Integrative Physiological Design: A Theoretical and Experimental Approach of Human Systems Integration

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Abstract. Human modeling in design consists of human system integration (HSI), human factors integrated with systems engineering. That involves augmenting human capabilities and improving human-in-the-loop systems global performance, robustness and safety by behavioral technologies. For such human-in-the-loop systems design, this paper proposes an integrative physiological approach based on Chauvet's mathematical theory of integrative physiology (MTIP). By applying MTIP principles as theoretical framework, the integrative physiological modeling is used to model HIS and experiment a gesture-based method for virtual environment (VE) design and human system integration assessment. To demonstrate the pertinence and practicability of the developed integrative approach, we apply it to a wearable interactive system made up of virtual environment technologies for gesture assistance. The design prototype was evaluated in weightlessness during parabolic flights and confirms the effectiveness of the integrative physiological modeling.

Keywords: human modeling design, human system integration, augmented human, virtual environment, gesture assistance, weightlessness.

1 Introduction

1.1 Human Modeling in Design

The major benefits of using human modeling in design include reducing the need for physical development; reducing design costs by enabling the design team to more rapidly prototype and test a design; avoiding costly design 'fixes' later in the program by considering human factors requirements early in the design process; and improving customer communications at every step of product development by using compelling models and simulations.

Thus, designing an artifact consists in organizing a coherent relation between structures and functions in a culture and context of usage [design=structure/function]. Modeling human consists in taking into account anatomical and physiological elements in the same model. It is to design functions by organizing a hierarchy of structural elements and their functions [human modeling=physiology (functions)

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/anatomy (structures)]. Such models should be used to create models of individuals rather than using aggregated summaries of isolated functional or anthropometric variables that are more difficult for designers to use. Therefore human modeling in design requires an integrative approach [1].

1.2 Augmented Human

Augmenting cognition and sensorimotor loops with automation and interactive artifacts enhances human capabilities and performance. It is extending both the anatomy of the body and the physiology of the human behavior. Designing augmented human beings by using virtual environment technologies means to integrate both artificial and structural elements and their structural interactions with the anatomy, and artificial multimodal functional interactions with the physiological functions. Thereby the question is how to couple and integrate in a coherent way, a biological system with a physical and artifactual system, the less or more immersive interactive artifact, in a behaviorally coherent way by organizational design.

For training or operational systems design this requires taking into account technical devices, artificial multimodal patterns of stimuli alltogether, and their integration into the dynamics of the human sensorimotor behavior. Thus augmenting human capabilities and enhancing human performance by using virtual environment technologies needs safe design principles for human system integration (HSI). To be safe and predictive, HSI models, interaction and integration concepts, methods and rules have to be well grounded. Just like physical laws and their theoretical principals ground the mechanics or materials sciences and the engineering rules (e.g. for airplanes design), HSI needs a theory of integration, a theoretical framework and it's general principals.

In this paper, according to our epistemological approach, we propose to use the mathematical theory of integrative physiology (MTIP) [3] [4] as a fundamental framework for human system integration and virtual environment design [7]. For illustrating this new paradigm we present an experimental protocol using graphical gesture to assess HSI and VE design carried out both in laboratory and in weightlessness [6]

2 Epistemology

Converging technologies for improving human performances, *augmented human*, needs a new epistemological and theoretical approach of the nature of knowledge and cognition considered as an integrated biological, anatomical, and physiological process, based on a hierarchical structural and functional organization. Current models for human - machine interaction or human-machine integration are based on symbolic or computational cognitive sciences and related disciplines. They even use experimental and clinical data; they are yet based on logical, linguistic and computational interpretative conceptual frameworks of human nature where postulate s or axioms replace predictive theory. It is essential for the robust modeling and the design of future rules of engineering for HIS, to enhance human capabilities and performance. *Augmented human* design needs both an integrative theory that takes into account the specificity of the biological organization of living systems, according to the principles of physics, and a coherent way to organize and integrate structural and functional artificial elements. Consequently, virtual environments design for augmented human involves a shift from a metaphorical, and scenario based design, grounded on *metaphysical* models and rules of interaction and cognition, to a predictive science and engineering of interaction and integration. We propose to ground HSI and augmented human design on an integrative theory of human being and its principles.

