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EYE MOVEMENT CONTROL AND TOP-DOWN SCANPATH VISION AS A DESIGN METAPHOR FOR ROBOTIC VISION AND CONTROL

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I. Eye Movement Control

1. Kinetics: Time Optimal Control of Saccades

Eye movements are elegant biological examples for application of time-optimal engineering control theory. The muscles that drive eyeball rotations are very long and strong and fast. The eyeball has low rotational inertia so that the internal viscosity of active muscle dominates plant dynamics; thus we may think of the system as a visco-elastic load. What controller signal shapes would produce a time-optimal movement? First, reciprocal innervation, proposed by Descartes (#149) and experimentally found by Sherrington, should be observed (Figure 1A). Next, a set of multipulse-step control signals first described by Clark and Stark (#137) can be justified on theoretical grounds by Bellman-Pontriagin bang-bang theory.

2. Dual Mode Control: Sampled Data Operator

Another beautiful example is the sampled data control model of Young and Stark (#27) that was experimentally verified by study of transient responses in normal subjects. A further exciting demonstration was found in the explanation of "macro-saccadic oscillation" found in patients with cerebellar disease that effectively removed the continual adaptive gain adjustment and left the patient with high gain instability oscillation (#156). (Figure 1B).

II. Higher Level EM Control and Scanpath Theory

3. Active Looking and the Kantian Theory of Perception

A more metaphoric theory, the Scanpath Theory has been developed by Noton and Stark (#110) and Stark and Ellis (#211) to account for the repetitive sequence of saccades that enable the eye and its fovea centralis to traverse over important sub-features of a picture or scene. This has been taken to mean than an internal cognitive model drives active looking in a top-down manner. The evidence to support this theory has to do with statistical proof that there is indeed repetition of scanpath sequences. Further evidence comes from studies of ambiguous figures wherein the same subject looking at the same picture switches both mental states of perception and patterns of repetitive saccadic sequences. Most recently, Brandt and Stark (in preparation) have used visualization tasks. A subject recalling a previously seen diagram demonstrates scanpath movements similar to those looking at the earlier viewed diagram; here only the internal model can be responsible for the scanpath sequence and, indeed, string editing distances support this finding quantitatively. (Figure 2A).

The philosopher, Kant, reasoned that internal representations (Platonic ideals) controlled active perception in a top-down procedure that could then organize sensation (without time and without space) received from the chaotic work of appearances. In this view, the virtual model within a human brain is more real than the external world of the naive realistic! (Figure 2B).

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III. Top-Down Robotic Vision

4. Models of Robots and ROIs

For our use of visual feedback, for use by autonomous algorithms, for use by manual operators, and for use by supervisory controllers. We have taken this top-down scheme from human vision and introduced it as a basic design principle in our Telerobotic Laboratory. Instead of searching for important features of the TRWE (telerobotic working environment) with bottom-up image processing algorithms, we instead use a top-down approach. We already know where a particular robotic link is located in 3D space, we know where the cameras are pointed, we know what important

parameters we need to measure. Thus, we use our knowledge in the form of forward-loop control model not only to control the robots and the cameras, but also to direct the image processing (#312 and A304). We construct ROIs (regions-of-interest) for each camera frame so that the image processing can be done rapidly and robustly (Figure 3A).

Within the ROIs, local thresholding and centroid calculations enable us to compute a feedback model, indicated by crosses that represent the visual measurement of the location of key on-the-scene-visual-enhancements. This, of course, is done dynamically so that rapid feedback permits closed-loop control of the robotic movement, with the human operator acting as a supervisory controller only (Figure 3B).

IV. Over-All Robotic Control Scheme

5. Model of RWE

The overall model (Figure 4A) permits one to appreciate the communication functions of our top-down image processing scheme. Communication is restricted to parameters of the visual models, an enormous bandwidth reduction compared to sending video pictures of a number of views of the TRWE. The supervisory controller looks not at the camera view of the scene, but rather at a model of the TRWE! Is this going to be satisfactory? (#T411, #313).

