**: incapacitated means *deprived of strength or power*. For example, sickness.

B. *HFACS faults taxonomy*

HFACS [15] introduces another fault taxonomy (Fig.5), based on the avionic context, which is by analyzing over 300 aviation accidents. In this taxonomy, faults are divided into the following categories [20]:

1) **Faults in pre-conditions for unsafe acts** include:
   a) **Environmental factors faults** include:
      i) **Physical environment faults** are faults related to physical environment such as unfavorable weather conditions.
      ii) **Technological environment faults** are faults in technological environment such as problem in equipment.
   b) **Condition of operators faults** include:
      i) **Mental states faults** arise when the operator is not in a proper mental state.
      ii) **Physiological states faults** arise when the operator is not in a proper physical state.
      iii) **Physical/mental limitation faults** arise when the operator does not have a specific physical/mental capability.
   c) **Personnel factors faults** include:
      i) **Crew resource management faults** arise when there is problem in managing human resource.
      ii) **Personal readiness faults** arise when a person is not ready to act properly.
2) **Unsafe supervision faults** include:
   a) **Inadequate supervision faults** arise when supervisors do not provide their personnel, adequate guidance, training, leadership, oversight and whatever are needed to do safe and efficient job.
   b) **Planned inappropriate operations faults** arise when unsuitable operations are planned by supervisors.
   c) **Failure to correct problem faults** arise when safety deficiencies are known by supervisors but not corrected.
   d) **Supervisory violations faults** arise when supervisors disregard rules and regulations willfully.
3) **Organizational influences faults** include:

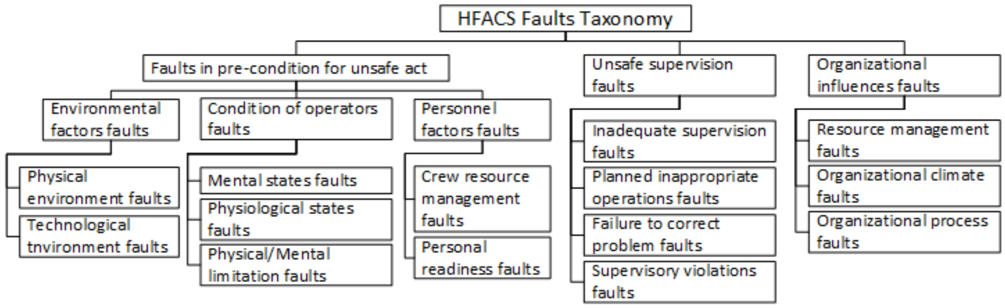

Fig. 5. HFACS faults taxonomy.

a) **Resource management faults** arise when there is problem in managing the resources such as personnel and monetary assets.
b) **Organizational climate faults** arise when working atmosphere such as organization's culture and policy cause human failure. Climate means *the prevailing trend of public opinion or of another aspect of life*.
c) **Organizational process faults** arise when there is problem in "corporate decisions and rules that govern the everyday activities within an organization".

C. SERA faults taxonomy

SERA [16] was developed as a tool for Canadian forces version of HFACS, but it can be used independent of HFACS. It divides faults to three categories including (Fig.6):