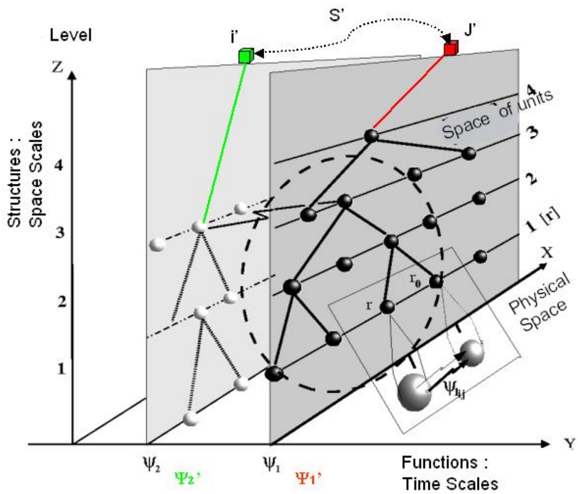

Fig. 1. 3D representation of the integrated augmented human design [7]

The human (Ω) is represented as the combination of the hierarchical structural (z) and functional (Y) organizations. The (x) axis corresponds to the ordinary physical or Cartesian space. Each physiological function ψ is represented in the *xψy* plane by a set of structural units hierarchically organized according space scales. Two organizational levels are shown: ψ_1 and ψ_2. The different time scales are on the *y* axis, while space scales, which characterize the structure of the system, are on the *z* axis. The role of space and time clearly appears. Ψ_{1ij} is the non-local and non-symmetrical functional interaction. Units at the upper levels of the physiological system represent the whole or a part of sensorial and motor organs. Augmented human (Ω') design consists in creating an artificially extended sensorimotor loop by coupling two artifactual structural units *I'* and *J'*. Their integration into the physiological system is achieved by the functional interactions (i.e. sensorimotor) they generate. From sensors outputs to effectors inputs, the synchronized computerized process *S*' controls and adapts the integration of the functional interactions artificially created into the dynamics of the global and coherent system.

3 Mathematical Theory of Integrative Physiology (MTIP)

Mathematical theory of integrative physiology [2] [3] [4] examines the hierarchical organization of structures (i.e., the anatomy), and of functions (i.e. the physiology), of a living system and its behavior. It introduces the principles of a functional hierarchy based on structural organization within space scales, functional organization within time spaces of the structural unit that are the anatomical elements in the physical space. It copes with the problem of structural discontinuity by introducing functional interaction, for physiological function coupling, and structural interaction, for anatomical structural coupling. Unlike interaction in physics, at each level of organization, functional interactions are non-symmetrical, leading to directed graph, non local, leading to non local fields, and augment the system stability of a living system by coupling two structural elements. It is a new theoretical paradigm for knowledge-based systems and augmented human design.

MTIP is thus applicable to different space and time levels of integration in the physical space of the body and the natural or artificial behavioral environment; from molecular level to socio-technical level; from drug design to wearable robotics, and to life and safety critical systems design. Thus augmented human design (fig. 1) is grounding augmented human modeling on the Chauvet's MTIP.

This kind of model assumes the existence of functional interactions between the engineered and the physiological sensorimotor systems [7].

4 Experience

The gesture based method for virtual environment design and human system integration assessment is a behavioral tool inspired by Chauvet's theoretical framework, i.e.: (i) an integrated marker for the dynamical approach of augmented human design, and the search for interaction primitives and validation of organization principles; and (ii) an integrated marker for a dynamical organization of VE integrative design.

By designing a virtual environment, a human in-the-loop system consists in organizing the linkage of multimodal biological structures, sensorimotor elements at the hierarchical level of the living body, with the artificial interactive elements of the system, devices and patterns of stimulation. There exists a "transport" of functional interaction in the augmented space of both physiological and artifactual units, and thus a *function* may be viewed as the final result of a set of functional interactions that are hierarchically and functionally organized between the artificial and biological systems.

