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Physiology-Driven Adaptive VR System: Technology and Rationale for PTSD Treatment

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Abstract

The design and development of a system for automated adaptation of virtual reality based scenarios driven by the subject's physiology is presented, with a rationale regarding application of the system in PTSD treatment. The system functions in two operating modes corresponding to the major phases of the treatment protocol. In the initial testing mode, the patient's general psychophysiological characteristics are identified and the audiovisual content of the later exposure sessions is customized to the patient. In the adaptive control mode, the therapist conducts exposure sessions, and the system strives to optimally individualize therapy according to the patient's psychophysiological profile and degree of sensitivity to various stimuli. Future evaluation of the system is discussed in the closing section.

Physiology-Driven Adaptive VR System: Technology and Rationale for PTSD Treatment

Large peacekeeping operations including hundreds of thousands of deployed soldiers, even with a conservative 10% prevalence estimate of posttraumatic stress disorder (PTSD), make PTSD a considerable problem in modern societies. Therefore, more innovative research is needed concerning new ways of battling PTSD from various aspects, such as diagnosis, treatment, prediction, and prevention.

The focus of the research presented in this paper is the design and development of a system for automated adaptation of virtual reality (VR) based scenarios driven by the subject's physiology and modulated by other components of the psychophysiological response, like subjective units of discomfort (SUDs). The intended application domain of the system is prompt PTSD treatment. The significance and importance of prompt PTSD treatment stem from the difficulties of treating long lasting combat-related PTSD. Among the most effective pharmacotherapy and psychotherapy methods (Foa, Davidson, & Frances, 1999; VA & DoD, 2004), which are generally considered comparably effective (Van Etten & Taylor, 1998), there is still no "silver bullet" for long-lasting combat-related PTSD. A recent extension of exposure therapy, VR exposure therapy, may also have better outcomes when applied promptly, as seen in 9/11 survivors (Difede & Hoffman, 2002), than with the long-lasting PTSD cases, as in Vietnam veterans (Hodges, Anderson, Burdea, Hoffman, & Rothbaum, 2001; Rothbaum et al., 1999).

VR exposure therapy for PTSD has been proposed as an alternative to imaginal exposure therapy (Rothbaum et al., 1999), which is regarded as the standard of care for PTSD (Difede & Hoffman, 2002). Difede and Hoffman (2002) mention that VR in comparison with imagination improves the patients' emotional engagement during retelling of their trauma, which is a predictor of positive treatment outcomes (Jaycox, Foa, & Morral, 1998). VR achieves better emotional engagement by confronting the patients with interactive three-dimensional synthetic environments that visually and aurally resemble their traumas.

The physiology-driven adaptive VR system for PTSD treatment strives to improve the advantages of VR exposure therapy. The system intends to provide the therapist with more comprehensive information about the patient's emotional reactions, and to relieve the therapist of technical and administrative issues that occur in VR exposure. With such additional assistance from the VR system, the therapists can increase their focus on the treatment and conduct more innovative and creative therapy. The expected final result is significantly more effective PTSD treatment.

To this end, the treatment protocol with the physiology-driven adaptive VR system mostly follows the established protocol of VR exposure therapy. The protocol consists of approximately 9–14 weekly or biweekly sessions, each lasting 45–90 minutes (Difede & Hoffman, 2002; Rothbaum et al., 1999).

The Concept of Control System Design

The physiology-driven adaptive VR system presented in the paper functions in two different operating modes, as explained in the remainder of the section. The modes correspond to the major phases of the treatment protocol.

Initial Testing

The initial open loop testing (Figure 1) is similar to conventional VR exposure therapy (Rizzo et al., 2004), where the therapist operates a user-friendly keyboard and mouse interface to select the desired stimuli. The initial testing corresponds to the first session of the treatment protocol (Rothbaum et al., 1999), which is devoted to the information gathering interview with the patient, familiarizing the patient with the VR technology, and relaxation training, as well as the initial identification of the patient's general psychophysiological characteristics.

While interviewing the patient, the therapist screens the description of the patient's traumatic event, in order to customize the audiovisual content of the later exposures to traumatic stimuli. By entering keywords via the Graphical Interface, customization is performed in line with the patient's trauma profile and in line with the stimulation capabilities of the system.

Identification of the patient's psychophysiological characteristics is necessary for configuration of the physiology-driven adaptive VR system. Here, the patient is exposed to various generic stimuli unrelated to the patient's trauma—neutral stimuli, relaxing stimuli, flashes, noise sounds etc.—in order to identify the general psychophysiological characteristics of the patient such as time constants, baseline values, and fluctuations of various physiological signals. The therapist sets up audiovisual content of the identification in the same way as for the exposure to traumatic stimuli; however, this setup need not be done per patient, but only once for a universal session that will apply to all patients.