6. Evaluation of Displays and HMD

Several evaluation studies of visual display requirements have been carried out in our laboratory (#301, #A313). Dr. Won Soo Kim and colleagues have established that, although for some purposes enhanced 2D displays enable the operator to perform satisfactorily, virtual 3D displays are robust to various deficiencies and enable performance at least as good as the best 2D displays. Also, models alone or models superimposed onto video pictures are better than video pictures for short-term robotic control tasks (Figure 4C, #A291). In another study, Dr. Greg Tharp and colleagues demonstrated that 5 to 15 Hz update rates for a stereo display were fast enough to permit the subject to slew his head freely without suffering a penalty in performance (delays were less than 1 frame interval). (Figure 4B).

V. Summary

Telerobotics with virtual environments is an exciting and worthwhile field of research. It offers challenges to engineering design of displays, of control, and of communication schemes. It relates to human performance since the human operator is a component either as a direct manual controller or as a supervisory controller. It will teach us more about human capacities and we can use knowledge of human plans and schemas to produce initial designs. We are also learning more about ourselves. Did we thing about "presence" before we considered telepresence?

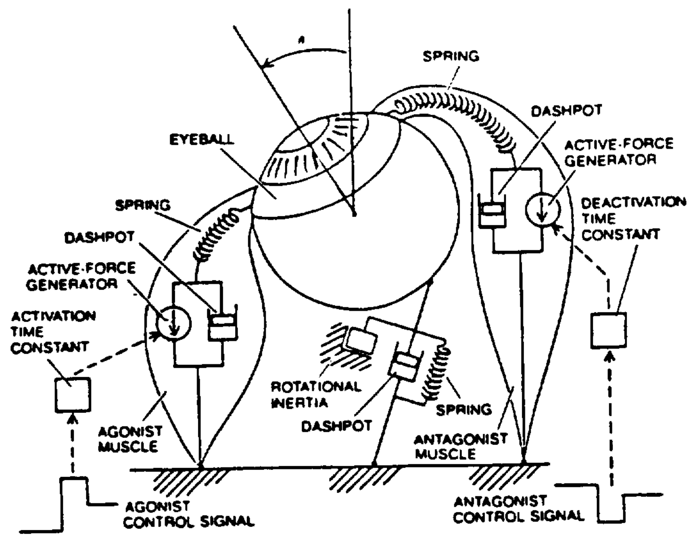


Figure 1A. Descartes model.

#149 Kenneth J. Ciuffreda and Lawrence Stark, "Descartes' Law of Reciprocal Innervation," *American Journal of Optometry and Physiological Optics 52:* 663-673 (1975)

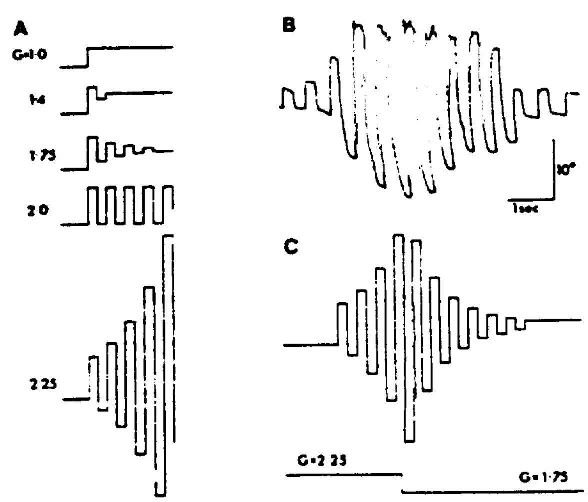


Figure 1B. SD clinical simulation.

#27 Laurance R. Young and Lawrence Stark, "Variable Feedback Experiments Testing a Sampled Data Model for Eye Tracking Movements." *IEEE Transactions on Human Factors in Electronics HFE-4:* 38-51 (1963)

#156 John B. Selhourst, Lawrence Stark, Alfred L. Ochs and William F. Hoyt, "Disorders in Cerebellar Ocular Motor Control. II. Macrosaccadic Oscillation: An Oculugraph, Control System and Clinico-Anatomical Analysis." *Brain 99:* 509-522 (1976).