We present results of experiments performed by three subjects on earth and in hypergravity and weightlessness during parabolic flights (Flight campaign n°8 CNES-SPACEHAB), using a virtual and augmented reality system for gesture assistance. Using analysis of three-dimensional hand movements (drawing of ellipses), we compare the dynamical sensory-motor integration and motor performance (orientation, shape, figural and kinematics features) with or without the assistance of virtual environments. Using this gesture-based method we evaluate physiological effects and integration of both change of gravity and artifactual environment on performance. We demonstrate how artificial visual information dynamically generated by a wearable virtual environment, may help gesture in the three-dimensional space parabolic flight, according to the MTIP principles

4.1 Integrative Physiological Design

Neurophysiology - Humans integrate multimodal sensorimotor stimuli in order to interact with their environment, be it natural or artificial (vision, vestibular stimulus, proprioception, hearing, touch, olfaction, taste..). When a subject is in a situation of weightlessness or of hypergravity, his sensorial system is submitted to an unusual pattern of stimuli. This dynamical pattern may largely influence the balance, the posture control, the spatial cognition and the spatial motor control of the subject [9]. If this coherence is absent, perceptual and motor disturbances appear, as well as illusions. These illusions are solutions built by the brain in response to the inconsistency between sensorial stimuli and internal processes. Therefore, the cognitive and sensory-motor abilities of the individual may be disturbed

Virtual environment as knowledge-based environment: Virtual reality and augmented reality technologies [12], because they are multimodal and aesthetic, are obviously the tools for the design and development of the assistance action and multimodal knowledge based artifactual environments. Knowledge is gathered from interactions and dynamics of the individual-environment complex and motivations. It is an evolutional, adaptable and integrative physiological process. It is fundamentally linked to emotions, mnesic process, perception and action. Then, designing an artifactual countermeasure system using virtual environment technology, a sensorimotor knowledge based environment, consists of making biological individual and artifactual physical system consistent. That needs an "eco-ethological" approach, both for the knowledge modeling, the interaction system design and the human system integration. Moreover, the coherence between artificial information and natural perceptual input is essential for the perception of space and the action within, especially during gravitational changes.

MTIP claims to develop experimental techniques to organize and to assess the behavioral coherence of the virtual environment design for augmented human performance. Because gesture is a high-level integrated sensorimotor and cognitive physiological function, it appears to be a primary expression of this global behavior and a behavioral tool for HSI and augmented human design[7].

4.2 Experiments

To test our assisting gesture prototype and highlight the dynamical principles of hierarchical organization of human systems integration and virtual environment design for assisting gesture in weightlessness, we set up a protocol according to a complex and incremental design. The experiments were performed during the 8th CNES Novespace parabolic flight campaign.

Devices: Head mounted display I-Glasses® immersive or see-trough, Frastrack Pohlemus® electromagnetic motion tracking system, workstation with a specific software design for managing and generating the visual virtual environment in real-time.

Protocol: Our protocol is based on graphical gesture analysis, more specifically of the drawing of ellipses within 3D-spaces. It's inspired by neurophysiology of movement [11] [9] [10]. Three right-handed trained volunteers were asked to draw ellipses (major axis 30 cm and minor axis 15cm) in two orientations of the three anatomical reference planes: vertical sagittal (VS) and transversal horizontal (TH). These drawing of ellipses were performed continuously and recorded during both the 1.8g ascent and the 0g parabola itself, feet in foot-strap (F) or in free-floating (FF), in two main situations: free gesture and assisted gesture wearing a visual virtual environment. Visual virtual environment was generated in immersion (RV) or in augmented reality (RA) (fig.2 and fig.3) .

Data analysis: sixteen gesture-related variables are calculated from data produced during the parabola and recorded from the sensor worn on the tip of the index finger of the working hand: kinematics (Number of ellipses), Average velocity , Covariation Vt/Rt, Amplitude), position (Global position, Position / x axis, Position / y axis, Position / z axis), orientation (Global orientation, Orientation / sagittal plane, Orientation / frontal plane, Orientation / horizontal plane) and shape (Mean area, Eccentricity, Major axis variation, Minor axis variation).

Statistical analysis: We use a method of multidimensional statistical analysis. Principal component analysis and hierarchical classification are calculated with SPAD 4.0® to show the differential effects of hypergravity and microgravity on graphical gesture for each subject wearing or not the system. A second goal of this exploratory statistics is to assess the design of our prototype and the dynamics of the human virtual environment integration in weightlessness and on earth.