Adaptive Control

VR exposure sessions are conducted in the adaptive control mode (Figure 2). Each exposure session includes gradual display of VR stimuli that are hierarchically organized from the least to the most traumatic for the individual patient. When exposure to traumatic stimuli starts, the system relies on the initial testing, including customization of the audiovisual content and the gathered knowledge about the patient's general psychophysiological characteristics, in order to display appropriate stimuli at appropriate times. Knowledge about the patient's psychophysiological characteristics is continually updated from measurements acquired during each exposure session. The therapist talks with the patient, observes the patient's behavior and aggregated patient's psychophysiological information, to achieve the most effective resolution of the patient's symptoms. The adaptive control mode thus enables optimally individualized treatment according to the patient's psychophysiological profile and degree of sensitivity to various stimuli.

The Adaptive Subsystem achieves appropriate patient excitation during the session by setting the unimodal psychophysiological reference input signal $UM_{ref}(t)$ to the Digital Controller. The Digital Controller computes required changes in valence and arousal of stimuli, in order to make the patient's unimodal psychophysiological measure $UM(t)$ track the reference input. Computed changes, as a control vector $\Delta\boldsymbol{u}(t)$, are then mapped by the Stimuli Generator to the corresponding audiovisual stimuli. The Subject's Aggregated Knowledge Database stores a patient's relevant parameters in the course of the treatment. Reference Knowledge Database is based on relevant data from literature, or integrates Subject's Aggregated Knowledge Databases of the previous patients.

Stimuli Generator

Stimuli Generator transforms the control signals into audiovisual stimuli, using realistic live video and audio in combination with a synthetic three-dimensional scene. Inclusion of a live scene is mainly based on expectations of its potential to cause more intense emotional response than a synthetic one due to its authenticity. Appropriate combining of the live and synthetic scene may maximize advantages and minimize disadvantages of both media.

One way of combining live and synthetic scenes in the context of the PTSD therapy has been described recently (Alcaniz, Juan, Rey, & Lozano, 2006; Botella et al., 2006). The authors use virtual environment as an external non-traumatic world in which the patient may review the videos related to the trauma, as well as images, sounds etc. The therapist may adjust some aspects of the virtual environment, like landscape, weather, time of day etc., in order to match the patient's emotional state. This is the "video within synthetic scene" approach.

Another approach, "synthetic elements within video", involves using synthetic elements to enhance and personalize the traumatic content of the video that resembles some aspect of the patient's trauma. For example, the video resembling a traumatic event that involved the patient and his comrades may be enhanced with synthetic animated characters having texture-mapped faces of the patient's comrades. Experimentation with these approaches is planned during further research and development of the physiology-driven adaptive VR system.

Control Signal Structure

In the discrete emotion view, emotions are classified by type (Bradley, 2000), such as joy, sadness, fear, anger, surprise, and disgust, which are primary emotions per (Damasio, 1999). The problem with such classification is related to the unclear relationship between physiological response patterns and discrete emotions (Bradley, 2000). To overcome this problem, valence and arousal concept has been used. The evidence shows there are physiological patterns associated with changes along the axes of valence and arousal, e.g. for heart rate, skin conductance etc. (Bradley, 2000). However, while valence and arousal are the principal components in classifying emotional stimuli, there is generally some loss of information when projecting discrete emotion space into valence-arousal space (Figure 3).

The control signal structure, illustrated by Figure 4, is designed to permit control over the major emotionally relevant features of the stimuli. The first distinction being made is between reflex stimuli, like loud brief noise or flash, and cortical stimuli, which include typical pictures, films, synthetic scene etc (cf. "stimType" on Figure 4). Less variability in reflex stimuli accounts for simpler structure of the associated control signals. Control signals for reflex stimuli specify separate arousal values for visual and auditory components. Control signals for cortical stimuli, with more degrees of freedom, first specify the targeted discrete emotion (cf. "dscrEm" on Figure 4). Due to the context of use, control signals need to be able to specify at least fear-eliciting stimuli, relaxing pleasant stimuli and neutral stimuli. According to Bradley (2000), sensory modality and media of presentation of the stimulus may both have impact on physiology. Therefore, the signals may target separately visual and auditory senses, but also allow delivery of congruent audiovisual scenery (cf. "sensMod" on Figure 4). Structurally valid control signals may also be those that specify incongruent visual and auditory stimuli; however, they may not be relevant to treatment. To control media of visual presentation, the control signals determine whether live video or synthetic three-dimensional visual stimuli are used, or perhaps their combination (cf. "visMed" on Figure 4). For successful automated physiology-driven adaptation, certain components of control signals need to be related to the resulting physiological response; therefore, the control signals also specify valence-arousal values for the stimuli (cf. "valAr" on Figure 4).