1) **Faults in pre-conditions to active failures** include:
   a) **Personnel faults** include:
      i) **Physiological faults** are not proper physiological state of the individual such as drowsiness, medical illness.
      ii) **Psychological faults** are not proper psychological states, attitudes, traits, and processing biases.
      iii) **Social faults** are problems in interaction among groups and teams.
      iv) **Physical capability faults** are problems in physical abilities to sense and perform an action.
      v) **Personnel readiness faults** are not being in a proper state in the sense of a physiological, psychological, physical and mental readiness to perform a task.
      vi) **Training and selection faults** are lack of skills and knowledge required to do the job.
      vii) **Qualification and authorization faults** are lack of legal pre-requisites to perform a task.
   b) **Task faults** include:
      i) **Time pressure faults** are lack of enough time to carry out the task.
      ii) **Objectives faults** are unclear, inappropriate, inconsistent and risky task objectives.
   c) **Working condition faults** include:
      i) **Equipment faults** are not proper condition of tools used to perform the task.
      ii) **Workspace faults** arise when physical arrangement and layout of the workspace is not in a proper condition.
      iii) **Environment faults** arise when conditions of the environment in which the activity is performed, is not suitable.
2) **C2S (Command, Control and Supervision) faults** include:
   a) **Forming intent faults** are problems in "goal setting process".
   b) **Communication of intent faults** are problems in "perceiving the intent by the subject audience".
   c) **Monitoring and supervision faults** are problems in "detecting and correcting ill-formed actions and disturbances".
3) **Organizational influences faults** include:
   a) **Mission faults** are problems in "what the organization is supposed to achieve". Mission means *a strongly felt aim, ambition, or calling*.
   b) **Provision of resources faults** are problems in "what the organization uses to achieve the mission". Provision means *the action of providing or supplying something for use*.
   c) **Rules and regulations faults** are problems in "Constraints on the process the organization uses to achieve the mission". Regulation means *a rule or directive made and maintained by an authority*.
   d) **Organizational processes and practices faults** are problems in "the way the organization should do it".
   e) **Organizational climate faults** are problems in "attitudes that affect how the people in the organization perceive the mission, what they actually do, and how they actually do it".
   f) **Oversight faults** are problems in "providing feedback so that managers can form a perception of organizational health and how well it is achieving its mission".

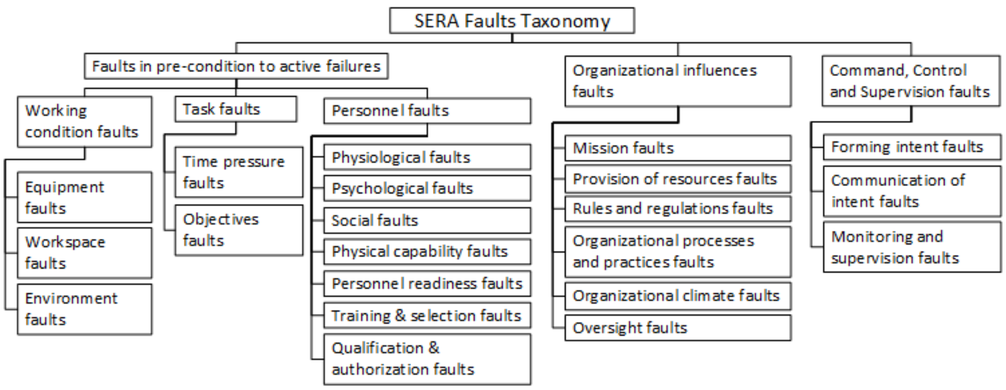

Fig. 6. SERA faults taxonomy.

D. Driving faults taxonomy

Stanton and Salmon [17] present a taxonomy of faults leading to driving failures with an overview of the literature on human failures in road transport based on dominant psychological mechanisms involved, including perception, attention, situation assessment, planning and intention, memory and recall and action execution. Based on this taxonomy (Fig.7) faults include:

