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ANALYSIS OF THE HUMAN OPERATOR SUBSYSTEMS

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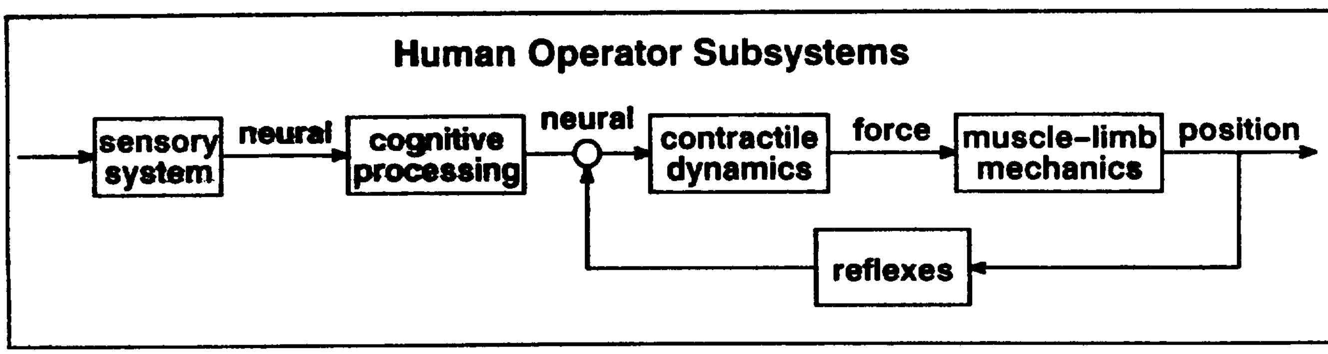
Except in low-bandwidth systems, knowledge of the human operator transfer function is essential for high-performance telerobotic systems.. This information has usually been derived from detailed analyses of tracking performance, in which the human operator is considered as a complete system rather than as a summation of a number of subsystems, each of which influences the operator's output. Limitations in analytic techniques and insufficient knowledge about the characteristics of the human operator have resulted in these "black box" depictions of tracking performance. One consequence of this approach is that it has been impossible to determine the source of change in the parameters of the transfer function under different conditions. Studies of one of these subsystems, the limb mechanics system, demonstrate that large parameter variations can occur (e.g., the elastic stiffness of a limb can change over a 50-fold range for different levels of muscle activation), that can have a profound effect on the stability of force-reflecting telerobot systems.



One of the objectives of our research is to decompose the performance of the human operator system (i.e., its damping, natural frequency, pure delay, static gain) in terms of the subsystems depicted above, in order to establish how the dynamics of each of these elements influence the operator's responses. For example, the delays associated with each subsystem are different (ranging from 15ms for contractile dynamics to over 150ms for cognitive processing), and for some subsystems the transformations are linear and time invariant, whereas for others they are nonlinear and time varying. Recent advances in nonlinear system identification make it possible to characterize the dynamics of the human operator subsystems in a single experimental session. Ideally the same equipment and analytic procedures should be used in all phases of this process. On the basis of the results from such an analysis, it should be possible to predict for any given operator the conditions (e.g., muscle-joint segment, type of controlled response, mechanical properties of the human interface) under which control is optimal.

With this objective in mind, we have constructed an apparatus for studying the human neuromuscular system in terms of its neural (contractile dynamics), mechanical (limb mechanics), perceptual (sensory thresholds), and tracking (human interface) characteristics. The apparatus consists of two powerful computer-controlled linear actuators instrumented with displacement and force transducers. With this equipment the neuromuscular function of the muscles controlling the elbow can be determined by imposing small, wide-bandwidth, stochastic length perturbations to the forearm. In addition the mechanical, reflex, and neural excitation to force dynamics of the neuromuscular system controlling the elbow flexor/extensor muscles can be measured, sensory thresholds can be calculated, and finally the tracking dynamics of the human operator control system can be determined. To date, studies of these subsystems have been limited to single joints such as the elbow, and the effects on tracking performance of varying the response type and human-interface properties have been investigated.

The characteristics of the human operator in a pursuit-tracking task change as a function of the operator's response. When subjects track a visually presented target either by changing the position of their forearm or by modulating the forces generated by the elbow flexor and extensor muscles, force control is superior to position control in terms of response delay (100 ms less), but subjects are more accurate when position is the controlled variable. Position control is, however, influenced by the mechanical properties of the human interface, and in particular changes in manipulator stiffness affect both response delay (less at higher [up to 2000 N/m] stiffness amplitudes) and tracking accuracy (more accurate at lower [< 1500 N/m] amplitudes).