Valid control signals are those and only those obtained with a specific kind of depth-first traversal that extracts sequences of round nodes of the tree in Figure 4. The traversal starts at the topmost node and recursively follows branches, visiting successively each subnode of an encountered composite node and visiting exactly one branch of a branching or round node. Example control vectors obtained in this manner are shown in Table 1. Values "undef" and "real" represent the absence of a particular stimulus, and a real number from segment [0, 100], respectively. As real numbers are used for valence and arousal only, pleasure of the stimulus increases as valence goes from 0 to 100, with totally neutral stimuli (neither pleasant nor unpleasant) having valence of 50; arousal increases from 0 to 100, with 0 denoting no arousal. Part of the signal before the valence-arousal specifications is a descriptor that specifies the *class* of the signal.

Control Signal Interpretation and Disambiguation

Interpretation of control signals enables selection of appropriate scene elements that will be displayed to the patient. Scene elements in the Stimuli Generator's database are annotated in advance with values complying with the control signal structure and, during session, appropriate metric is applied to select the scene element nearest to the received signals.

Metric, which determines the distance of scene element annotations from the received control signals, can be defined in a variety of ways. Two kinds outlined here are several variants of a class centered and valence-arousal centered metrics, as illustrated in Figure 5. Class centered metric sets infinite distance for annotations that do not match the control signal in tags specifying the class of the signal. Thus, the metric definitely selects some scene element in the same class as the received control signals, when such scene elements exist. Minimization of typical Euclidean distance to the received signal, applied on valence-arousal parts of scene element annotations in the wanted class, gives the scene element that is to be displayed. Other possibilities for selection of scene elements may minimize distance of either valences or arousals. With valence-arousal centered metric, class of the signal is irrelevant. Thus, selection of the scene element for display is done by minimization of some distance to the received signal, applied on valence-arousal parts of all scene element annotations.

Figure 6 shows an example of mapping the step function (significant and sudden change in control signal) to the available stimuli within the Stimuli Generator. The control signal specifying relaxed emotional state is matched with the relaxing landscape video, and the signal specifying intense fear results in the display of traumatic improvised explosive device explosion. Hypothetical unimodal psychophysiological measure is shown, reflecting reaction to the traumatic video, and illustrating some parameters of the response (delay T_{UMd} and settling time T_{UMs}). More details on unimodal psychophysiological measure calculation are provided in the following section.

As the first step, a preliminary part of the Stimuli Generator has been developed that interprets the signals of the form (*stimulus*, *arousal*) within the class of the cortical synthetic visual stimuli. The signals are read from the 3-column file, where the signals take up second and third column. Number in the first column specifies elapsed time, from the beginning of the session, when the stimulus designated by the control signal in the same row is to be displayed. The stimuli used include plane in level flight, helicopter in level flight, and an explosion on a terrain. Disambiguation of control signals is related to determining the entry positions of the objects in the scene, as well as direction of moving for mobile objects. Disambiguation is conducted by mapping the *arousal* value to the distance from the viewer, in a controlled and somewhat stochastic way, in order to ensure stimuli visibility and simulate natural unpredictability of events. Figure 7 illustrates the available stimuli, as well as differences in distances of stimuli to the viewer depending on the *arousal* values in the third column of the file.

Unimodal Psychophysiological Estimator

Unimodal Psychophysiological Estimator acquires psychophysiological response related to the patient's experiencing of emotions provoked by the audiovisual stimuli. For this reason, it utilizes various psychophysiological acquisition devices for skin conductance, heart rate, respiration rate, electromyography signals, peripheral skin temperature etc., and receives information regarding the patient's SUDs.

Unimodal psychophysiological measure, which represents the patient's arousal, has been introduced as a linear combination of differences between individual signals and their baseline values. As different physiological measures have different propagation times (Gratton, 2000), instead of momentary value a weighted average during settling time of individual physiological measure is taken. Thus, the formula for calculating the unimodal psychophysiological measure becomes

$$UM(t) = \sum_{i=1}^{N} a_i \cdot \left(\left(\frac{1}{T_{Si}} \int_{t-T_{Si}}^{t} PM_i(\tau) d\tau \right) - PM_{Bi} \right),$$

where UM is the unimodal psychophysiological measure, PM_i is the i-th physiological measure, PM_{Bi} is the mean value of physiological measure PM_i in baseline, T_{Si} is the settling time of physiological measure PM_i, and a_i the parameter that defines measurement reliability and the relation of physiological measure PM_i and patient's arousal.

There are other possible approaches to computation of unimodal psychophysiological measure, like estimation based on fuzzy logic (Popovic, Slamic, & Cosic, 2006). Selection of the preferred approach is a matter of further experimentation.