1) **Road infrastructure faults** include:
   a) **Road layout faults** are problems in road surface.
   b) **Road furniture faults** arise for example when traffic signs are not in proper condition.
   c) **Road maintenance faults** arise when there is problem in renovating the road.
   d) **Road traffic rules, policy and regulation faults** arise when there is not suitable rule, policy and regulation for road traffic.
2) **Vehicle faults** include:
   a) **Human machine interface faults** are problems in interfaces such as navigation interface.
   b) **Mechanical faults** are problems in mechanical part of vehicle such as problem in engine or gear box.
   c) **Capability faults** are problems in power of vehicle such as limitation of engine horsepower.
   d) **Technology usage faults** arise when a technology is not used properly.
3) **Driver faults** include:
   a) **Physiological state faults** are problems in physiological state of driver such as sickness.
   b) **Mental state faults** are problems in mental state of driver such as tiredness.
   c) **Training and experience faults** are problems in training and experience of driver to carry out the task properly.
   d) **Knowledge, skills and attitudes faults** are lack of required knowledge, skills and attitudes.
   e) **Context faults** are problems in context. Context means *the circumstances that form the setting for an event, statement, or idea, and in terms of which it can be fully understood*. For example when driver is in hurry.
   f) **Non-compliance faults** are problems in complying with rule or standards. Compliance means *the state or fact of according with or meeting rules or standards*. For example, unqualified driving is a non-compliance fault.
4) **Other road user faults** include:
   a) **Other driver behavior faults** are problems caused by other drivers' unsafe acts.
   b) **Passenger influence faults** are problems caused by passengers.
   c) **Pedestrian behavior faults** are problems caused by pedestrian.
   d) **Law enforcement faults** are problems in complying with law. Enforcement means *the act of compelling observance of or compliance with a law, rule, or obligation*.
   e) **Other road user behavior faults** are problems caused by other road users' behavior.
5) **Environmental conditions faults** include:
   a) **Weather conditions faults** are not suitable weather condition such as fogginess.
   b) **Lighting conditions faults** are not suitable lighting condition such as darkness.
   c) **Time of day faults** are problems caused by time of day.
   d) **Road surface conditions faults** are inappropriate road surface conditions.

E. SPAR-H fault taxonomy

SPAR-H [18] is a human reliability analysis method used in commercial US nuclear power plants. Faults based on this method are categorized to eight faults including (Fig.8):

1) **Available time faults** refers to faults in the amount of time available relative to the time required.
2) **Stress faults** refers to faults in the level of undesirable conditions and situations that prevent the operator form completing a task.

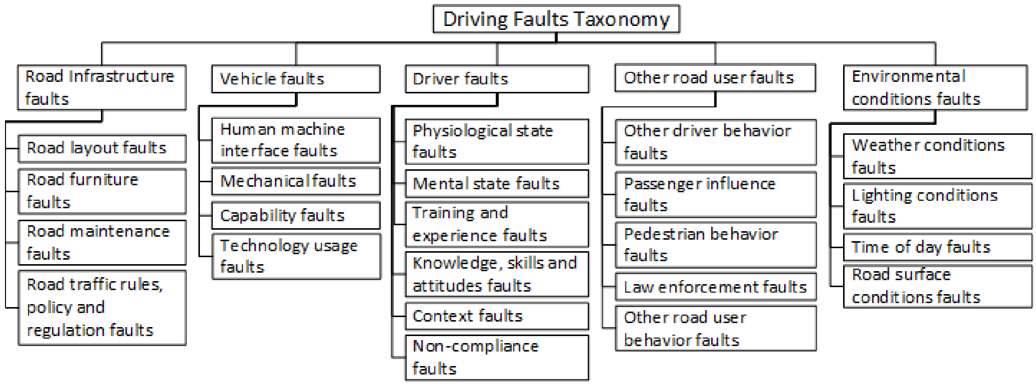

Fig. 7. Driving faults taxonomy.

3) **Complexity faults** refers to faults in difficulty of a task in a special context.
4) **Experience/Training faults** refers to faults in experience/training of the operators for carrying out the tasks.
5) **Procedures faults** refers to faults in availability and using of formal procedures for operating a task.
6) **Ergonomic faults** refers to faults in the equipment, displays and controls, layout, quality, and quantity of information available from instrumentation, and the interaction of the operator/crew with the equipment to perform the task.
7) **Fitness for duty faults** refers to faults in suitability of the operator for doing the task physically and mentally.
8) **Work process faults** refers to faults in inter-organizational safety culture, work planning, communication, and management support and policies.

IV. Our Proposed Fault Taxonomy

In this section, we propose a taxonomy of taxonomies by considering augmented reality effects. First, we adjust and organize the existing taxonomies as a product line. Then, we consider effects of augmented reality on these factors based on available experiments and studies. Finally, we propose a feature diagram for modeling existing taxonomies' commonalities and variabilities and effects of augmented reality.

