Generation of Skilled Multi-joint Reaching Movements under DOF Redundancy

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Human can move dexterously an upper limb through rotation of joints regardless the degree of freedom of the joints is redundant. In such case, however, there exists a myriad of arm poses for kinematically accomplishing a specified endpoint position and they cannot be determined uniquely. This is well-known not only as "Bernstein's DOF problem" in physiology but also as "ill-posedness of inverse kinematics" in robotics, and leads to the difficulty of motion control of an arm with redundant joints. Human can move such a redundant arm coordinately. If a mechanism of human movements is clarified, robot arms will be manipulated more dexterously.

This paper challenges this unsolved "DOF problem" from physical analysis of human reaching movements, and approaches to the principle of human skill. It is shown that the coordinated damping shaping at joints is very important to generate a skilled motion. Differently from the well-known approaches in motion control of an arm with redundant joints, which derive a unique joint trajectory optimized by some cost function, this paper suggests a novel approach such that a control signal is composed of only a task-space position error feedback together with damping shaping without using precise dynamics parameters. The effectiveness of the proposed scheme is also discussed.

First, in the case of planar reaching movements by an arm with four joints, an idea named "Virtual spring hypothesis" is introduced. The hypothesis translates reaching movements as effects of intentional force leading the endpoint to the target expressed as virtual spring-like force in task space together with joint dampings. In the proposed approach, there remains a possibility that some unexpected self motion is incurred during movements due to the joint redundancy when the joint damping factors are selected inadequately. However, such a redundancy problem is resolved by determining the joint damping factors so as to meet the order of square root of the inertia matrix of the arm. Furthermore, the proposed method can generate human-like coordinated motion. The convergence to the target in such a movement is theoretically verified by using the ideas of "stability on a manifold" and "transferability to the sub-manifold." Next, the virtual spring hypothesis is extended to "Virtual spring-damper hypothesis" by considering effects of virtual damper in parallel to the virtual spring in task space. It is shown that the additional virtual damper effects can generate easily quasi-straight endpoint trajectories, which are well-known as typical characteristics of human skilled movements. The convergence in this case is also verified theoretically. These ideas are applied, furthermore, to three-dimensional reaching movements under the gravity effects, motion generations of industrial robot arm with redundant joints, and object manipulations by a hand-arm system. Based upon the idea of the virtual spring-damper hypothesis, the task-space iterative learning control (ILC) is suggested in order to accomplish any trajectory trackings. Its effectiveness is also verified by theoretical analyses, computer simulations, and experiments. Whereas in the conventional ILC the learning term has been constructed almost at the joint level, the proposed method accomplishes trajectory trackings through the task-space level learning with adequate damping shapings even in the case of an arm with redundant joints.