Adaptive Subsystem

The Adaptive Subsystem is the central component for optimally individualized PTSD treatment, which selects and adjusts all relevant parameters of the system according to the individual patient's psychophysiology. Discrete-event adaptation gives reference values to the Digital Controller, Stimuli Generator, and takes as input the SUDs, Unimodal Psychophysiological Estimator output etc. The Adaptive Subsystem incrementally gathers knowledge about the patient's psychophysiological profile, stores this knowledge in the Subject's Aggregated Knowledge Database, and uses this knowledge with information from the Reference Knowledge Database. During and after each session, the Adaptive Subsystem updates the patient's relevant parameters and corrects the scene element annotations to represent the patient's individual estimates of anxiety that is associated with these elements, and stores this information into the Subject's Aggregated Knowledge Database. Subsequent sessions reuse the knowledge gathered during the previous sessions. At the end of all the sessions, Subject's

Aggregated Knowledge Database contains the relevant patient and other data from which the analysis across sessions may update expert rule base of the Adaptive Subsystem.

During exposure sessions, Adaptive Subsystem performs the patient's identification continuously, because the patient's psychophysiology, as an object of control, is unknown, complex, nonlinear and time variant system. Therefore, it is necessary to determine and keep up-to-date the knowledge regarding time constants, propagation times and settling times of physiological measures, baseline values of the physiological measures, values on exposure to reflex stimuli, as well as cortical stimuli representing typical signals in system identification theory (impulse, step, ramp etc.). With temporal fluctuations of the identified parameters of the patient, parameters a_i of the unimodal psychophysiological measure and the parameters of the Digital Controller can be adjusted.

Digital Controller

Digital Controller on the basis of the patient's unimodal psychophysiological measure $UM(t)$ tracks the reference unimodal psychophysiological measure $UM_{ref}(t)$. Main components of the Digital Controller are a mechanism for computation of the tracking error, controller based on fuzzy logic rules and interpreter, shown in Figure 8.

Inputs to the Fuzzy Logic Controller are the tracking error (TE) and its derivative $d/dt\ TE$, which represent the trend of the tracking error change. There are various ways of choosing the valence and arousal of the stimulus to get the same physiological response; therefore, the change of stimulation intensity ΔSI is used as the controller output. The interpreter then maps the change of stimulation intensity into the change of control signals $\Delta \boldsymbol{u}(t)$.

Input and output variables of the Fuzzy Logic Controller are represented as linguistic variables consisting of seven fuzzy sets with characteristic names, like {"negative big", "negative medium", "negative small", "zero", "positive small", "positive medium", "positive big"}. Besides deciding on the number of fuzzy sets for each linguistic variable, further degrees of freedom relate to the type and actual shape (triangular, trapezoid, Gaussian etc.) of membership functions defining the fuzzy sets. Figure 9 illustrates possible partition into fuzzy sets, for input variables TE and $d/dt\ TE$, and output variable ΔSI.

Decision making in Fuzzy Logic Controller is accomplished by fuzzy inferencing with fuzzy if-then rules. Fuzzy rule base contains a rule for every combination of the input fuzzy sets. Here, a few rules are illustrated:

- If tracking is ideal, maintain stimulation intensity,
  if (TE = "zero" and $d/dt\ TE$ = "zero") then (ΔSI = "zero"),
- If the patient is somewhat under-aroused, give more unpleasant arousing stimulus,
  if (TE = "positive small" and $d/dt\ TE$ = "positive small") then (ΔSI = "positive small"),
- Larger tracking error or derivative of tracking error mandate more intense stimulation,
  if (TE = "positive medium" and $d/dt\ TE$ = "positive small")
  then (ΔSI = "positive medium"),
  if (TE = "positive small" and $d/dt\ TE$ = "positive large") then (ΔSI = "positive medium").

Conclusion

This paper has presented an ongoing design and development of a physiology-driven adaptive VR system for PTSD treatment, describing the clinical rationale and major components of the system. Control signals and matching scene element annotations have been analyzed. Based on stimuli content, customization from the patient's interview and suitable psychometric tests, the Stimuli Generator resolves control signals via scene element annotations into the appropriate stimuli. The unimodal psychophysiological measure has been derived from various physiological signals in order to accurately represent the patient's emotional state. An accurate representation of the patient's emotional state is crucial for the correct functioning of the automated physiology-driven changes in the patient's level of exposure.

The physiology-driven adaptive VR system for PTSD treatment described in the paper attempts to build on the advantages of conventional VR exposure therapy over imaginal exposure therapy. Relieving the therapists of technical and administrative issues that occur in VR exposure and providing them with comprehensive, yet succinct, information about the patient's emotional state, may help the therapists conduct more effective PTSD therapy. However, after the working system is developed, these hypotheses need to be confirmed by experiments. Evaluation of the system against contemporary VR therapy systems according to various criteria is very important for its clinical utility. The most important and costly evaluation is a direct evaluation of treatment efficacy comparing therapists using the physiology-driven to a manually controlled VR system in a randomized controlled clinical trial. Except on the type of VR system employed, treatment efficacy depends on the patient's characteristics and the therapist's knowledge about the treatment method, so these confounding variables need to be controlled. Secondary criteria for a comparative evaluation, possibly correlated with treatment efficacy, include ease of use of the therapist's computer interface, quality of information about the patient's emotional state presented to the therapist etc. Further criteria may be measures of the system design qualities, like extensibility to account for new traumas or different hardware. After satisfactory evaluation results, the presented VR system would offer the therapists a promising tool for treating combat-related PTSD.