A. Fault Categorization Based on State-of-the-art Taxonomies

Based on five taxonomies, we retrieve and organize fault categories in Table. 1. The rational for the fields of table's columns is: 1) fault category based on state-of-the-art taxonomies; 2) subsection number of the related taxonomy and related fault category. For example, physical state fault that is a personnel fault category, is mentioned in five taxonomies. Different terms may be used for fault categories in various taxonomies, but based on explanation, we organized them to have a categorization based on all five taxonomies. In HFACS (Subsection III.B), fault category 1.b.ii, which is physiological states faults and in SERA (Subsection III.C), fault category 1.a.i refers to physiological faults.

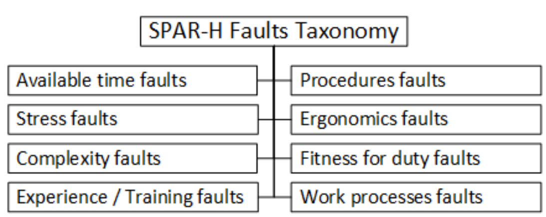

Fig. 8. SPAR-H faults taxonomy.

B. Effect of Augmented Reality

In this section, we explain about effect of augmented reality on fault categories based on available studies and experiments. For some of the categories, there is not any study or experiment to show the effect of augmented reality. Thus, we cannot provide any extension related to those categories for our taxonomy. AR effects on faults would be positive or negative and in both cases we need to consider them, because even positive effects can introduce new types of faults to the system, in case of failing to provide the expected effects.

1) Task faults: An experiment presented in [4], was designed to investigate user performance during AR-guided manual tasks and results indicate decrement in users performance. In this experiment, optical see-through (OST) head-mounted display (HMDs) is used for connect-the-dots task, which is a manual task with high precision. As it is explained in this study, the reason for decrement of performance is that focal length in available OST HMDs is at least 2 meters and users can not focus on both virtual and real content for manual tasks. However these results are for HMDs and for manual tasks with high precision, from this example we can elicit AR-guided task as an influencing factor on human function. In this example, it is not the task itself that would cause human failure, instead it is fault in AR-guided task that can cause human failure.

2) Physical and mental state faults: There are some jobs with difficult situations and repetitive tasks that threaten operators' mental and physical healthy states. For example, mental and physical states of astronaut crews in long-duration

TABLE I
FAULT CATEGORIZATION BASED ON STATE-OF-THE-ART FAULT TAXONOMIES

Fault category	Taxonomy: fault
1.Personnel faults	III.B:1.c/1.c.ii, III.C:1.a/1.a.v
1.1.Physical state faults	III.A:3, III.B:1.b.ii, III.C:1.a.i, III.D:3.a, III.E:2
1.2.Mental state faults	III.A:3, III.B:1.b.i, III.C:1.a.ii, III.D:3.b, III.E:2
1.3.Physical/ Mental capability faults	III.A:2.b/3 , III.B:1.b.iii, III.C:1.a.iv, III.D:3.d, III.E:7
1.3.1.Training/ Experience faults	III.C:1.a.vi, III.D:3.c/3.d , III.E:4
1.4.Social faults	III.B:1.c.i, III.C:1.a.iii, III.D:4, III.E:2
1.5.Authorization faults	III.C:1.a.vii, III.D:3.f/4.d, III.E:8
2.Task faults	III.C:1.b, III.A:1.a
2.1.Time pressure faults	III.A:1.c, III.C:1.b.i, III.E:1
2.2.Objectives faults	III.A:2.a, III.C:1.b.ii,
2.3.Complexity faults	III.E:3
2.4.Procedure faults	III.E:5
3.Environment faults	III.C:1.c
3.1.Equipment faults	III.B:1.c, III.C:1.c.i, III.D: 2, III.E:6
3.2.Condition faults	III.A:1.b, III.B:1.a.i, III.C:1.c.ii-iii, III.D: 1/3.e/5, III.E:6
4.Organization and regulation faults	III.B:3, III.C:2/3
4.1.Resource management faults	III.B:3.a, III.C:3.b
4.2.Organizational climate faults	III.B:3.b, III.C:3.e
4.3.Organizational process faults	III.B:3.c, III.C:3.d, III.E:8
4.4.Supervision faults	III.B:2.a-c, III.C:2.c
4.4.1.Forming intent faults	III.C:2.a
4.4.2.Communication of intent faults	III.C:2.b
4.4.3.Monitoring and supervision faults	III.C:2.c
4.4.4.Supervisory violation faults	III.B:2.d
4.5.Rules and regulations faults	III.C:3.c, III.D:1.d
4.6.Oversight faults	III.C:3.f
4.7.Mission faults	III.C:3.a