4.3 Results

Hypergravity (1.8g): Exploratory statistics show the effects of a prototype for assistance to gesture. Without assistance, the drawings of ellipses vary in an important way , both in shape (mean area, major and minor axis) and in position (global position and on the y axis). Orientation of gesture also has an influence. Global position and eccentricity present a larger variation in the TH orientation for the three operators. Inter-individual differences are a little more important in the VS orientation. The use of the gesture assistance improves the drawing of ellipses for both orientations with a difference between VR and RA, nevertheless. Graphical gesture is more accurate using immersive environment than augmented reality. We observe few inter-individuals variations and no orientation influence with virtual reality.

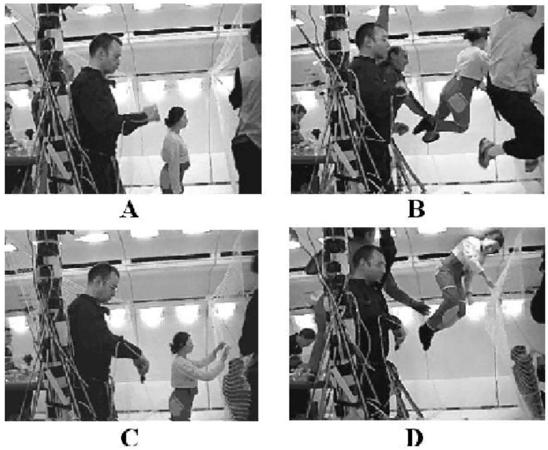

Fig. 2. Drawing of SV (A,B) and HT (C, B) ellipses without assistance in hypergravity (1,8g – A, C) and microgravity (0g – B,D)

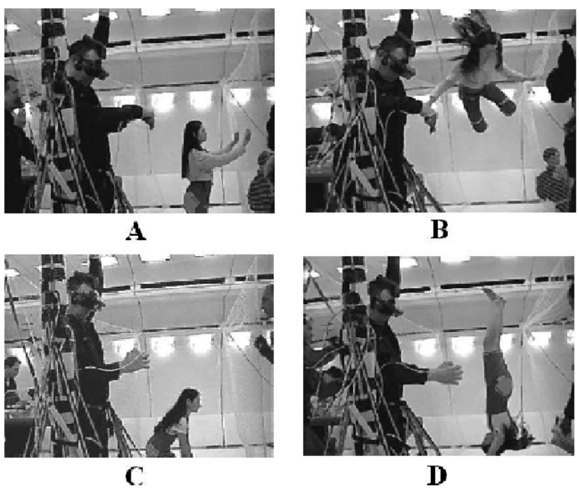

Fig. 3. Drawing of SV (A,B) and HT (C, B) ellipses with gesture assistance in hypergravity (1,8g – A, C) and microgravity (0g – B,D)

While with augmented realty assistance, see-trough helmet, gesture variations depend on both the individuals and the orientation. Differences are narrow for subject 1 and 2. Subject 3 presents broader variations of the global orientation in TH orientation regarding horizontal and frontal variations. In hypergravity, immersive assistance, virtual reality, is more efficient than augmented reality; moreover there are no differences as far as the foot-straps is concerned.

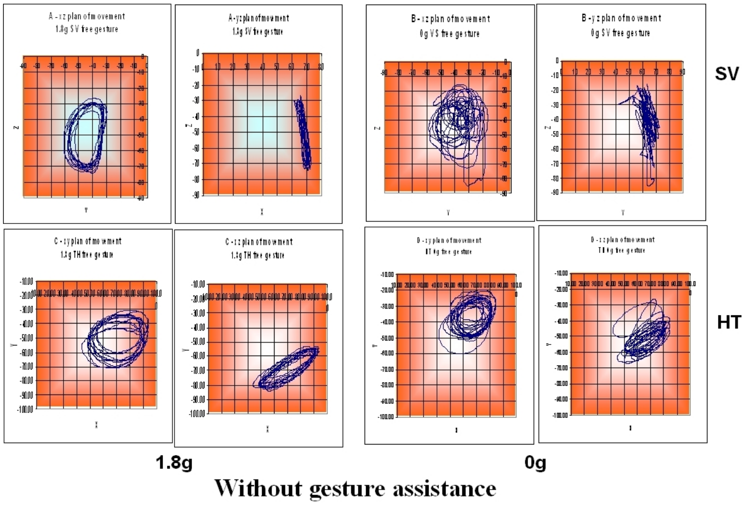

Fig. 4. Example of graphical gesture plotting of SV and HT ellipses drawn without assistance in hypergravity (1,8g) and microgravity (0g)