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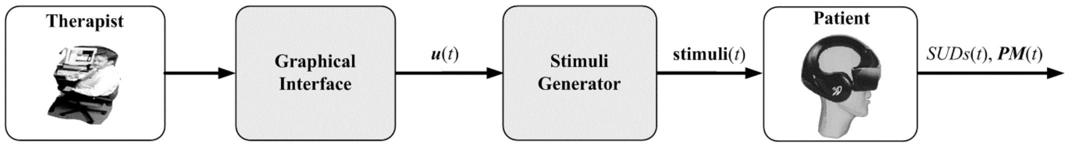
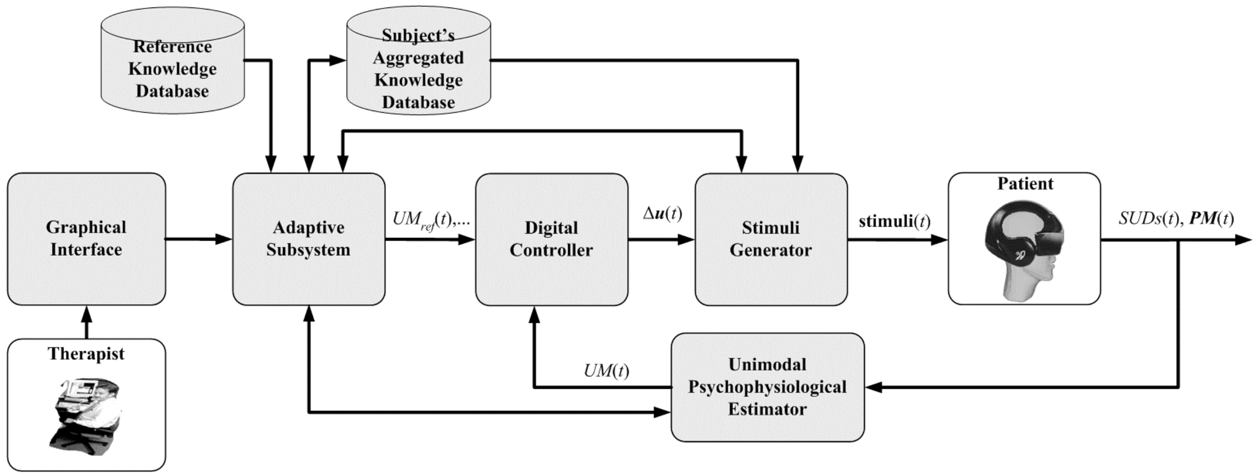
Table 1
Examples of Control Vectors with Explanations

Signal	Explanation
(reflex, undef, 15)	Reflex stimulus, without visual component, with auditory component of arousal 15. Example is a quiet startling sound.
(reflex, 60, 80)	Reflex stimulus, with visual component of arousal 60 and auditory component of arousal 80, respectively. Example is a moderately bright and sudden flash, delivered together with a loud startling sound.
(cort, fear, congr, syn3d, 30, 70)	Cortical stimulus, eliciting fear, with congruent visual and auditory components, visual component is synthetic, valence of components is set to 30, arousal is set to 70.
(cort, neutr, sep/incon, video, 45, 10, 50, 5)	Cortical stimulus, eliciting sadness, separate or incongruent visual and auditory components, visual component is live video of valence 45 and arousal 10, auditory component has valence 50 and arousal 5.