missions on the moon would be deteriorated and new technologies such as immersive virtual reality and augmented reality are examined to be used in order to upkeep mental and physical health [21]. AR/VR technologies also have been used for treatment of several mental disorders on clinical and health psychology and have provided important contributions to mental health [22]. These technologies can be considered as restorative mental and physical health measures and if not provided can cause human failure, so as AR-caused faults, restorative mental health measure faults and restorative physical health measure faults can be considered.

3) Social faults: In an experiment presented in [11], with the aim of investigating AR effects on interpersonal communications, results show that people using AR have lower social presence and they feel significantly less connected. However this experiment was done by headset, the results can be used for other applications that operator is the person who sees AR and other people are not aware of these AR information and it disrupts common ground between interactants. As an augmented reality factor, social presence can be considered, because using AR can influence on social presence and by decreasing that it would cause human failure. Interpersonal attraction that refers to how much participants like each other, also was studied when using AR and results show that there was no significant difference on interpersonal attraction while using AR.

4) Mental/Physical Capability faults: Based on an experiment presented in [23], neurological effects of AR or effects of AR on the brain was measured, using brain-imaging technology. Results show that AR doubles brain visual attention in comparison to non-AR tasks and increases brain cognitive activity. Memory encoding is 70% higher when using AR, which means that AR delivers information in a powerful way to be retained in memory. AR elicits an astonishing response in the brain, so brain elicitation can be considered as a factor that is correlated with AR and brain elicitation faults can be added to our taxonomy as AR-related faults.

5) Training/Experience faults: AR has the power to provide interactive ways to engage learners and strengthen their motivation for learning and to enhance their experience through computer graphics elements [24]. Interactive training/experience can be considered as a factor that can effect human performance and interactive training/experience faults are AR-related faults.

6) Environment faults: Augmented reality technology integrates elements from virtual reality with elements from real world, thus we have an augmented environment that can be considered in our taxonomy. This augmented environment includes virtual objects that can be stationary or manipulated by user [25] and faults in augmented environment would cause human failure.

7) Organization and regulation faults: A study in [26] investigates key factors that facilitate adoption of AR technologies by e-commerce firms. This research shows that by emergence of AR, adoption of AR will be added as a new factor in organization and regulation that problem in this adoption would introduce a new fault that is organization and regulation AR adoption fault.

C. Proposed Feature Diagram

A feature diagram is presented in Fig. 9, for modeling existing taxonomies' commonalities and variabilities and effects of augmented reality, which is called AREFTax. It shows physical/mental state, physical/mental capability, environment and condition faults are common faults in all taxonomies. It means that these faults or subcategories of them in Table. 1 are in all taxonomies. There are also some more features based on augmented reality effects that are explained in Subsection IV.B. These features are shown by dotted lines. For example, as it was explained, augmented reality would decrease social presence, thus social presence faults can be considered as a new fault, which can cause human failures.

V. Automotive AR-equipped System

In this section, we use an augmented reality Collision Warning System (CWS) in a car that is an automotive domain-related socio-technical safety-critical system. Collision warning systems are special types of Advanced Driver Assistance Systems (ADAS), which provide notifications for drivers about potential hazards around the vehicle to avoid collisions. There are different technologies for presenting collision warning information such as AR, which is useful for providing visual clues and annotations on the user's view [27].