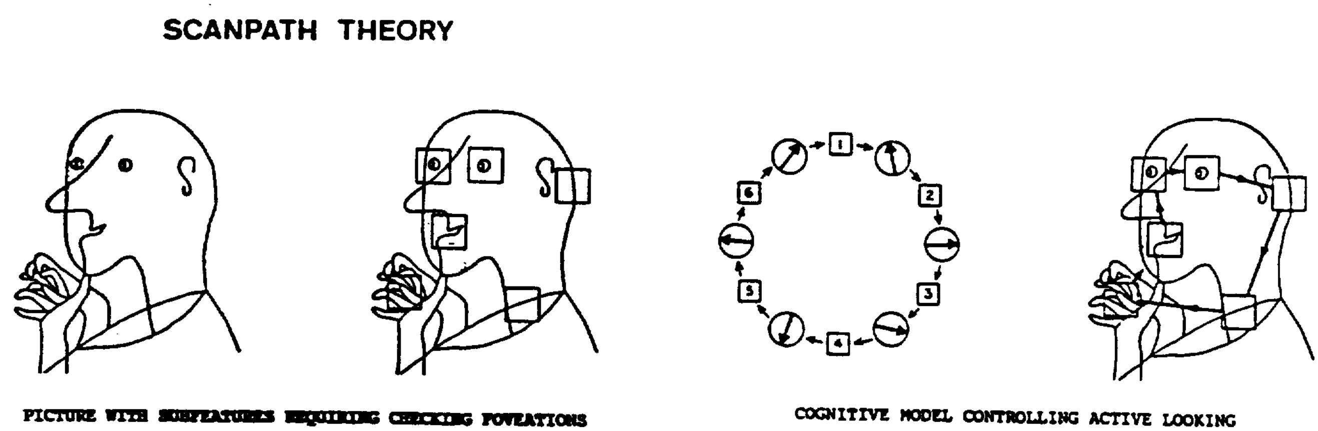


Figure 2A. Scanpath theory.
#110 David Noton and Lawrence Stark, "Eye Movements and Visual Perception." *Scientific American 224:* 334-43 (1971).

#211 Lawrence Stark and Stephen Ellis, "Scanpaths Revisited: Cognitive Models Direct Active Looking." In: *Eye Movements, Cognition and Visual Perception*, ed. Fisher, Monty and Senders, New Jersey: Eribaum Press, 193-226 (1981).