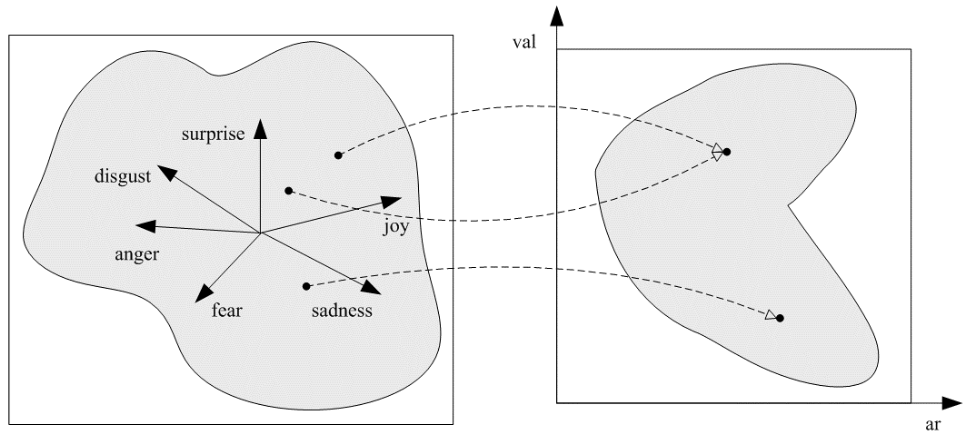
Figure Captions

Figure 1. Initial testing.
Figure 2. Adaptive control.
Figure 3. Conceptual mapping of the discrete emotion space based on Damasio's primary emotions to the valence-arousal space. Shaded areas represent distribution of stimuli; distribution in discrete emotion space is randomly drawn, and "boomerang" shape in valence-arousal space is based on (Bradley, 2000).
Figure 4. A tree defining the structure of the control signals.
Figure 5. Using class centered (left), and valence-arousal centered (right) metric for selection of the annotated scene element that minimizes typical Euclidean distance (point *E*), valence distance (point *V*), or arousal distance (point *A*) from the control signal (point *C*). Control signal is assumed to be specified as "neutr", and all available annotated scene elements are assumed to be represented by the shaded areas marked with "fear", "neutr" and "relax".
Figure 6. Step function realized in terms of control vectors, shown with the corresponding stimuli and change in unimodal psychophysiological measure. The images are courtesy of Wikipedia.
Figure 7. Two snapshots of the virtual environment just after 40 seconds (left), and just after 90 seconds (right), as designated by the arrows pointing at contents of the file with control signals. Vertical lines show the positions of the explosions and the ensuing smoke, and horizontal lines the moving directions of the plane and helicopter.
Figure 8. Structure of the Digital Controller.
Figure 9. Input and output variables of the Fuzzy Logic Controller.


Therapist
Graphical Interface
u(t)
Stimuli Generator
stimuli(t)
Patient
SUDs(t), PM(t)



Reference Knowledge Database
Subject's Aggregated Knowledge Database
Graphical Interface
Adaptive Subsystem
$UM_{ref}(t)$,...
Digital Controller
$\Delta \boldsymbol{u}(t)$
Stimuli Generator
stimuli(t)
Patient
$SUDs(t)$, $\boldsymbol{PM}(t)$
Therapist
$UM(t)$
Unimodal Psychophysiological Estimator



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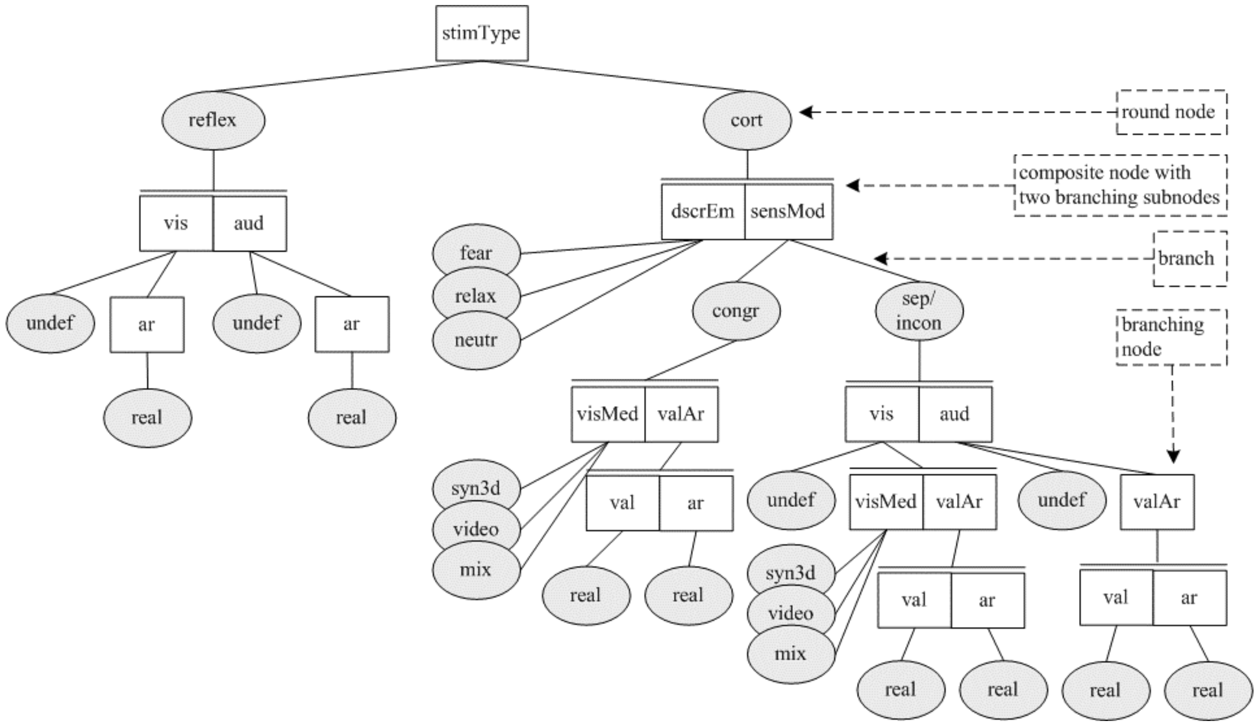
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relax
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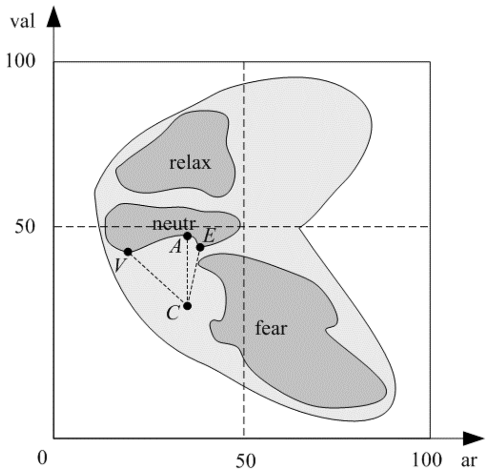