New technologies such as HUDs are AR capable and provide the opportunity to show AR information on the windshield of the car. The advantage of using this technology is that driver does not need to refocus to see outside, after looking through AR information [8].

We consider a HUD on the windshield of a car to provide notification or navigation information for driver to avoid collision. For example when another car is in close distance, navigation information for changing the lane would be proposed on the windshield. We discuss about different possible faults to see if the proposed taxonomy deals with all possible faults for this example.

In this example, which is a socio-technical system, there are three components including human, organization and technical component (AR-technical component). We use the proposed fault taxonomy to model these components and their subcomponents and to show the possibility of modeling AR-related subsystem failure behavior. Organizational factors influencing human functioning are organization and regulation AR adoption and rules and regulation. Thus, organization and regulation AR adoption and rules and regulation can be considered as subcomponents of organization component. Human can be modeled using various states and functions. In this example, we consider social presence, deciding and executing functions as three subcomponents of human component. An AR-HUD component contains three primary subcomponents: a projector unit that produces an image on a combiner, a combiner that is a flat piece of glass and can be the windshield of the car and a video generation computer that generates the information that should be displayed by projector unit [8]. To illustrate the case study, we explain about three scenarios depicted in Fig.10. AR-related modeling elements and faults are shown by gray color, to show the effect of AR and the contribution of the proposed taxonomy.

In the first scenario, content provided by AR-HUD is wrong and leads to the driver's failure. For example, there is failure in combiner of AR-HUD, which is an AR-technical component. This failure is an external fault for human component and would cause human failure. In our taxonomy these kinds of failures that are dependent on the specific AR-technology and AR-device, are presented as augmented environment fault, which is a feature of environment in the proposed feature diagram.

In the second scenario, content provided by AR-HUD is correct, but there is failure in organization and regulation AR adoption, which is an external fault for human component and