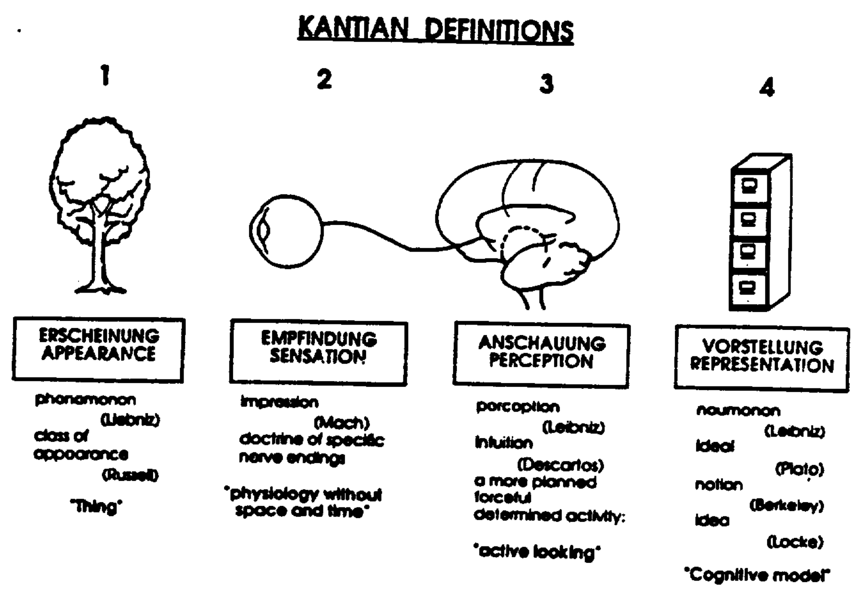
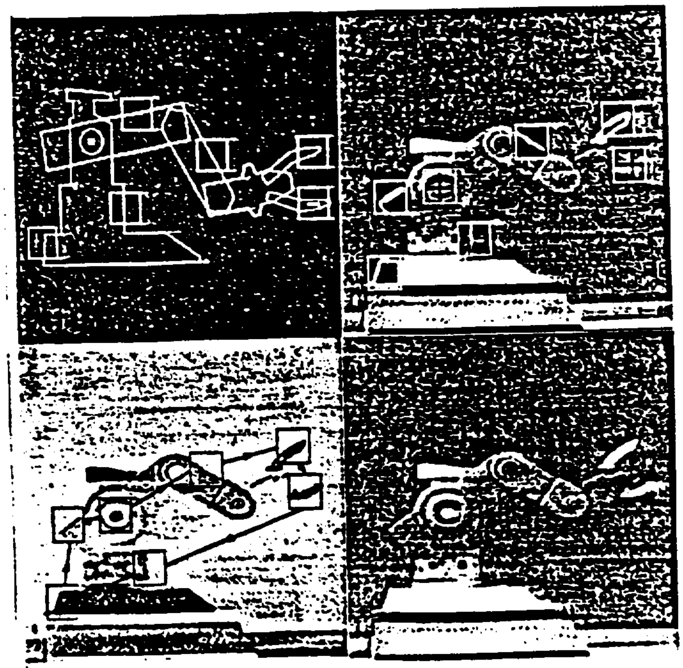
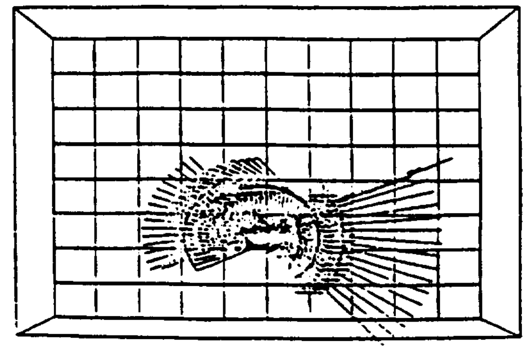


Figure 2B.
#287 L. Stark, W.H. Zangmeister, B. Hannaford and K. Kunze, "Use of Models of Brainstem Reflexes for Clinical Research." In: *Clinical Problems of Brainstem Disorders*; Thieme Publishers, New York: 172-184 (1986).



A



B

Figure 3A and 3B.
#312 Lawrence Stark, Barbara Mills, An Nguyen, Huy X. Ngo, "Instrumentation and Robotic Image Processing Using Top-Down Model Control." *Robotics and Manufacturing*, Jamshidi et al., eds., ASME, NY (1988): 675-682).

#A304 An Nguyen and Lawrence Stark, "3D Model Control of Image Processing." NASA Conference of Space Telerobotics, Pasadena (1989).

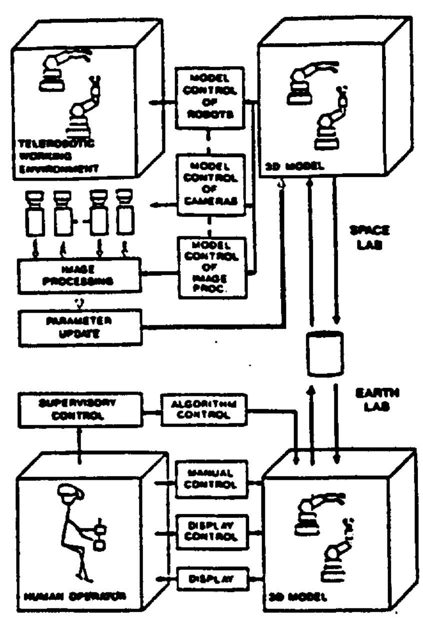


Figure 4A.
#313 Lawrence Stark, et al., "Telerobotics: Problems and Research Needs." *IEEE Transactions, Aerospace and Electrical Systems 24:* 542-551 (1988).

#T411 Lawrence Stark, "Biological Redundancy," in progress.