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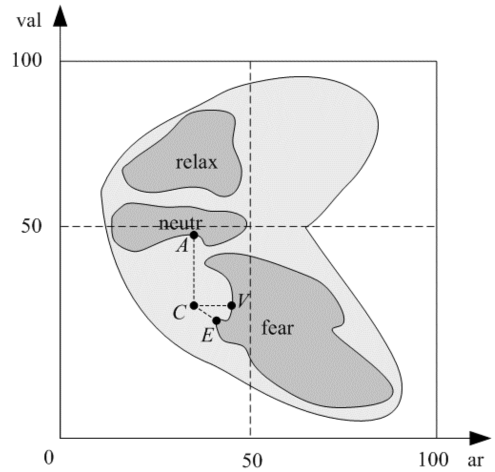

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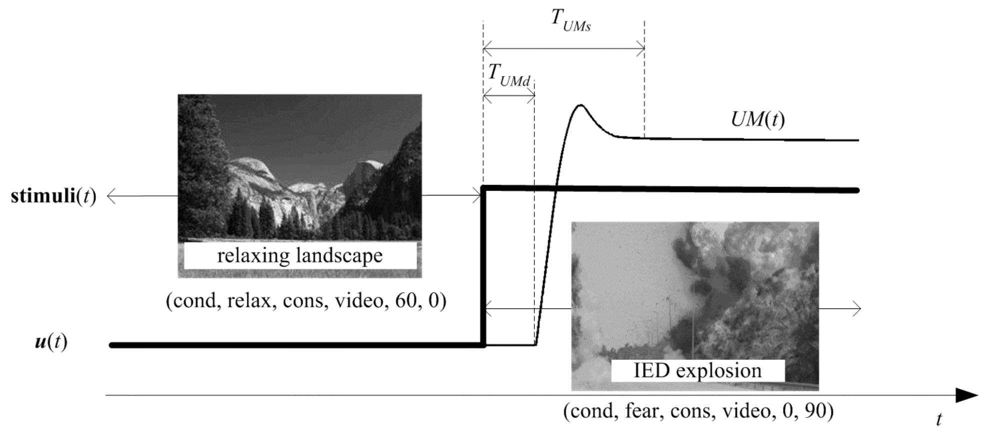
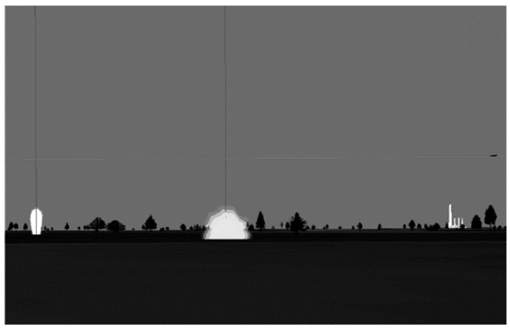
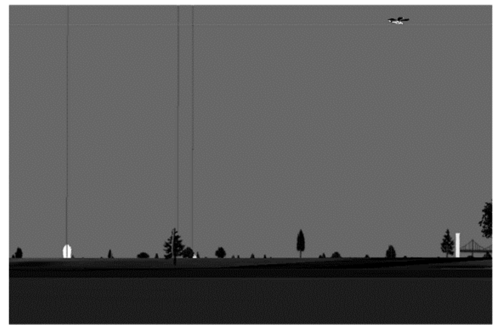