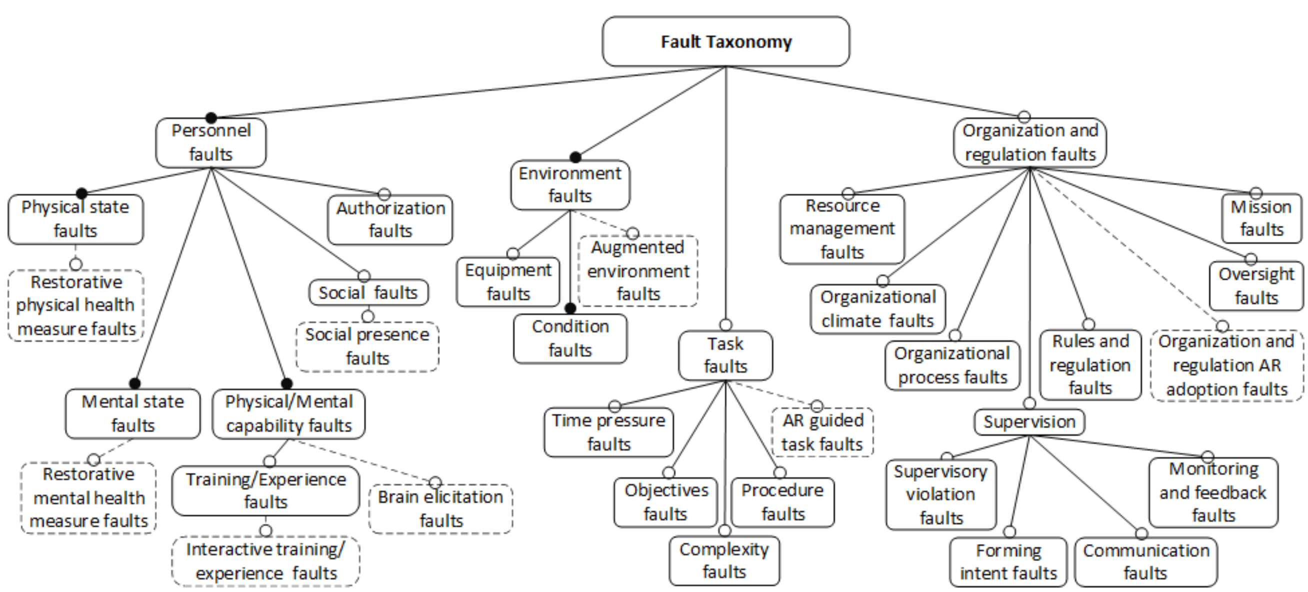

Fig. 9. Proposed feature diagram for fault taxonomy.

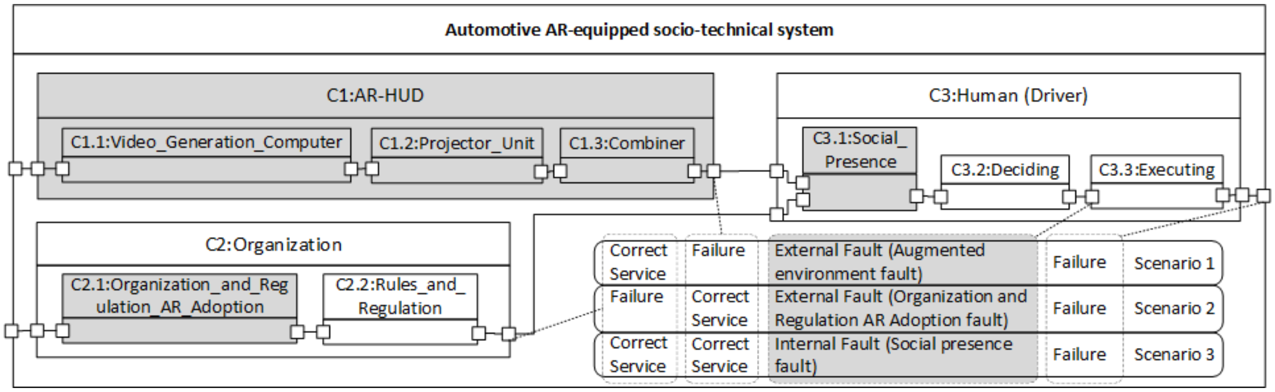

Fig. 10. Using the proposed fault taxonomy in an automotive AR-equipped socio-technical system modeling.

we represent it as organization and regulation AR adoption fault as a feature of organization and regulation fault in the proposed feature diagram. This subcomponent is based on the AR-extended faults part of the taxonomy. For example, when the organization does not provide facilities for using AR in organization and when the organization does not provide AR-related rules and regulation.

In the third scenario, there is failure in social presence of the driver, which is an internal fault for deciding and then for executing subcomponents and causes human failure. For example, when driver miss the common ground with other people, this failure would lead to wrong decision and wrong action. This subcomponent is also AR-related fault and thanks to the proposed fault taxonomy, it is possible to use it for extending modeling elements and for considering AR-related faults while doing risk analysis.

As it is shown in this example, the proposed taxonomy can be used for enhancing modeling of internal and external faults leading to human failures, used in modeling techniques of risk analysis tools.

VI. Conclusion

In this paper, first, we presented a review of the state-of-the-art taxonomies of faults leading to human failures, then we proposed an arrangement of taxonomies through a feature diagram that clarifies commonalities and variations between different taxonomies in a perceivable manner. Finally, the taxonomy is extended for augmented reality applications by adding faults stemmed from AR as new features to the proposed feature diagram. Application of this taxonomy is in risk analysis to increase safety in systems containing AR.

There are some opportunities to be considered as future work. In the future, this taxonomy can be used for extending modeling elements of influencing factors on human failures in SafeConcert [28], which is a metamodel for modeling technical and socio entities in socio-technical systems. Extended modeling elements can be used as the foundation of risk analysis tools such as Concerto-FLA [29], which is a risk analysis tool for socio-technical systems.

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