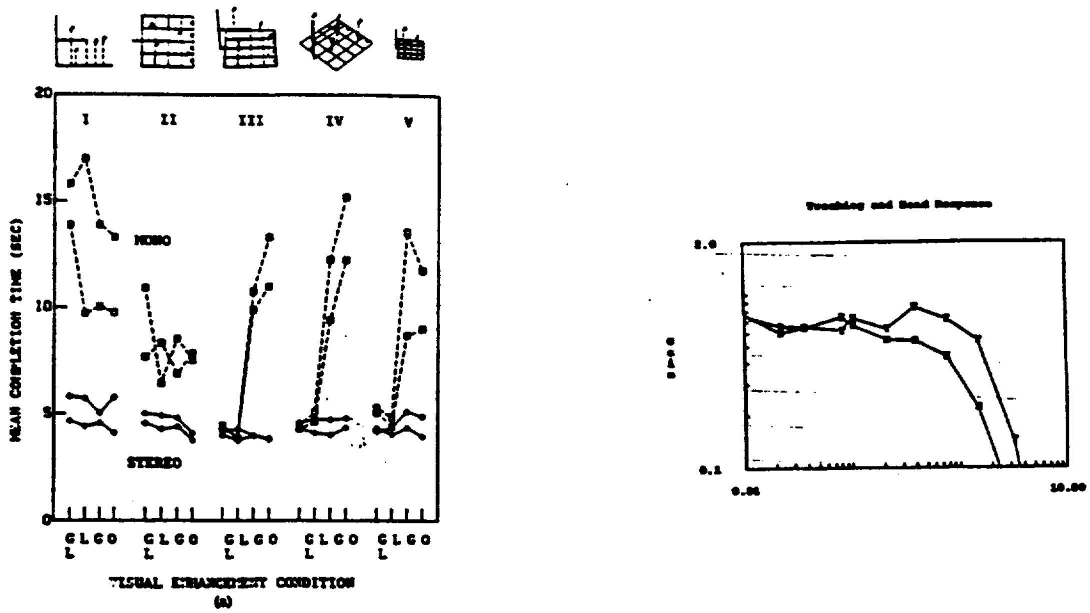


Figure 4B.
#301 Won Soo Kim, Frank Tendrick, Stephen Ellis and Lawrence Stark, "Visual Enhancement in Pick-and-Place Tasks: Human Operators Controlling a Simulated Cylindrical Manipulator." *IEEE Journal of Robotics and Automation RA-3:* 426-436 (1987).

#A313 Gregory Tharp, Andrew Liu, Hitomi Yamashita, Lawrence Stark, Brenda Wong and Jurgen Dee, "A Helmet Mounted Display to Adapt the Telerobotic Environment to Human Vision." Johnson Space Center, Texas (1989).

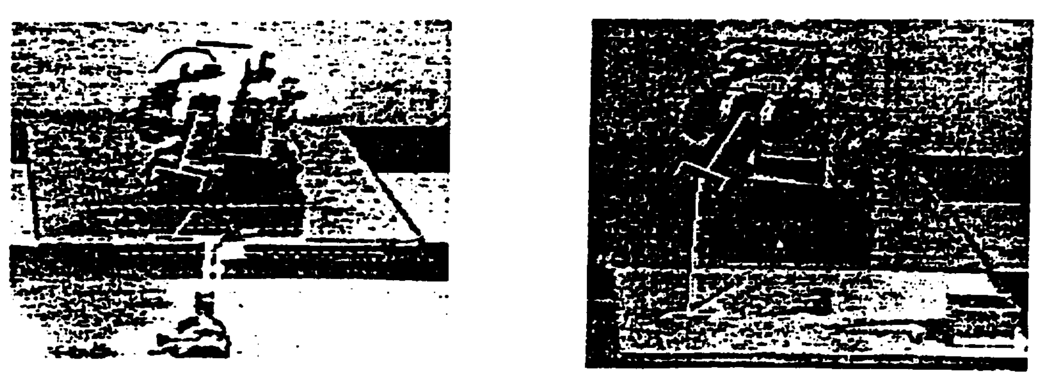


Figure 4C.
#A291 Kim, W. S., Takeda, M. and Stark, L., "On-the-screen Visual Enhancements for a Telerobotics Vision System." *Proceedings IEEE International Conference, Systems, Man & Cybernetics,* Beijing (1988).