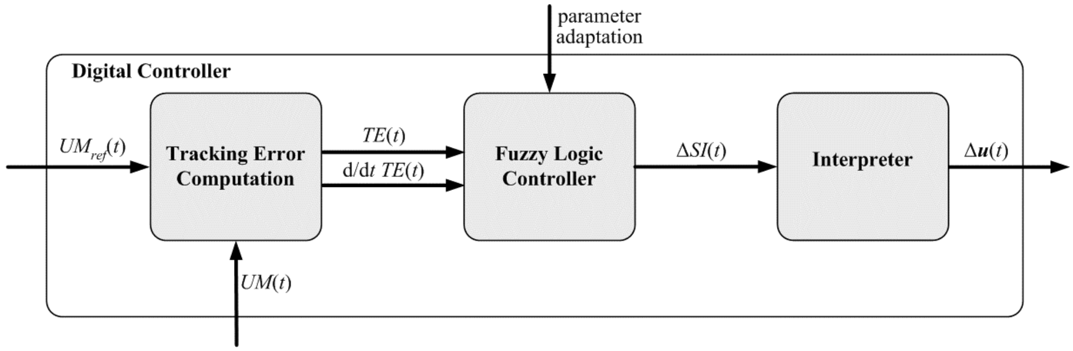
T_{UMs}
T_{UMd}
$UM(t)$
stimuli(t)
relaxing landscape
(cond, relax, cons, video, 60, 0)
$\boldsymbol{u}(t)$
IED explosion
(cond, fear, cons, video, 0, 90)
t

30 plane 50
35 explosion 94
40 explosion 97
70 heli 80
85 explosion 90
89 explosion 85
90 explosion 80

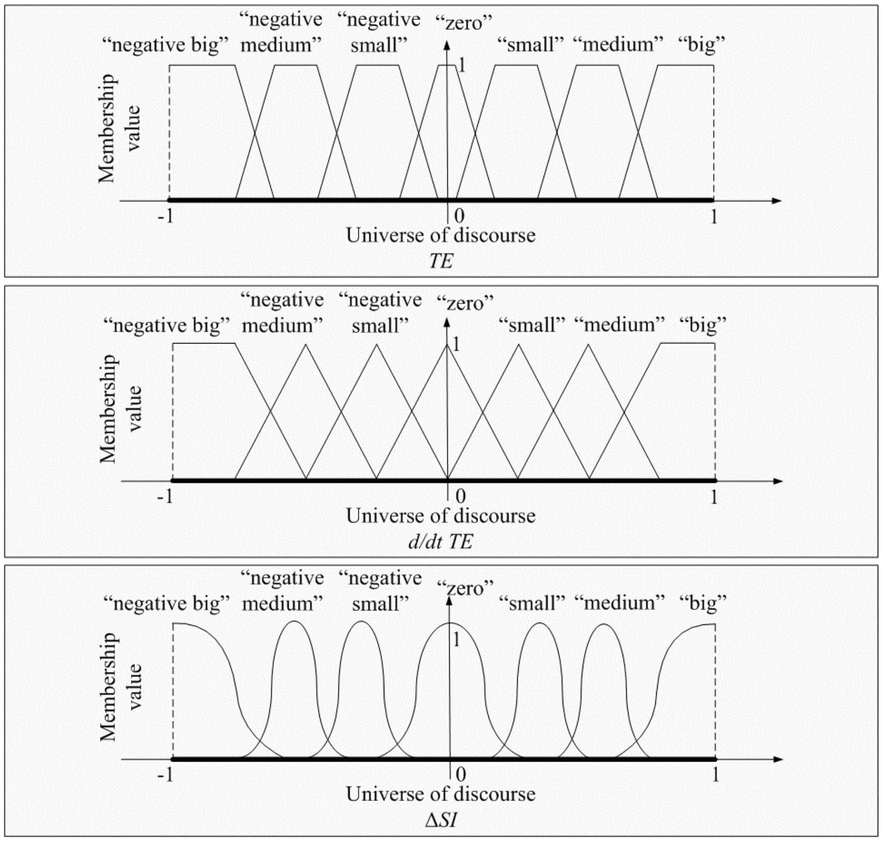


30 plane 50
35 explosion 94
40 explosion 97
70 heli 80
85 explosion 90
89 explosion 85
90 explosion 80





parameter adaptation
Digital Controller
UM_ref(t)
Tracking Error Computation
TE(t)
d/dt TE(t)
Fuzzy Logic Controller
ΔSI(t)
Interpreter
Δu(t)
UM(t)



"negative big"
"negative medium"
"negative small"
"zero"
"small"
"medium"
"big"
Membership value
1
-1
0
1
Universe of discourse
TE
"negative big"
"negative medium"
"negative small"
"zero"
"small"
"medium"
"big"
Membership value
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-1
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Universe of discourse
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ΔSI