Microgravity (0g): Exploratory statistics prove the efficiency of virtual reality for assistance of graphical gesture in weightlessness. Immersive virtual environment improves position and orientation of drawn ellipses significatively and operator's behaviors are quite similar with feet in foot-straps. In free floating, there is also a homogeneous behavior in the VS orientation with VR assistance, but there are more inter-individual differences in TH orientation. In micro gravity our RA prototype brings less improvement than VR. RA main efficiency is on spatial orientation of gesture, especially on VS. For kinematics, position and shape variables, RA efficiency depends on both gesture orientation and individuals, with no influence of feet strapping.

In microgravity, the main inter-individuals differences depend on spatial orientation wearing RA assisting system or without assistance. For these two situations, subject1 presents fewer differences than the two others. His behavior is homogenous for both orientations and feet strapped or not. For TH orientation s1 presents a quite similar behavior with both VR and RA. With RA graphical gesture is close to s2 and s3 in VS orientation of action. Subjects s2 and s3 wearing RA systems are very sensitive to free floating. Their behavior is similarly dependant on gesture orientation with RA or without assistance.

Without assistance (Fig.4): Drawing of ellipses in hypergravity presents most changes of shape and position according to orientations and in VS plan of movement there are more inter-individual variations. Microgravity is mostly effecting orientation and position.

With assistance (Fig.5): Virtual environment, whether immersive virtual reality or augmented reality, improve graphical gesture in 3D space during parabolic flights. In hypergravity their effects are similar. In microgravity, VR is more efficient than RA especially concerning improvement of spatial orientation of gesture and position. Furthermore VR reduces inter-individual differences for VS and TH orientation with feet strapped and only for SV orientation in free floating.

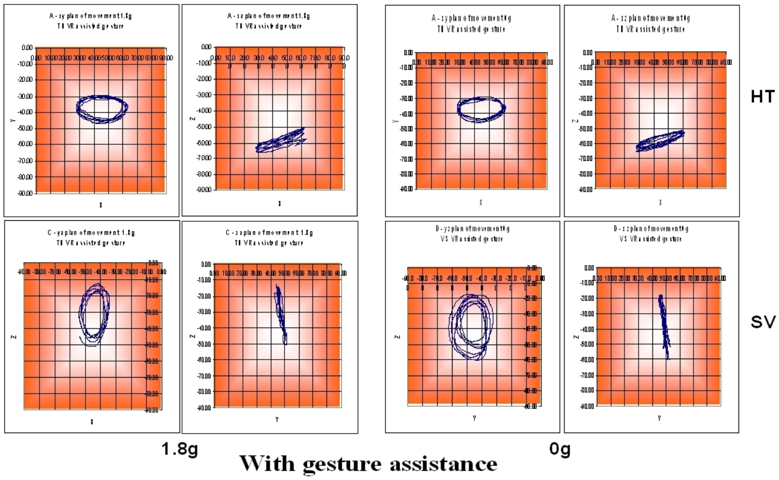

Fig. 5. Example of graphical gesture plotting of SV and HT ellipses drawn with assistance in hypergravity (1,8g) and microgravity (0g)

These experiments show (Fig.4 and Fig.5) the pertinence and practicability of the developed integrative approach of human modeling design for augmented human design and human system integration by showing improved motor skills and gesture performance.

5 Conclusions and Applications

Human modeling in design for the purpose of building human-in-the-loop systems can be a complex and dynamic endeavour. Augmented human design, i.e. assisting gesture technologies, needs an integrative approach that takes into consideration the specificity of biological organization of living systems, according to the principles of physics, and a coherent way to organize and integrate structural and functional artificial elements. Our experiments demonstrate the full potential of virtual environments for gesture assistance in weightlessness and in hypergravity. They assess the pertinence and the reliability of human systems integration modeling based on the MTIP principles.

Therefore, integrative physiological design is a framework for future developments of both augmented and cooperative human and environment. As virtual environments or wearable technologies, integrative artifacts will found the next assisting and countermeasures tools and smart environments for human space activities. Integrative physiological design will be necessary to model forthcoming architecture of safety critical systems or to develop applications to human on earth in the likes of surgeons, service engineers , physically challenged or elderly people.

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